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Technical Memorandum

To: Jeffrey Kimble, U.S. EPA, Enbridge Oil Spill Federal On-Scene Coordinator
From: Weston Solutions, Inc. Region 5 START Contractor
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Subject: Enbridge Oil Spill, Kalamazoo River Bathymetry and Floodplain Topography Updates Used for 2014 Site Hydrodynamic and Sediment Transport Models

1.0 INTRODUCTION

During 2011-2012, as part of the Enbridge Oil Spill response activities, Enbridge contractors developed an initial two-dimensional (2D) site hydrodynamic and sediment transport model for the affected portion of the Kalamazoo River between Talmadge Creek and Morrow Dam, which was submitted to U.S. EPA in April 2012 (Enbridge, 2012a). A location map showing the affected portion of the Kalamazoo River is provided for reference in attached Figure 1. Based on a review of the model, U.S. Geological Survey (USGS) and Weston/START project personnel provided written comments to Enbridge identifying numerous deficiencies in the model and requesting necessary updates and corrections (U.S. EPA, 2012). Enbridge declined to perform the updates and corrections and, as a result, U.S. EPA, Weston/START and USGS, plus other project scientific support personnel took over continued development of the 2D site model in early 2013.

Updates and corrections to the river bathymetry and floodplain topographic inputs to the model were undertaken by Weston/START, and were a major component of the continued Kalamazoo River 2D model development. The bathymetry updates and corrections were initiated in part to make use of a large data set of new point bathymetry measurements collected by Enbridge during 2012, as part of the Spring 2012 Submerged Oil Poling Reassessment task, which were not available at the time of the initial model development. The new 2012 point bathymetry dataset provided expanded coverage in some portions of the river; more importantly, the addition of a large number of new points distributed along river transects allowed use of improved, along-channel interpolation methods to better represent the river channel bathymetry. As the work progressed and, as practical, additional project bathymetry data collected in 2013-2014 were incorporated into the updates primarily in off-channel/backwater locations and other locations within Morrow Delta where data were previously lacking.

The purpose of this Technical Memo is to: i) identify and describe all source data used for the bathymetry and topographic updates to Enbridge's 2012 model, ii) describe the data analysis and interpolation methods used for the updates, and iii) present the elevation update results including comparisons with the previous model grid elevations. It is noted that the raster files of updated bathymetry and topography are stored and maintained as part of the U.S. EPA project files and they have been used as input files for all 2013-2014 updates to the site hydrodynamic and sediment transport models by USGS and others.

2.0 BACKGROUND AND APPROACH

Complete and accurate bathymetry and topographic information are required in order for two-dimensional and three-dimensional hydrodynamic models of channelized water bodies to be reliable (e.g., Merwade et al., 2008). Typically, the required information is obtained through interpolation based on a limited number of observed or measured input elevation data. Problems inherent in applying conventional interpolation methods to channelized settings are well documented and include creation of erroneous interpolated bathymetry owing to input points that are widely separated from a given target location along the channel but approach proximity because of irregular channel bends; also, erroneous bathymetry may arise from input points that are close to a target location but occupy dissimilar positions relative to the channel centerline or thalweg (e.g., strongly anisotropic channel slopes exist) (e.g., Merwade et al., 2006). These problems tend to be diminished in cases where input data are abundant, but are exaggerated where input data are relatively scarce (e.g., Merwade et al., 2006).

In a published comparison study of channel interpolation methods applied to different river settings, Dr. V. Merwade and others demonstrated that accurate channel interpolation results could be obtained by simple linear interpolation between corresponding input points located along spaced channel transect lines (e.g., Merwade et al., 2008). The accuracy of the channel interpolation results obtained in this study was based on comparison against independent observed elevation points. It was noted in the study that conventional interpolation methods were capable of similar accuracy, but were typically more complex to implement, or required a greater density of input data, or both. The authors further indicated that a custom GIS tool for performing the along-channel linear interpolation was publically available for use by standard GIS software; the output results from this GIS tool reportedly consisted of a series of created mesh points, with interpolated bathymetry values, located at spaced intervals between the input sections. Based on the results of the comparison study, and the apparent similarities between data used for the respective studies and the available input data for the Kalamazoo River, the custom GIS tool developed by these authors was considered for possible use to update the bathymetry for the affected Kalamazoo River segment.

In December 2012, Dr. V. Merwade was contacted and agreed to perform a preliminary review of available bathymetry input data for representative impacted segments of the Kalamazoo River. In a follow-up telephone conversation, Dr. Merwade confirmed that the available input data were generally sparse overall, but that the transect data included in the package provided to him were adequate to perform the along-channel, linear interpolation using his custom GIS tool. Dr. Merwade further recommended that the best approach to make use of all available data would be a two-step interpolation process, involving: i) an initial step of linear interpolation between input sections (e.g., input transect points) using the custom GIS tool, and ii) a second step using conventional interpolation methods in which the inputs would consist of interpolated points generated by the initial step (e.g., Merwade tool mesh points), combined with any additional observed bathymetry points located in the target reach (R. Zelt, U.S. Geological Survey, teleconference notes, 2013). This latter recommendation was implemented by Weston/START using limited trial data sets from the Kalamazoo River; however, it was found that even with the addition of the Merwade mesh points (e.g., trial along-channel point separation = 100 feet), the input data for the second step were still sufficiently sparse that the typical unwanted effects of applying standard interpolation methods to an irregular channel setting were still evident. In follow-up discussions, Dr. Merwade did not recommend increasing the density of the Merwade mesh points primarily due to concerns about program execution. Instead, to counteract the unwanted effects, Weston/START decided to perform the second interpolation step in straightened river coordinates such that the interpolation was only based on the along-channel separation between points, and to apply an interpolation method that used an elliptical search radius to counteract slope anisotropy. This modified two-step approach appeared to yield satisfactory results and was used by Weston/START, thereafter, as the primary process for updating the channel bathymetry. Further details regarding implementation of respective interpolation steps are described below.

It is noted that the above modified two-step interpolation process was only employed in channelized portions of the river. The bathymetry for non-channelized backwater portions of the river were interpolated from available input data using conventional (e.g., natural neighbor) interpolation methods in standard x-y coordinates. In all cases, interpolations of the off-channel backwater areas were completed in the final interpolation step, as described in the next section.

In the above-noted study, Merwade and others also highlighted the further common problem of how to obtain accurate interpolated bathymetry and topographic elevations in transition areas along the boundaries between the waterway and the adjacent overbank (e.g., near-bank locations) from limited input data (e.g., Merwade et al., 2008). A common difficulty in using combined input data sets of bathymetry and overbank topography point measurements is unwanted influence of waterway points on the overbank interpolation results, and vice versa, which potentially lead to interpolation inaccuracies and erroneous transition zone slopes. A universal approach for addressing this problem was not described in the study; rather, some general recommendations to assess transition zone slope conditions and develop site-specific methods for representing the bathymetry and topography in these areas were included. Following these general guidelines for the case of the Kalamazoo River, Weston/START observed that the waterway boundary remained approximately fixed for low-flow through bank full flow conditions at most locations along the affected river section, and the transition slopes between low flow and bank full flow water surface elevations were very steep to near-vertical. As documented by the USGS stream gages and other project staff gages, the bank elevation difference between low flow and bank full conditions was approximately 1-2 feet above Battle Creek, and 2-4 feet below Battle Creek (e.g., smaller elevation differences exist in impounded areas in both segments). The approach used by Weston/START to represent the transition zone slopes, included: i) overbank and waterway interpolations were done separately, using separate and exclusive input data sets from each respective area; ii) separate low-flow bank elevation points for the waterway interpolation and bank full bank elevation points for the overbank were incorporated in the final interpolation step for each respective area to constrain the interpolated bank elevations to expected values; and iii) in all cases, the interpolated overbank topography rasters and waterway bathymetry rasters created during any intermediate steps were combined by mosaicking in GIS without any overlap between raster cells (e.g., boundary line consisted of the waterway boundary) in order to preserve the steep elevation change between the respective areas. Details regarding the GIS steps and other procedures used to implement this approach are provided in the following section.

The scope of the Weston/START bathymetry and topographic updates included providing inputs for the existing 2D models and for newly created smaller scale models for specific sub-regions of the project area, such as sediment trap locations and the Morrow Delta. The existing models have fairly large cell sizes ranging from approximately 20 feet by 50 feet to 50 feet by 125 feet for the riverine grid, and 50 by 50 feet for the floodplain grid, whereas the grid types and scales to be used for the sub-region models were not fully known when the updates were initiated. In the absence of specific dimension requirements for the sub-region model grids and associated inputs, a uniform interpolation scale (i.e., raster cell size) of 5 feet by 5 feet was used for the Weston/START bathymetry and topographic updates. This scale was selected in part to allow representation (and possible model incorporation) of typical elevation variation found along the Kalamazoo River main channel and channel margins, as well as representation of potentially significant local elevation variations, such as channels having minimum horizontal dimensions of 5-10 feet located at the inlets to some sediment traps, river side channels, and within Morrow Delta distributary channels. Assuming use of standard GIS techniques to apply the raster values to any respective model grids, the selected raster scale was deemed to be generally suitable for providing representative inputs to model cells having dimensions ranging from a few feet (e.g., likely minimum cell size for sub-region models) to several tens of feet (e.g., existing model cells).

3.0 SOURCE DATA USED FOR BATHYMETRY AND TOPOGRAPHIC UPDATES

Bathymetry and topographic data from several sources were used for the original and updated compilations. The source data used for the compilations are listed in attached Table 1, and are described below.

3.1 Bathymetry Data

The different bathymetry data sources listed in Table 1, are described in the following subsections.

3.1.1 Poling Bathymetry Points

A major source of bathymetry data for the affected Kalamazoo River reach consisted of point measurements of bathymetry collected by Enbridge, as part of comprehensive submerged oil poling reassessment surveys performed in 2011 (e.g., Enbridge, 2011a) and 2012 (e.g., Enbridge, 2012b), to characterize the occurrence of submerged oil remaining in the river. Both surveys included point measurements located along the full affected reach from Talmadge Creek to Morrow dam. As described in other project documents, each poling observation was accompanied by a Real-Time Kinetic Global Positioning System (RTK-GPS) measurement of location and water surface elevation, and water depth, from which the bathymetry was calculated.

Poling points from both 2011 and 2012 were generally concentrated in depositional areas, but both surveys also included bathymetry point measurements located along regularly spaced river transects that did not correspond to specific depositional areas. The typical separation distance between the assessment poling points was approximately 50 to 100 feet in depositional areas, and 300 to 500 feet in other, non-depositional areas. The 2011 poling dataset was substantially larger, in part, because it included repeat measurements of many areas performed to assess the status of submerged oil recovery activities. The 2012 dataset was found to contain more points and more uniform point distributions within the impounded areas located immediately upstream of the three dams along the affected reach (e.g., Ceresco, Mill Ponds, Morrow Delta and Lake Impoundments), relative to the 2011 set, which helped improve the reliability of the updated bathymetry compilations for these important areas. It is noted that after 2012, the assessment poling data were collected using less accurate, non-RTK-GPS instruments and, therefore, post-2012 poling data were not used for the bathymetry updates.

An additional dataset of poling points that was used for the original and updated bathymetry compilations consisted of Enbridge provided 2010 longitudinal profile bottom elevation poling measurements recorded at 100 to 300 ft. intervals along the thalweg of the affected reach (e.g., Tetra Tech, 2011; Enbridge, 2012a). This dataset provided important point coverage for many river segments from which other data were very limited, especially prior to 2012. In addition to their use in the bathymetry compilations, these points were also used to calculate a detailed longitudinal profile of the river gradient.

A separate dataset of poling points that was available for the updated but not the original bathymetry compilation was the Enbridge 2012 supplemental poling bathymetry points. These supplemental poling points were primarily collected along river transects, including many locations that coincided with the previous HECRAS model cross-section lines, as well as new transect locations. These points helped fill gaps in the previous point coverage, and the distribution along transects also allowed for simpler implementation of the improved channel interpolation methods used for the updated bathymetry compilation.

Importantly, the estimated position and vertical precisions for each poling measurement were calculated and logged by the RTK-GPS instruments. The position uncertainties for the RTK-GPS measurements were typically smaller than the elevation values by a factor of two. The elevation uncertainties ranged from less than 0.1 feet to more than 1.0 feet. Possible reasons for the large uncertainties included poor satellite distribution, interference from variable tree canopy cover and other obstructions, or spurious signal interferences from nearby water surfaces. For the original bathymetry compilation, the poling bathymetry datasets were filtered to retain only those points having RTK-GPS elevation uncertainties ≤ 0.2 feet, and the same filter criteria were used for updated bathymetry compilation. For reference the point totals in all of the poling datasets, before and after filtering, are listed in Table 2.

3.1.2 HECRAS Bathymetry Points

The HECRAS bathymetry points were provided by Enbridge and consisted of a large dataset of regularly spaced points along cross-section lines that intersected both the channel and the overbank areas in the upper and lower river segments. The distribution of the points suggested that they were most likely derived from the cross-section station data contained in the input geometry files for the previous HECRAS models for the upper river (e.g., MP 2.00 to MP 17.25; Hoard, et al., 2010), and the lower river (e.g., MP 17.25 to MP 40.00; Enbridge, 2011b; AECOM, 2011a and 2011b). The points were provided in GIS format with a projection coordinate system defined as Michigan State Plane South (FIPS 2113) and defined units of meters. According to the Enbridge modeling report, the HECRAS points were used in the previous river bathymetry compilation completed for the original hydrodynamic model (Enbridge, 2012a).

As a check, START compared the provided HECRAS bathymetry points against the cross-sections and a corresponding river center-line exported from the original HECRAS input geometry files, which were specified in units of feet (e.g., U.S. customary units = survey feet). The resultant river center-line from the input geometry files projected in survey feet showed good agreement with the expected location based on the project aerial imagery and the existing waterway boundary; however, the corresponding cross-section lines in survey feet from the input files were systematically offset approximately 25.8 feet east of the provided HECRAS bathymetry points. As the model geometry files represent the likely source data for the points, this suggested that the HECRAS point locations, as provided, were erroneous. This was supported by inspection of the HECRAS point elevations along north-south oriented channel segments which showed westward displacement of points with deeper, channel-like elevations onto land areas along one bank, and points with land elevations displaced into the channel along the opposite bank. The magnitude and direction of the offset suggested that an error was made in the conversion of the HECRAS bathymetry point locations (e.g., northing, easting) to state plane meters, in which the starting HECRAS station location coordinate units were incorrectly assumed to be in international feet. Such an error would lead to a much larger displacement in the east-west orientation relative to north south, because the state plane easting coordinate values for the project area are approximately 50 times greater than the corresponding state plane northing values. The locations of the HECRAS points were recalculated in feet and correctly projected as survey feet so that they aligned with the data obtained from the HECRAS model input files. Thereafter, the corrected locations were used for all START bathymetry updates. As discussed in a later section, this correction is the likely cause of differences observed between the updated bathymetry and the previous compilation in many areas.

A further feature of the HECRAS bathymetry point dataset was the apparent inclusion of points with estimated elevation values. These were readily identified in the upper river where they coincided with sections containing very few channel points (e.g., similar to the original geometry file station distributions), and this information was also confirmed with USGS personnel. Thereafter, HECRAS bathymetry points (e.g., with corrected locations) were only used from cross-sections with confirmed bottom elevations (e.g., approximately 25 percent of total upper river sections), and the upper river HECRAS points from the non-measured locations were excluded from further use. It is noted that the unmeasured HECRAS sections in the lower river were not as readily recognizable from the point distributions. For purposes of the updates, the HECRAS points along lower river cross-sections were omitted if complete transects of 2012 bathymetry points were available from the same or nearby locations, and were provisionally retained otherwise. All subsequent interpolated bathymetry results based on the retained corrected HECRAS bathymetry points were checked for agreement with nearby independent observed bathymetry points and corrected or eliminated, as necessary.

3.1.3 Other Bathymetry Data

Other bathymetry data used for the Weston/START bathymetry updates included bathymetry point measurements collected by Enbridge for several different operational tasks during 2012-2014, including sediment trap bathymetry monitoring (e.g., all traps; 2013 data only), E4 Containment Boom bathymetry monitoring (e.g., Morrow Delta and Neck; Fall 2012 and 2013 data), and pre-dredge bathymetry measurements (e.g., Morrow Delta only; Spring 2014 data). Some of the earliest E4 Boom bathymetry monitoring points collected in late 2012 were made using the RTK-GPS instruments; however, all subsequent 2013 E4 Boom bathymetry monitoring points and sediment trap bathymetry points, and the Morrow Delta pre-dredge bathymetry measurements were made by total station survey instruments combined with a series of fixed survey monuments installed for the project. Combined inputs consisting of the operational bathymetry point measurements and poling bathymetry points were used for the updated compilation where both types of data were available. The added operational bathymetry point measurements resulted in increased bathymetry input point totals and point densities for select sediment trap locations along the river, and in the Morrow Delta.

Bathymetry coverage for most of Morrow Lake and the neck area was provided by single-beam sonar data from a large-scale survey completed by Enbridge in 2010 (Enbridge, 2011c). The sonar data were provided in processed format, as a semi-continuous GIS raster with a cell size of 5 feet. The sonar data collection was discontinued near the upstream end of the neck because shallow water depths upstream of this location (e.g., in the Morrow Delta) prevented use of the sonar equipment. Shallow water conditions also resulted in isolated gaps in the sonar coverage along shorelines and around some islands in Morrow Lake. The dam operator did not allow acquisition of sonar data near Morrow Dam in 2010, which yielded a similar gap in bathymetry coverage extending approximately 400 feet upstream of the dam.

Bottom elevation measurements made within the impoundment areas during 2012 and 2013 velocity surveys were another source of bathymetry data used for the updates. The 2012 measurements performed by Enbridge consisted of manual measurements of water depth at taped intervals of 10 feet along full river transects (e.g., Enbridge, 2012c); GPS locations and water velocities were recorded at a minimum of three locations per transect. The locations for the taped measurements were calculated from the transect GPS coordinates, and the bottom elevations were calculated from the measured depths using water surface elevations obtained from nearby surveyed staff gauges. A total of 6 transects of manual bottom elevation measurements from the Ceresco impoundment, and 3 transects from the Mill Ponds impoundment, were used to augment the available poling bathymetry point data. Bottom elevations were recorded by USGS personnel during a 2013 Acoustic Doppler Current Profiler (ADCP) velocity survey that again focused primarily on the impoundment areas (Reneau, et al., 2014). Locations and water surface elevations measurements for the ADCP survey transects were provided by an RTK-GPS instrument; the ADCP instrument provided velocity measurements as well as bottom depths, which were converted to elevations using the RTK-GPS measurements. The resultant data consisted of detailed bathymetry point measurements located along the respective transects. Bottom elevations from two combined east-west and north-south ADCP transects located closest to the dam were used to provide a more complete representation of the bathymetry within the sonar data gap near the dam for purposes of the updates. Additionally, ADCP bottom elevations from a third transect located immediately downstream of 35th Street were used to provide bathymetry information where measured data from other sources were generally lacking.

A final source of data used for the bathymetry and topographic updates consisted of water surface elevations (WSELs) recorded by temporary on-site stage recorders installed by the USGS in 2013 within the major impoundments along the affected reach (e.g., stage recorder locations at MP 5.80, MP 14.80, MP 36.50, MP 37.80, and MP 38.50; Reneau, et al., 2014). The stage recorder WSELs were used to develop elevation values for bank points included in the final interpolation of both the waterway bathymetry and the overbank topography. The bank points were assigned locations along the GIS waterway boundary polygon. The bank point elevation values were calculated by projecting representative observed WSELs upstream from each stage recorder using the average river gradient values reported previously by Enbridge (e.g., Enbridge, 2012a; Tetra Tech, 2011). The bank point elevations used in the waterway bathymetry interpolation were developed using starting WSELs recorded at low discharge conditions (e.g., USGS Kalamazoo River Marshall Gage discharge = 400 cfs), while bank point elevations used in the separate overbank topography interpolation were developed using starting WSELs recorded during approximate bank full discharge conditions (e.g., USGS Marshall Gage discharge = 1100 cfs, or USGS Battle Creek Gage discharge = 1600 cfs). Average river gradient values determined for each one-half mile river segment from the 2010 longitudinal profile poling dataset were used for both sets of bank points, with minor adjustments (e.g., Tetra Tech, 2011).

3.2 Topographic Data

Data used for updates and corrections to the overbank floodplain topography consisted primarily of Light Ranging and Detection (LiDAR) data obtained from two sources, including LiDAR data for Calhoun County originally provided by the City of Battle Creek to the USGS for the initial upper river HECRAS model (e.g., Hoard et al., 2010), and LiDAR data acquired by Enbridge along the entire affected reach in both Calhoun and Kalamazoo Counties during April 2011 (Enbridge, 2011d). Both data sets were fully processed and available in electronic form; however, the Calhoun County LiDAR was processed in digital elevation format (e.g., 10 x 10 ft. raster), whereas the Enbridge LiDAR was only available in 1 foot contour line format. A comprehensive comparison between overlapping portions of the two LiDAR data sets was not performed by Weston/START. However, a previous report describing the data compilation for the lower river HECRAS model indicated general agreement between elevation values for the two LiDAR data sets to within one to three feet (AECOM, 2011b). In a more limited comparison against independently surveyed ground elevations for monitoring wells installed in floodplain locations along the affected reach, Weston/START found near coincidence between the monitoring well ground elevations and the Calhoun County LiDAR elevations, whereas the Enbridge LiDAR values were typically 0.5 to 1.5 feet lower (e.g., R. Johnson, Weston/START, email communication, 2014). The Calhoun County LiDAR was used for the overbank topography updates between MP 2.0 and MP 15.75, based on the historic use of this data set for the original upper river HECRAS model and the slightly better areal coverage of islands located in the upper river provided by the Calhoun County LiDAR data set, as well as the apparent agreement between this data set and the independent monitor well ground elevation data set. The Enbridge LiDAR data set was used for overbank updates in the remainder of the affected reach from MP 15.75 to Morrow Dam.

It is noted that some floodplain locations along the affected Kalamazoo River reach contained isolated, small waterbodies or water covered areas (e.g., separate from the main river waterway), for which LiDAR elevations were not available due to inability of this technology to penetrate water. The 2011 poling bathymetry dataset included overbank poling measurements in most of these water bodies (e.g., referred to as “strike bathymetry points”), and the strike points were used along with the available LiDAR to complete the overbank elevation updates.

3.3 Archived Data Files

The majority of the source bathymetry data and other supporting electronic files used for the Weston/START updates are contained in the Enbridge ArcGis project geodatabase, a copy of which was initially provided by Enbridge to U.S. EPA in August 2012, and was updated approximately weekly by Enbridge through September 2014. The geodatabase includes source files for all poling reassessment data from 2010-2014, supplemental 2012 poling bathymetry transect measurements, all operational monitoring bathymetry measurements, the Morrow Lake compiled sonar bathymetry, plus files for the updated waterway boundary, and the 100-year floodplain boundary. Enbridge source data used for the updates but not contained in the geodatabase includes the longitudinal profile poling bathymetry point dataset, and a bathymetry point dataset created from the respective HECRAS model geometry files, both of which were provided separately as part of the initial 2D model file submittal (e.g., Enbridge, 2012a), plus the April 2011 project aerial imagery, processed files of Enbridge project LiDAR, and the complete lower river HEC-RAS model files, all of which were obtained separately from Enbridge. Copies of all Enbridge files that were not included in the geodatabase have been stored and maintained by Weston/START as part of the U.S. EPA project files. Non-Enbridge bathymetry and topography source data includes the Calhoun County processed LiDAR data, the complete upper river HEC-RAS model files, ADCP velocity transect bottom elevations, and the stage recorder WSELs, all of were obtained directly from the USGS. Copies of the non-Enbridge source data files have similarly been stored and maintained as part of the U.S. EPA project data files.

4.0 DATA ANALYSIS AND INTERPOLATION METHODS USED FOR BATHYMETRY AND TOPOGRAPHIC UPDATES

The analysis steps required for the bathymetry updates consisted of consolidating the input elevation data from the various sources described above and performing the updated elevation interpolations for the waterway and overbank portions of the project area. The interpolations were performed using standard GIS software and tools which are identified in the following subsection. The data consolidation and interpolation steps used for each portion of the waterway (e.g., riverine, Morrow Delta and Morrow Lake), and the overbank areas, are detailed in the further subsections below.

4.1 GIS Software and Project Coordinate Systems

The data analysis and interpolation steps were performed using the ArcGIS program, version 10.0, from Environmental Systems Research Institute (ESRI). The ArcGIS Spatial Analyst and ArcGIS Geostatistical Analyst extensions were used for the (NN) interpolations and radial basis functions (RBF) interpolations, respectively. Tools available at the ArcInfo license level, such as linear referencing tools and raster mosaicking were also utilized. Dr. Merwade's custom Create Bathymetry Mesh (ArcGIS 10 version) tool was installed as an add-on and works within the ArcGIS environment.

Some data analysis and data creation were done outside of the ArcGIS environment using Microsoft Excel, such as the review and editing of cross-section inputs for use in the channel interpolation, and calculation of bank point elevations. The final results of these steps were converted to shapefiles or feature classes that were then brought into ArcGIS.

The coordinate system of the project GIS geodatabases, shapefiles, and ArcMap data frames were defined as Michigan State Plane South Zone (FIPS 2113) referenced to the North American Datum 1983 (NAD83) as international feet, and all data processing was conducted using this coordinate system. Most GIS files provided by Enbridge were projected to this same coordinate system, however, some were provided in US feet or meters. Prior to merging any input layers, all datasets were reprojected to NAD83 Michigan State Plane South Zone international feet, if necessary. The elevations for all source files used for the updates, including those obtained from Enbridge and others, were referenced to the North American Vertical Datum of 1988 (NAVD88).

4.2 Riverine Waterway Bathymetry Interpolation

The riverine portion of the waterway includes the river channel and connected backwater areas along the affected reach, exclusive of the Morrow Delta. As noted in Section 2.0, additional intermediate steps were required to perform the elevation interpolations for the river channel portion of the waterway, in particular. The intermediate steps used for the river channel, and for completing the interpolation of the full riverine waterway, are described in the following subsections.

4.2.1 River Channel Interpolation - Application of Merwade GIS Tool

The first step for the river channel interpolation was application of the Merwade Bathymetry Mesh tool. The required inputs for the Merwade Mesh Tool are listed below and described in the following paragraphs.

- River reach line (e.g., Bezier curve format)
- Channel boundary line
- Input cross-section lines (e.g., straight, z-line format)

The river reach line used for the Kalamazoo River was a modified thalweg line created by fitting a bezier curve line to the Longitudinal Profile Bathymetry points along the riverine waterway. It is noted that the longitudinal points exhibited a complex pattern in Morrow Lake and, therefore, the reference Bezier line was simplified to follow an approximate center-line trace through the lake, before connecting with the longitudinal points at MP 37.75. The x,y locations and the distance from a starting origin (e.g., m-coordinate) are defined for vertices along a Bezier curve . The center-point of Morrow dam was chosen as the origin for the reference bezier line, and the line was extended from the dam to the upstream end of the affected reach (e.g., MP 2.0).

The channel boundary was a modification of the Kalamazoo River waterway line provided by Enbridge. The modifications included local realignment to exclude tributaries and backwater areas, and conversion of the line to a polygon (e.g., channel boundary polygon). The effect of the realignment was to limit the Merwade interpolation to the main channelized portion of the river. As expected, the channel boundary polygon coincided with the original waterway line at most locations.

The input cross-section lines relied primarily on the 2012 observed bathymetry points that were collected along river transects. Input cross-sections were created at most locations where complete point transects (e.g., across the full river width) existed. If a complete set of 2012 transect points was not available at a given location, due to filtering or other reasons (e.g., non-collection), the transect was augmented and completed using nearby points available from other datasets (e.g., longitudinal profile poling, 2011 poling, and 2012 poling datasets). It is noted that input cross-sections were not created if a nearby section with equivalent elevations already existed; in these cases the transect points were used as independent observed bathymetry points in the later interpolation steps. Input cross-sections were also created using the retained HECRAS bathymetry points from select locations, as described above. Regarding the HECRAS data, one further exception was that HECRAS bathymetry points located along bridge transects were not used as inputs for the channel interpolation because even in cases where they are supported by bottom elevation measurements, these points were typically not representative of nearby channel elevations. Instead, where possible, new sections were created from nearby observed point data located slightly upstream or downstream of the bridge locations. For reference, the total numbers of input cross-sections for the upper and lower river from both data sources are listed in attached Table 3. The upper river input sections were generally distributed between MP 2.0 and MP 5.50, and from MP 6.0 to MP 15.50; the lower river input sections were distributed from MP 16.75 to MP 36.70. The indicated gaps where input sections were not constructed consisted of locations immediately upstream and downstream of Ceresco and Battle Creek dams, and along the concrete channel river segment in Battle Creek. These excluded areas contained many channel shape and elevation irregularities for which conventional interpolation methods were better suited. The bathymetry updates for the excluded areas were thus completed separately in the final riverine waterway interpolation step.

Some initial processing steps were required to create the input cross-sections. These included the construction of target straight section lines that were approximately aligned with the selected transect points and oriented perpendicular to the banks, and projection of the selected points onto the created lines. Additionally, cross-section plots were created in Microsoft Excel (e.g., elevation vs. distance from the bank), to allow graphical review the data prior to use for the channel interpolation. In a few cases of erratic bathymetry point values, best-fit curves to the projected point data were determined in Excel and calculated x,y,z points corresponding to points along the fitted curves were used as substitute values for those sections. In most cases, the (projected) bathymetry point values were used without modification.

Following the initial processing steps, the input cross-section lines for the Merwade tool were created in GIS by converting the projected points for each transect to Z-lines (3D-lines); the nodes (e.g. vertices) for the resulting Z-lines corresponded to the x,y,z values for the input projected points. The direction for each input Z-line was defined from the left descending bank to the right descending bank. Each cross-section line was given a new numeric identifier corresponding to the m-coordinate of the intersection between the cross-section and reference thalweg line.

Three additional parameters were needed to execute the bathymetry mesh tool. These were the number of interpolated profile-lines (i.e., number of mesh lines oriented along the channel), spacing between interpolated cross-sections (i.e., mesh line spacing perpendicular to the channel), and the average channel width. The number of profile-lines was set to 10 and the cross section spacing was set to 100 ft. The length of the cross sections spanning the channel boundary was used to calculate the average channel width per mile section using the project mile marker layer as reference. In general, the tool was executed for every one-mile river section. In some sections, the tool failed where the channel width had a large range. In those cases, the tool was executed over a smaller stretch of river with updated average channel width.

The output of the Merwade mesh tool consisted of a curvilinear-orthogonal mesh of intersecting profile and cross-section lines at the specified spacing extending between the input sections, with interpolated elevation values assigned to the intersection nodes. The nodes of the output mesh were converted to points which contained the z-values populated by the tool.

A series of intermediate interpolation checks were performed in which the mesh tool output elevations were compared to nearby observed bathymetry (i.e., elevation) point data for each one-half mile river segment. These checks were intended to identify any large or systematic elevation differences that may indicate input cross-section errors. The input cross-sections created from HECRAS bathymetry points in the lower river were of particular concern because these points had undocumented measurement histories, and the point elevations along some of these sections may be estimated values. In fact, initial interpolated elevations that were biased (e.g., 1-2 feet) above or below nearby observed bathymetry points were found in the vicinity of several of the lower river sections created from the HECRAS points[1]. In each case, as consistent with the procedures described previously, the HECRAS bathymetry points used for the input cross-section were omitted and a new replacement cross-section was created at the nearest location containing a full transect of bathymetry point measurements, which was then used in a repeat interpolation. These checks also identified an upper river input cross-section near MP 10.25,

[1] Locations of lower river HECRAS sections removed following review of initial channel interpolation results = MP21.75, 22.50, 24.25, 24.50, 24.75, 25.75, 26.25, 26.50, 27.25, 28.25, 32.00, 33.25, 33.50, 33.75, 34.00, 34.50, 34.75, 35.25, 35.50, 35.75, 36.00, 36.25, 36.50.

which exhibited elevations that were two to three feet higher than nearby observed bathymetry points and were approximately equal to the local overbank elevations. This section was created from corrected HECRAS bathymetry points and corresponded to a location where bottom elevations were measured. The unrealistically high elevations reported for this section were attributed to a measurement error, and the section was removed prior to performing a repeat interpolation for this river segment. Following these corrections, the elevation differences between observed bathymetry points and the final interpolation values for this step were generally on the order of ± 1.0 feet at most channel locations, although larger differences were found locally.

It is noted that mesh points that intersected islands and other anomalous locations such as tributary entry points for which the tool yielded obviously incorrect elevations, were flagged and excluded from use in the subsequent bathymetry interpolation steps.

4.2.2 River Channel Interpolation – Combined Interpolation of Mesh Points and Point Bathymetry Inputs in Straightened Coordinates

A second intermediate step performed for the channel portion of the riverine waterway was a combined interpolation of the points created using the mesh tool together with other observed bathymetry points. This step allowed further refinement of the channel bathymetry where the additional observed points were available for use. As noted above, the combined interpolation step was performed in straightened river coordinates to prevent unwanted influences caused by channel bends and/or channel slope anisotropy.

In general, the channel extents for the second intermediate interpolation step were the same as in the previous step. However, an exception was that the downstream interpolation limit for the lower river segment was extended to MP 36.87, which was slightly downstream of the last Merwade mesh output points. This was done to help ensure a smooth and accurate transition of the interpolated elevations between the riverine and delta segments of the waterway.

To conduct the river straightening steps, it was first necessary to merge the points from all selected bathymetry input datasets. The merged input included the filtered bathymetry point datasets, the bathymetry mesh points that were retained following the QC checks, and added control points. The transect points that were used to create the input sections for the previous channel interpolation step were not re-used in the current interpolation step in straightened coordinates. In most cases, only input points that were located within the main river channel and 50 ft beyond were included. Per the exception in the previous paragraph, additional observed channel bathymetry points from the Morrow Delta were retained as inputs to extend the downstream limit of this interpolation step to MP 36.87.

Control points had assigned locations and elevations (e.g., xyz coordinates), and were used to ensure that realistic interpolated elevations were obtained in areas with limited or no data. Typical waterway locations where they were used included transitional settings between the main river channel and backwater or side-channel areas. In many cases, the elevations for these points were based on measured water depths for excluded poling points that did not meet the RTK-GPS elevation measurement filter criteria, combined with estimated water surface elevations from nearby retained points. In cases where such data were not available, the control point elevations were chosen to be intermediate between the nearby channel elevations and the interior backwater or side-channel elevations. It is noted that control points were also used in overbank settings where independent ground elevation data were available (e.g., Ceresco and Battle Creek dams), or in partially submerged overbank locations where the LiDAR coverage was incomplete or deemed unreliable (e.g., small unnamed tributaries and/or wetlands). Control point elevations for the latter areas were based on nearby ground elevations together with the estimated water depths.

The process for transforming X,Y coordinates of the input points to straightened space, or S,N coordinates, was multi-step. First, the ESRI ArcToolbox, "Generate Near Table" tool was used to calculate the shortest distance from each input point to the thalweg ([Near_Dist]) and the X, Y coordinates of the corresponding nearest thalweg location ([Near_X] and [Near_Y]). All [Near_X] and [Near_Y] values were converted to points as a shapefile and the distance of each point along the thalweg in reference to the Morrow Lake Dam origin was calculated using the "Locate Features Along Route" tool. This distance became the observed point S coordinate magnitude, and the [Near_Dist] value became the observed N coordinate magnitude. All S coordinate values were positive, while the N values were negative for locations between the left descending bank and the thalweg, and positive for locations between the thalweg and the right descending bank. . The channel boundary polygon was also transformed for use in the straightened coordinates by applying the same transformation steps to created points at the polygon vertices.

A table of the S, N, and elevations of each input point was converted to a GIS feature class and loaded into a data frame with undefined coordinate projection (e.g., units were set equal to input units of feet). The "Radial Basis Functions" tool in the ESRI Geostatistical Analysis Tools was used for interpolating the elevations within the new data frame using the following input parameters:

- Sector type = 1 sector
- Major semi-axis (e.g., S direction) = 50 feet, with 15 maximum neighbors
- Minor semi-axis (e.g., N direction) = 5 feet, with 10 minimum neighbors
- Radial basis function = completely regularized spline
- Output cell size = 5 by 5 feet

Separate RBF rasters developed for the upper and lower river segments were clipped to the straightened channel boundaries to remove all calculated elevation values located outside the channel. The remaining RBF interpolation results were then converted from raster to RBF interpolated points with S_i, N_i, and Z_i values populated in the attribute table.

The RBF interpolated points were back-transformed to X-Y space using the following method, which is illustrated for an example interpolated point in attached Figure 2. First, a set of thalweg line direction angles (α) was calculated at regular 5 ft. intervals along the thalweg , such that the calculation locations coincided with the S_i coordinates; this was done using the following python code and saved to Kzoo_Thalwag_v3_5ft_avg_direction (v20140403) (e.g., modified from http://forums.arcgis.com/threads/29432-Get-line-direction-orientation-as-a-numeric-field):

```
math.atan2((!Shape.lastpoint.Y! - !Shape.firstpoint.Y!),(!Shape.lastpoint.X! -
!Shape.firstpoint.X!)) * (180 / math.pi)
```

The X,Y coordinates along the thalweg at the same specified S_i locations were populated in the attribute table as [Thalweg_X], [Thalweg_Y], and [S_i], respectively. This information was joined to the RBF results table by linking the shared [S_i] field. Finally, the coordinates for each RBF interpolated point (X_i,Y_i) were calculated using the formulas below.

X_i = ([Thalweg_X])+[N_i]*(COS(RADIANS([α]+90)))

Y_i = ([Thalweg_Y])+[N_i]*(SIN(RADIANS([α]+90)))

The complete set of RBF interpolation points that were back transformed from SN space to XY space following these steps (e.g., for a given river segment) were converted to a shapefile and brought back into the project GIS. Inspection of the results in GIS confirmed that the back-transformed interpolated points were located within the original channel boundary extents and distributed on approximately 5-10 ft centers, as expected. Minor follow-up editing was required to remove back-transformed points that intersected some mid-channel islands. Final editing was also used to remove any RBF interpolated points located in areas immediately upstream and downstream of the Ceresco and Battle Creek dams, which were updated separately in the final interpolation step.

4.2.3 Final Riverine Interpolation Step and Incorporation of Off-channel Backwater Areas

The objectives of the final interpolation step were to complete the elevation updates for the connected, non-channelized backwater segments of the waterway, and to produce a final raster representation of the updated elevations for the full riverine waterway in standard XY format that could be readily combined with the overbank raster. The final waterway interpolation step was performed using conventional interpolation methods.

The input for the final interpolation step consisted of a merged point file containing the edited back-transformed RBF interpolated elevation points for the channel, the observed bathymetry point data for the non-channel backwaters and other areas excluded from the previous interpolation steps (e.g., dam, concrete channel areas), added backwater control points, and bank points. The back-transformed RBF point data set was edited to remove any points that intersected mid-channel islands as noted above, prior to merging. Also, it is noted that the bathymetry mesh points were not used as inputs for this step.

The typical problems associated with applying conventional interpolation methods to channelized settings, as noted above, were mostly eliminated in the final interpolation step by the dense array of available RBF input points located within the channel. For example, the dense input point distribution ensured that the interpolated elevation results for any given channel location would be determined by numerous, nearby input points occupying similar channel positions, thereby eliminating the usual concern about points with dissimilar locations unduly influencing interpolations in channelized settings. A further important aspect of this input distribution was that it constrained the final interpolated elevations to closely resemble the input values. This was considered a desirable outcome, as the final interpolation step was therefore not expected to significantly alter the channel elevations obtained in the previous RBF step. The bank elevations were not expected to have a large influence on the final interpolated elevations for the channel; however, the addition of these points along the backwater waterway boundaries likely helped prevent unwanted influence to interpolated elevations from observed bathymetry points, in cases where the observed points were separated across backwater islands or other irregular shoreline segments.

The final riverine waterway interpolations were performed using the ArcGIS Spatial Analyst extension, “Natural neighbor Interpolation” tool, setting the output cell size to 5 feet. Separate final interpolations were done for the upper river (e.g., MP 2.0 to MP 15.75), and lower river segments (e.g., MP15.75 to MP 36.85). The output rasters created for these respective areas were assigned the same raster origin, which was used thereafter for all overbank topography and combined output rasters. The output rasters were clipped along the Kalamazoo River waterway line that was provided by Enbridge. The clipped rasters resulting from this step provided the intended raster representation of the full riverine waterway updated bathymetry.

4.3 Overbank Topography Interpolation and Combined Raster Formation

The updates to the overbank topography were done separately from the corresponding updates to the waterway. The areal coverage of the topographic updates initially included all land areas within or near the 100-year floodplain boundary along the affected portion of the Kalamazoo River (e.g., MP 2.0 to MP 40.00). Follow-up corrections were performed to expand the overbank topography coverage to coincide with the floodplain model grid limits, which extended to the upstream interstate I-69 river crossing and included small subareas that were located outside the 100-year floodplain boundary. The data consolidation and interpolation steps for the overbank updates, which were performed separately for upper and lower river segments, are described in the following paragraphs.

Ground elevations for the upstream segment (e.g., revised limits, MP I-69 to MP 15.75) were based on the Calhoun County LiDAR data, in 10 by 10 feet raster format. Ground elevations for the Downstream Area (e.g., MP 15.75 to MP 40.0), were based on Enbridge's LiDAR dataset which was provided as 1-foot contour lines and was converted to a 10 by 10 feet raster file using the “Topo to Raster” tool in the ArcGIS Spatial Analyst extension. Both overbank input raster datasets were clipped to a polygon which was a 500-foot buffer beyond the 100-year floodplain line and converted to overbank LiDAR points. Any converted points that fell within a water body or other unwanted locations such as along bridge surfaces were removed and supplemented with observed points (e.g., strike bathymetry points) or control points, as appropriate.

Merged input datasets were created for the overbank interpolations which included the overbank LiDAR points, observed bathymetry point measurements located in isolated non-connected overbank waterbodies (e.g., “strike bathymetry points”), added control points, and the Kalamazoo waterway bank points populated with bank-full elevations. The control points were used primarily within the overbank (e.g., isolated) water bodies to augment the observed strike point values; elevations for the control points were assigned based on nearby observed elevation points, or a combination of nearby LiDAR ground elevations and water depths estimated from detailed aerial imagery or other field knowledge.

Separate NN interpolations were performed on the merged overbank point sets from the upper and lower river segments, using a cell size of 5 feet, and a common origin for each raster. The resultant rasters were clipped to remove the area within the river waterway line and clipped back to the greater of the HDM floodplain model grid or a 100 ft buffer of the 100-year floodplain line. Detailed checks were made to confirm that the resulting overbank interpolated elevations matched the input ground elevations.

To form the combined rasters, each clipped upstream and downstream overbank interpolation raster was mosaicked to the corresponding riverine waterway interpolated raster. Since each overbank and riverine raster shared the same clip boundary along the river waterway line, were the same cell size (5 ft.), and snapped to the same origin, there were no overlapping cells during the combined raster mosaicking process.

Initial versions of the combined overbank and waterway rasters for the upper and lower river segments were completed in October 2013 and January 2014, respectively. For reference, the attached Table 4 lists the completion dates (including revisions), and the rivermile extents for the waterway and overbank portions of each raster. Follow-up corrections to the interpolated overbank topography to encompass the full limits of the floodplain model grid were done using the same procedures, and completed for both the upstream and downstream segments in April 2014. Post-April 2014 changes to the lower river segment consisted of further evaluation and adjustments to the Morrow Delta bathymetry. Details of the sequence of work and the incorporation of the final adjustments to the Morrow Delta bathymetry are described in the following section.

4.4 Morrow Lake Delta and Morrow Lake Bathymetry Interpolation

Updates to the Morrow Lake Delta and Morrow Lake bathymetry were multi-step and consisted of several revisions. An initial version completed in April 2013, was focused on updating the bathymetry for the Morrow Lake Delta and neck areas, to provide corrected elevations for these areas in the initial 3D model. Merged input points for this version consisted of filtered 2011 and 2012 bathymetry points, and bank points created along the Kalamazoo River waterway in the delta and neck that were assigned an elevation of 775.5 ft. This dataset provided broadly spaced input point coverage for most delta locations; however, filtering removed many points and resulted in sparse point coverage in portions of the neck, in particular. A 5 ft. output raster of interpolated elevations was created from these input points using the inverse distance weighted average (IDW) tool in ESRI's Spatial Analyst extension. The IDW raster result was clipped to the waterway line, and boundary lines located just downstream of MP 37.75, and just upstream of the 35th Street Bridge. This raster was then mosaicked to the Enbridge sonar raster using the mosaic mean method. The extent of the sonar layer covered most of Morrow Lake and the neck but did not cover the delta; retention of the sonar data in the neck was important because of the sparse point inputs for the IDW raster in this area. Prior to mosaicking, the sonar layer was clipped along a line near MP 37.60, which was close to the upstream limit of the sonar raster. The resulting final mosaic therefore consisted of unchanged sonar data representing the lake, IDW interpolation in the delta proper, and the mean of overlapping sonar and IDW rasters in the neck.

The next revision to the Morrow Lake and Delta bathymetry raster was developed in August 2013. At that time, it was recognized that the 2013 USGS ADCP transect bottom elevation data could be used to update the bathymetry for the area located immediately upstream of the Morrow dam for which sonar data were previously unavailable. Bathymetry updates for this area were considered important to verify reliable inputs for the 3D model in the vicinity of the dam. The previous sonar coverage gap had an irregular shape with maximum extents located approximately 150 ft. north, 150 ft. south, and 400 ft. upstream of the dam center point. This gap was filled using data from two, 2013 USGS velocity transects located 150 and 300 feet upstream of the dam, respectively, plus a few scattered point bathymetry measurements made in this general vicinity (e.g., north and south of the dam). Direct application of standard interpolation methods to the velocity transect bathymetry data, which exhibited very close spacing between points along the lines (e.g., less than 5 ft spacing), and much wider spacing between the transect lines, was not expected to yield reliable results. As a preliminary step, inferred 1-ft. elevation contour lines were therefore hand drawn from the input points. The contour lines were converted to elevation control points having a more uniform distribution than the original points which were then used as inputs, along with other observed bathymetry points, for a NN interpolation. The resultant interpolated raster (e.g., 5 ft. cell size) was clipped to the waterway, and a boundary line located approximately 50 feet outside the original sonar gap limits, and mosaicked to the original sonar raster.

In February 2014, the January 2014 downstream riverine and overbank raster was mosaicked to the existing Morrow Delta and Lake waterway raster (e.g., combined IDW/sonar) to provide a provisionally complete waterway raster for the lower river from MP 15.75 to MP 40.00. The mosaicking step included clipping of the existing Morrow Delta waterway raster at MP 36.82, and performing a mosaic blend of raster values within the remaining overlapping segment from MP 36.82 to MP 36.87. This provisional version incorporated fully updated, final bathymetry down to MP 36.82, and in the lake, but the Morrow Delta waterway elevations (e.g., MP 36.82 to MP 37.78) were still considered preliminary, pending the addition of further observed bathymetry points (e.g., 2013 operational monitoring data) and corrections to the bank points, as well as final evaluation of the delta interpolation methods.

The final revisions to the Morrow Lake Delta raster occurred in July 2014. Changes from the previous delta versions included the addition of new input data consisting of 2013 operational monitoring bathymetry points (e.g., E4 boom monitoring; 37.75 Islands, Delta Z and Delta A sediment trap monitoring), and corrected bank points, plus 2014 pre-dredge bathymetry points, and previously removed 2012 bathymetry points with recalculated elevations based on corrected water surface elevations. The addition of the operational monitoring bathymetry points was straightforward and provided improved input point coverage in the neck (e.g., E4 boom monitoring, 37.75 Islands) and sediment trap locations, relative to the previous interpolation version. Similarly, the 2014 pre-dredge bathymetry points provided added point coverage in the sediment traps and along distributary channels located in the southern part of the delta. The revised bank points were based on a new, 25-ft. spacing along the waterway boundary and updated interpolated elevation information available from the USGS stage recorders located at MP 36.50 and MP 37.80, and they were applied to the delta islands as well as the other delta shore areas. The reintroduced 2012 bathymetry points consisted of observed points that were previously removed by filtering based on large water surface elevation uncertainties. New water surface elevations for these points were recalculated based on the average of nearby points (e.g., same quarter-mile delta segment) collected on the same dates. Such a correction was possible, in part, because numerous nearby delta points were available for most collection dates; also, the delta water surface gradient was small (e.g., 0.1 foot per quarter-mile) so the potential errors resulting from applying a non-specific average water surface value within a given limited segment, rather than location specific values, were small. The reintroduced 2012 bathymetry points added many new observed point locations along the main north channel, as well as along distributary channels in the central and southern delta. It is noted that 2012 bathymetry points with horizontal uncertainties greater than 1 ft. were not included in the delta updates.

The final delta bathymetry update included use of the RBF interpolation method with the elliptical search radius in the main, north channel portion of the delta, and NN interpolation for all other locations. The RBF method was selected for the north channel area to help ensure that the finished raster would retain the channel shape and anisotropy characteristics evident for this part of the delta. Mosaicking was used to combine the interpolation results for different parts of the delta, and to join the completed final delta interpolations to the upstream and downstream portions of the river. For reference, the extents of the respective final delta interpolation updates are shown in attached Figure 3.

The north channel RBF interpolation was performed in straightened coordinates so that the elliptical search and weighting would be applied consistently along the channel direction. An estimated channel boundary extension through the delta between MP 36.78 and MP 37.40 was created for this purpose.

The RBF interpolation was performed using the merged delta input bathymetry points, following the same steps described above for the riverine waterway through creation of back-transformed RBF points located within the created delta channel extension. A final NN interpolation of the RBF points, in standard x,y coordinates with a 5-ft. raster cell size, was performed and clipped to the delta channel boundary shown in Figure 3.

The NN interpolation for the delta, exclusive of the north channel, was performed using a merged file of all available observed bathymetry points, plus bank points, and appended points located in the river channel between MP 36.75 and MP 36.87 that were created from the previous RBF interpolation of the (lower) riverine waterway channel. The latter RBF (upstream) channel points were considered to accurately represent the channel bathymetry and were retained to help produce a smooth final transition to the existing lower river waterway raster. The NN interpolation for this step was performed in x,y coordinates using the standard 5 ft. cell size and raster origin. The resultant NN raster was clipped along the boundaries shown in Figure 3, to create overlap with the adjacent delta rasters. Mosaicking of the main delta NN raster to the other respective delta rasters shown in Figure 3, was performed using the mosaic mean method.

5.0 RESULTS

The completed rasters were evaluated through visual comparison between elevation maps and the respective input elevation point data in GIS as well as comparisons between the raster and available independent bathymetry and topographic data. A further comparison was also performed between the updated elevations applied to the model grids and the previous model grid elevations. The results of these comparisons are described in the following sections.

5.1 GIS Review of Updated Elevation Rasters

Initial evaluation of the completed rasters focused on comparing the raster elevations against the observed input values in GIS. This comparison revealed differences of less than 0.2 feet between the observed and corresponding raster elevations for channel locations in particular, as consistent with the mostly exact interpolation methods used for these areas (e.g., RBF interpolation). Similar small magnitude differences between observed and raster elevations of 0.2 to 0.4 feet, were also found for most backwater and overbank locations.

Elevation contour lines based on the completed raster elevation values were inspected in GIS to assess the elevation variation between the input points, and they generally showed that the interpolated elevations varied smoothly between the input points. The contours highlighted the slope characteristics of the completed raster, and confirmed that the channel slopes were steeper perpendicular to the channel boundaries and more gradual parallel those boundaries, as consistent with the expected anisotropic trends. Strong localized elevation gradients visible from the contour lines helped identify a handful of spurious input points; despite having acceptable height quality criteria, these points were typically offset by several feet from adjacent elevation input points most likely due to erroneous RTK-GPS water surface elevation data. Such points were omitted, and corrected final interpolations were performed for the corresponding locations.

It is noted that the elevations contours revealed a few channel elevation anomalies that appeared to result from use of the RBF interpolation method with the elliptical search radius, and were thus considered interpolation artifacts. These cases occurred where relatively few observed bathymetry input points were available and the reference thalweg line used for the river straightening step changed orientation abruptly relative to the channel boundary line orientation. In such instances, it was possible for nearshore observed elevation points to influence the interpolated elevations for nearby in-channel locations causing in-channel upward elevation anomalies (e.g., if in-channel observed points were not available); the alternative of mid-channel points influencing nearshore interpolated values was also possible, which resulted in nearshore downward elevation anomalies. Abrupt thalweg line orientation changes and the associated interpolation artifacts were most evident in shallow, widened portions of the river; thus, most of these were found above the Ceresco dam from approximately MP 2.75 to MP 5.25, and within the engineered channel segment from approximately MP 16.75 to MP 18.75. The typical magnitude of the elevation anomalies resulting from this source was estimated to be approximately 0.5 to 1.0 feet, and the maximum horizontal dimensions were estimated to be 50 feet by 150 feet. Elimination of the anomalous elevation artifacts would have required creating an alternate, less-variable reference line for use in the channel interpolations performed in straightened coordinates (e.g., river center-line), or use of alternate search radius parameters for these river segments. Given the small magnitude and limited areal extent of the elevation anomalies associated with the interpolation artifacts, which were not expected to have a large effect on the final model cell elevations, corrections were not performed and the artifacts were retained in the final raster versions.

5.2 Updated Raster Comparison with Other Measurement Data

Additional measured elevation data that were not used for the interpolation were available from a few locations and they were used to independently evaluate the completed raster reliability. These data included bathymetry measurements (e.g., bottom elevations) recorded along several river channel transects during the 2013 USGS ADCP velocity surveys (Reneau et al., 2014), and independently surveyed ground elevations reported by Enbridge for a small number of monitoring wells installed within or adjacent to the floodplain along the affected reach (e.g., Enbridge, 2010).

Vertical profile comparisons of the updated waterway raster elevations and the measured ADCP bottom elevations are provided in Figure 4, for representative velocity transect locations in the Ceresco, Mill Ponds and Morrow Delta areas. The raster and ADCP elevations were generally similar with localized elevation differences indicated along some of the transects; the magnitude of the observed elevation differences ranged up to approximately 1.0 feet vertically, and extended 100 feet or less horizontally along the profiles (e.g., Figure 4). The observed differences could be caused by actual elevation variations that were not detected by the more widely spaced raster input points, but were detected by the more or less continuous ADCP measurements. Alternatively, small errors in the elevation measurements for the raster input points could contribute to some of the differences. In general, the agreement between the ADCP and the raster elevations supports the reliability of the updated rasters, and indicates that the new rasters can be used to provide representative average elevations for the model grid cells located in the channel.

The available overbank comparison data are distributed over a wide range of locations and elevations and are summarized in separate comparison graphs for the upper and lower river in Figure 5. Differences between the independent observed ground elevations and the corresponding interpolated raster values were shown to be less than 0.5 feet at all but one of the available locations. The exception, indicated in Figure 5b, corresponds to a strongly sloping floodplain margin location in the lower river where the updated raster value was approximately 2.0 feet below the reported ground elevation. The elevation difference at this location is most likely a localized feature, caused by the sloping ground surface and the up to 5 feet of horizontal separation between the ground elevation survey point and the corresponding reference location for the raster elevation (e.g., raster cell size = 5 by 5 feet). Although the overbank elevation data are few in number, they likewise generally support the reliability of the updated elevation rasters.

5.3 Comparison of Updated and Previous HDM Grid Elevations

Enbridge provided copies of the previous waterway elevation raster (cell size = 5 feet, units = survey feet), a floodplain elevation raster (cell size = 27 meters), and floodplain and riverine model grids with bottom elevations defined for individual grid cells corresponding to those used in the previous model. According to the Enbridge HDM model report, the elevations for individual model grid cells represented averages of the enclosed raster cell elevations (e.g., multiple raster cells per model grid cell; Enbridge, 2012a). For purposes of the preliminary evaluation presented herein, new average (i.e., mean) elevations for individual model grid cells were determined from the updated elevation rasters and compared against the model cell elevation values used for the original models. Maps of the difference between the updated and previous grid cell average elevations were the primary tool used for this comparison, from which the location and magnitude of the differences could be readily identified. It is noted that new grid cell average elevations were calculated for both the riverine and floodplain grids, which was intended to allow for separate, cell-by-cell difference comparisons of updated versus original elevations for each grid. However, preliminary inspection of riverine and floodplain elevation and elevation difference maps revealed many waterway locations where co-located riverine and floodplain model cells from the previous Enbridge grids had assigned elevations that differed by one to three feet. Many of these occurrences could not be attributed to the differing grid geometries, suggesting instead that errors were made by Enbridge in the step of calculating or assigning the raster elevations to either the previous riverine or the previous floodplain model grid. In view of this discrepancy, for the comparisons presented herein, elevation differences for waterway locations were based entirely on the riverine grid results, and floodplain grid elevation difference results were compared for non-waterway, overbank locations only.

The updated mean elevation for each model grid cell was calculated from the enclosed raster values using the ArcGIS Zonal Statistics tool. Prior to calculating the means for the riverine model grid, the updated raster was first clipped at the waterway boundary to exclude contributions from overbank raster cells that intersected riverine cells (e.g., some riverine model cells extended slightly beyond the waterway boundary); the riverine model grid elevations were thus determined exclusively from raster cells located in the waterway. In the case of the Cartesian floodplain model grid, which did not align with the river boundaries, model cells with areas located more than halfway within the waterway were considered part of the waterway and the corresponding model grid cell elevations were determined exclusively from enclosed waterway raster cells, while elevations for floodplain grid cells with areas located more than halfway outside the waterway were determined from the elevations of enclosed overbank raster cells only.

Maps showing the difference between the updated and previous riverine model grid elevations, and the corresponding observed data for the updated compilation, for a representative upper river waterway segment are provided in attached Figure 6. This figure shows that the updated elevations were above the previous values by 0.5 to 1.5 feet for many near shore model cells, but it also includes several discrete river transect locations where the new model grid elevations were below the previous values by more than two feet. The increased in near shore model grid cell elevations was attributed to the use of new observed bathymetry points for the updated compilation that included representative mid-channel and near shore points (e.g., recorded along river transects), in locations where the previous raster and model grid elevations relied primarily or exclusively on longitudinal profile points recorded along the lowest elevation river thalweg. Examples of this situation are shown in Figure 6a, upstream of MP 11.75 and upstream of MP 12.00. As noted above, the reliance on the longitudinal points for the previous compilation was necessary in some river segments because other data were not available; however, the resulting previous channel elevations for these segments were likely unrealistically low, especially in the near shore areas. The updated, higher near shore grid elevations such as those shown in Figure 6, were thus considered reasonable and generally consistent with the expected results. Comparison of Figure 6a and 6b show that many of the discrete, large elevation decreases along river transects coincided with former HECRAS bathymetry points that were used in the previous compilation but were not used for the updates because they included incorrect point locations and estimated elevations. Examples of large elevation decreases that resulted from removal and replacement of HECRAS bathymetry points along three former sections were found immediately upstream of MP 11.50 (one section), and immediately downstream of MP 11.75 (two sections). The large downward elevation changes in these areas suggest that the removed HECRAS bathymetry points had unrealistically high elevations and they may have included some miss-located overbank points. Elevation changes resulting from removal of former HECRAS bathymetry points along three other sections included in Figure 6 were approximately neutral. The river segment from MP 12.00 (e.g., Raymond Road) to MP 12.25, shown in Figure 6, was an unusual area in which a large number of former HECRAS overbank points appeared to be erroneously displaced into the channel and contributed to anomalously high previous raster and riverine model grid elevations. The elevations for the Raymond Road area were substantially lowered in the updated raster and riverine model grid through correction to HECRAS point locations, which eliminated overbank points from the channel, plus the addition of many new 2012 observed bathymetry point data (e.g., Figure 6). It is noted that the predominantly downward elevation changes for the Figure 6 segment resulting from the combined correction to the Raymond Rd. area and removal of the other former HECRAS bathymetry points, as described above, were likely large enough to cause detectable changes in the model results. In general, the removal of these points is expected to yield overall model results that are more reliable.

Similar maps of the updated versus previous riverine model grid elevation differences, and the corresponding observed bathymetry point data, for a representative lower river waterway segment are provided in Figure 7. Significant trends observed in the lower river, which are illustrated in Figure 7, included updated elevations for many near shore model grid cells that were 1-2 feet above the corresponding previous values, and the occurrence of numerous discrete, full transects for which the updated elevations were more than 2 feet above the previous values. Several of the discrete large elevation increases along river transects, as well as the overall elevation increase of near shore model grid cells, were again attributed to the use of new observed bathymetry points for the updated compilation that included representative mid-channel and near shore locations (e.g., recorded along river transects), whereas the previous raster and model grid elevations relied primarily or exclusively on longitudinal profile points recorded along the lowest elevation river thalweg. Examples of discrete, large elevation increases along river transects resulting from the added point data were found downstream of MP 24.00, upstream of MP 24.25, and downstream of MP 24.50 (e.g., Figure 7). The trend of increased near shore model cell elevations was particularly widespread and prominent for the lower river, because of the even greater reliance on the longitudinal points for the previous compilation (e.g., fewer other data were available for this river section). It is noted that despite the predominantly upward elevation changes to the updated model grid cells evident in Figure 7, the resulting low flow water depths inferred from comparison with the corresponding estimated bank elevations remained in the range of 3 to 7 feet at all model cell locations within this segment, which was considered reasonable and provided further evidence that the previous model grid elevations were probably unrealistically low. Several of the discrete transects with large elevation differences again coincided with former HECRAS bathymetry points that were used in the previous compilation, but were excluded and/or replaced for the updated compilation. Examples of large elevation differences along discrete transects resulting from removal of former HECRAS bathymetry points are shown in Figure 7 near the midpoints of the MP 23.75 to MP 24.00, and MP 24.00 to MP 24.25 segments, and also immediately downstream of MP 24.25. Although elevation corrections resulting from the former HECRAS point removal were primarily upward for the illustrated segment, downward corrections associated with removal of former HECRAS points were observed in other segments. As before, the magnitude of the elevation changes indicated in Figure 7, were probably large enough to cause detectable changes in the model results, and the updates are expected to yield improved overall model results.

Comparisons of the updated and previous floodplain model grid cell elevations are presented for representative overbank locations in the upper river (Figure 8a) and lower river (Figures 8b and 8c). Figure 8a shows that the updated floodplain grid elevations in the upper river were generally above the previous values by 0.5 to 2.0 feet. This difference was expected and reflects use of the Calhoun County LiDAR input data for the upper river overbank raster and model grid updates. The previous 100-year floodplain boundary and inundation boundaries for other flow events were developed from HECRAS using the same Calhoun County LiDAR topographic data as the current updates and, thus, the inundation areas resulting from the updated floodplain grid elevations would not be expected to differ significantly from those previous features. However, combined with changes and corrections to the waterway portion of the floodplain grid, the overbank differences shown in Figure 8a could result in detectable differences relative to the EFDC model results reported by Enbridge for high flow events which were obtained using the previous floodplain grid elevations. The updated and previous floodplain grid overbank elevations for the lower river showed general agreement over large portions of the lower river floodplain, but the updated values were predominantly above the previous floodplain grid elevations by 0.5 to 1.5 feet in the middle section from approximately MP 25.00 to MP 34.00 (e.g., Figures 8b, c). The differences were surprising given that the same input data were used for both lower river elevation compilations (e.g., Enbridge LiDAR). Although the overbank elevation differences were smaller in magnitude than those found for the upper river, combined with changes and corrections to the waterway portion of the floodplain grid, the updated overbank elevations could again lead to detectable differences in the model results relative to the previous Enbridge floodplain model simulations.

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TABLES

TABLE 1. SUMMARY OF BATHYMETRY AND TOPOGRAPHIC DATA SOURCES
ENBRIDGE OIL SPILL, MARSHALL, MICHIGAN,
KALAMAZOO RIVER BATHYMETRY AND TOPOGRAPHY UPDATES USED FOR 2014 SITE MODELS

LOCATION	SOURCE DATA TYPE	SOURCE DATASETS	
		Original Elevation Compilation (Enbridge, 2012a)	Updated Elevation Compilation
Bathymetry	Poling Bathymetry Points	• 2011 Reassessment Poling Bathymetry Points • 2010 Longitudinal Poling Bathymetry Points	• 2011 Reassessment Poling Bathymetry Points • 2010 Longitudinal Poling Bathymetry Points • 2012 Reassessment Poling Bathymetry Points • 2012 Supplemental Poling Bathymetry Points
	HECRAS Bathymetry Points	• All Points	• Corrected Points [1]
	Operational Bathymetry Points		• 2012-2013 E4 Boom Bathymetry Monitoring Points • 2013 Sediment Trap Bathymetry Monitoring Points • 2014 Pre-dredge Bathymetry Points
	Velocity Transect Bottom Elevations		• 2012 AECOM Bottom Elevation Points • 2013 USGS ADCP Velocity Transect Bottom Elevation Points
Topography	LiDAR	• Enbridge Project LiDAR (I-69 to MP 40.00)	• Calhoun County LiDAR (I-69 to MP 15.60) • Enbridge Project LiDAR (MP 15.60 to MP 40.00)
	Poling Bathymetry Points	• 2011 Strike Bathymetry Points	• 2011 Strike Bathymetry Points

NOTES:
[1] HECRAS point locations corrected as described in Section 3.1.2

TABLE 2. SUMMARY OF POLING BATHYMETRY POINT TOTALS
ENBRIDGE OIL SPILL, MARSHALL, MICHIGAN,
KALAMAZOO RIVER BATHYMETRY AND TOPOGRAPHY UPDATES USED FOR 2014 SITE MODELS

POLING BATHYMETRY DATASET	POINT TOTALS	
	Unfiltered	Filtered [1]
• 2011 Reassessment Poling Bathymetry Points	21, 908	6,721
• 2010 Longitudinal Poling Bathymetry Points	1,736	1,719
• 2012 Reassessment Poling Bathymetry Points	7,766	3,903
• 2012 Supplemental Poling Bathymetry Points	1,689	1,401

NOTES:

[1] Filtered point totals include points with RTK-GPS elevation uncertainties $\leq$ 0.2 feet; also, duplicates and points with no recorded elevations were excluded from the filtered totals.

TABLE 3. SUMMARY OF CHANNEL INTERPOLATION INPUT CROSS-SECTIONS
ENBRIDGE OIL SPILL, MARSHALL, MICHIGAN,
KALAMAZOO RIVER BATHYMETRY AND TOPOGRAPHY UPDATES USED FOR 2014 SITE MODELS

LOCATION	CHANNEL INTERPOLATION INPUT CROSS-SECTION TOTALS	
	Input Cross-sections from New/Existing Transect Points	Input Cross-sections from HECRAS Bathymetry Points
Upper River (MP 2.0 to MP 15.6)	116	26
Lower River (MP 15.6 to MP 40.0)	101	97

NOTES:
[1] HECRAS point locations corrected as described in Section 3.1.2

TABLE 4. SUMMARY OF COMPLETED BATHYMETRY AND OVERBANK RASTERS
ENBRIDGE OIL SPILL, MARSHALL, MICHIGAN,
KALAMAZOO RIVER BATHYMETRY AND TOPOGRAPHY UPDATES USED FOR 2014 SITE MODELS

RASTER ID	COMPLETION DATE	RASTER EXTENT		COMMENT
		Waterway	Floodplain/Overbank	
Upper River	October 2013	MP 2.00 – MP 15.60 • Final	MP 2.00 – MP 15.60 • 100-year floodplain boundary + 100 ft extent	Initial combined raster; overbank incomplete.
	April 2014	MP 2.00 – MP 15.60 • Final	I-69 – MP 15.60 • Final; expanded to model grid extent	Complete combined raster.
Lower River	April 2013	MP 36.50 – MP 40.00 • Provisional IDW interpolation for MP 36.50 – MP 37.75 • Morrow dam area coverage gap		Morrow delta and lake waterway extent only.
	August 2013	MP 36.50 – MP 40.00 • Provisional IDW interpolation for MP 36.50 – MP 37.75		Morrow delta and lake waterway extent only.
	January 2014	MP 15.60 – MP 36.85 • Updates complete for lower river except Morrow delta	MP 15.60 – MP 40.00 • 100-year floodplain boundary + 100 ft extent	Initial combined raster; Morrow delta/lake waterway not included; overbank incomplete.
	February 2014	MP 15.60 – MP 40.00 • Provisional IDW interpolation for MP 36.85 – MP 37.75	MP 15.60 – MP 40.00 • 100-year floodplain boundary + 100 ft extent	Prelim. combined raster; provisional Morrow delta bathymetry; overbank incomplete.
	April 2014	MP 15.60 – MP 40.00 • Provisional IDW interpolation for MP 36.85 – MP 37.75	MP 15.60 – MP 40.00 • Final; expanded to model grid extent	Prelim. combined raster; provisional Morrow delta bathymetry.
	July 2014	MP 15.60 – MP 40.00 • Final; includes MP 36.85 – MP 37.75 update	MP 15.60 – MP 40.00 • Final; expanded to model grid extent	Complete combined raster.

NOTES:
"MP" denotes an abbreviation for river milepost; "IDW" is an abbreviation for inverse distance weighting (e.g., as referenced in Section 4.3).

FIGURES

FIGURE CAPTIONS

FIGURE 1 Location map of the Kalamazoo River affected by the July 2010 Enbridge Line 6B oil spill.

FIGURE 2 Schematic diagram illustrating the method used to back-transform an example radial basis function interpolated point located in the river channel from straightened coordinates (S_i,N_i) to geographic coordinates (X_i,Y_i).

FIGURE 3 Morrow Delta map showing the extent of separate elevation subrasters (in x-y coordinates) that were mosaicked together to form the final delta bathymetry and topographic raster.

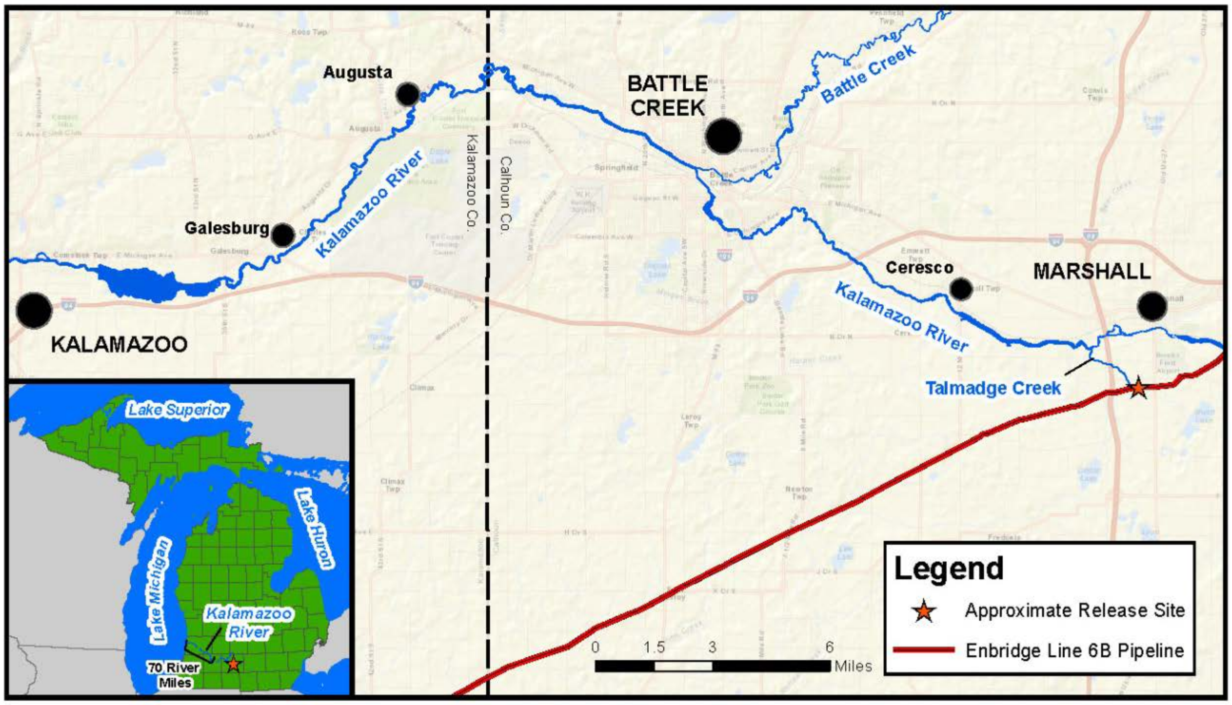
FIGURE 4 Vertical-profile graphs of the final updated bathymetry raster elevations and the 2013 USGS ADCP velocity transect bottom elevations for ADCP transects located at Ceresco (4a), the Mill Ponds (4b), Morrow Delta (4c), and the Morrow delta narrows (i.e., neck) (4d).

FIGURE 5 Comparison of updated topography raster elevations versus Enbridge survey elevations for selected floodplain locations in the upper river (5a), and lower river (5b).

FIGURE 6 Map of the difference between the updated riverine grid cell average elevations (e.g., determined by zonal statistics from the final updated bathymetry raster) and the previous Enbridge riverine grid cell elevations (e.g., updated elevations minus the previous Enbridge elevations) (6a), and the corresponding bathymetry input point locations (6b), for an upper river segment.

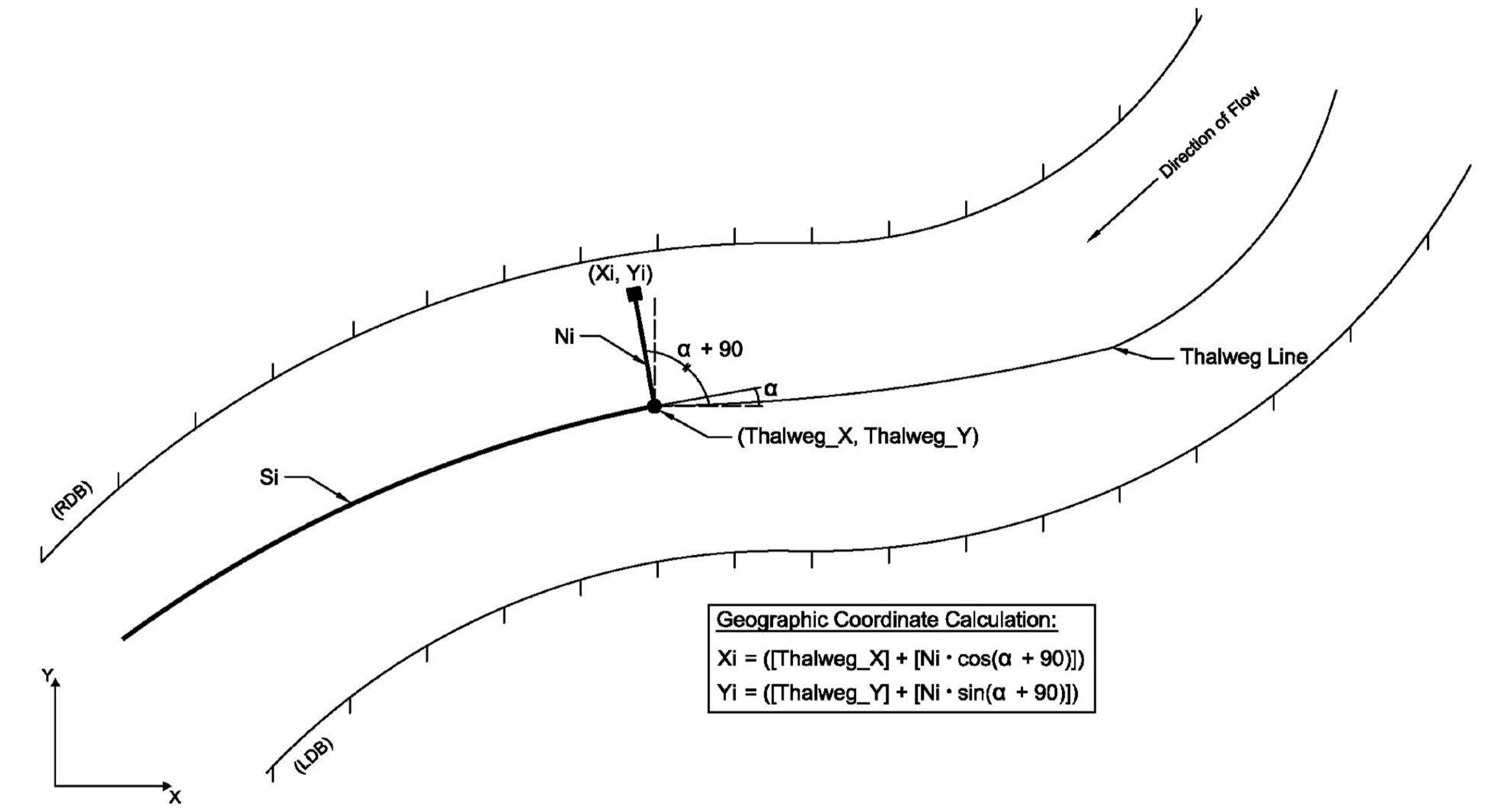
FIGURE 7 Map of the difference between the updated riverine grid cell average elevations (e.g., determined by zonal statistics from the final updated bathymetry raster) and the previous Enbridge riverine grid cell elevations (e.g., updated elevations minus the previous Enbridge elevations) (7a), and the corresponding bathymetry input point locations (7b), for a lower river segment.

FIGURE 8 Comparison maps of the difference between the updated floodplain grid cell average elevations (e.g., determined by zonal statistics from the final updated combined bathymetry and topographic raster) and the previous Enbridge elevations (e.g., updated elevations minus the previous Enbridge elevations) for overbank areas at MP 10.00 to MP 10.50 (8a), MP 23.50 to MP 24.00 (8b), and MP 26.50 to MP MP 27.00 (8c).



Augusta
BATTLE CREEK
Battle Creek
Galesburg
Kalamazoo River
Kalamazoo Co.
Calhoun Co.
KALAMAZOO
Ceresco
MARSHALL
Kalamazoo River
Talmadge Creek
Lake Superior
Lake Huron
Lake Michigan
Kalamazoo River
70 River Miles
Legend
Approximate Release Site
Enbridge Line 6B Pipeline
0 1.5 3 6
Miles

Figure 1.



Legend

River Channel Boundary

■ Example Interpolated RBF Point

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FIGURE 2

MARSHALL, MI PIPELINE RELEASE
KALAMAZOO RIVER, MI

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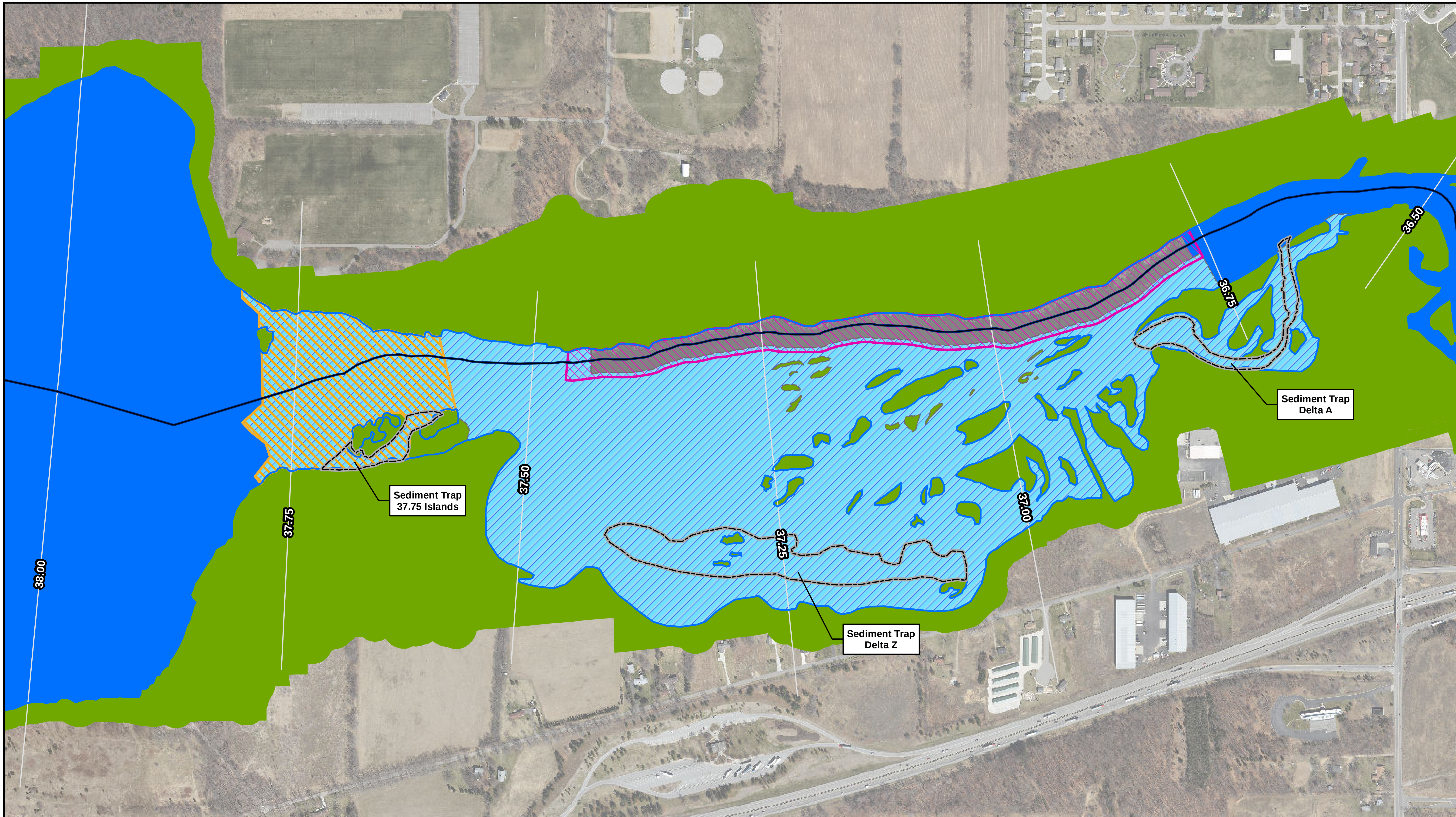

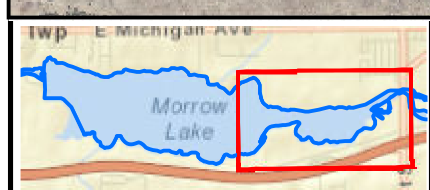

Delta North Channel Revised Interpolation Area (July 2014)
Morrow Delta Revised Interpolation Area (July 2014)
Clipped Enbridge Sonar Extent
Riverine and Lake Interpolation Extent
Overbank Interpolation Extent

Waterway
Thalweg

N W E S

0 250 500 Feet

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FIGURE 3

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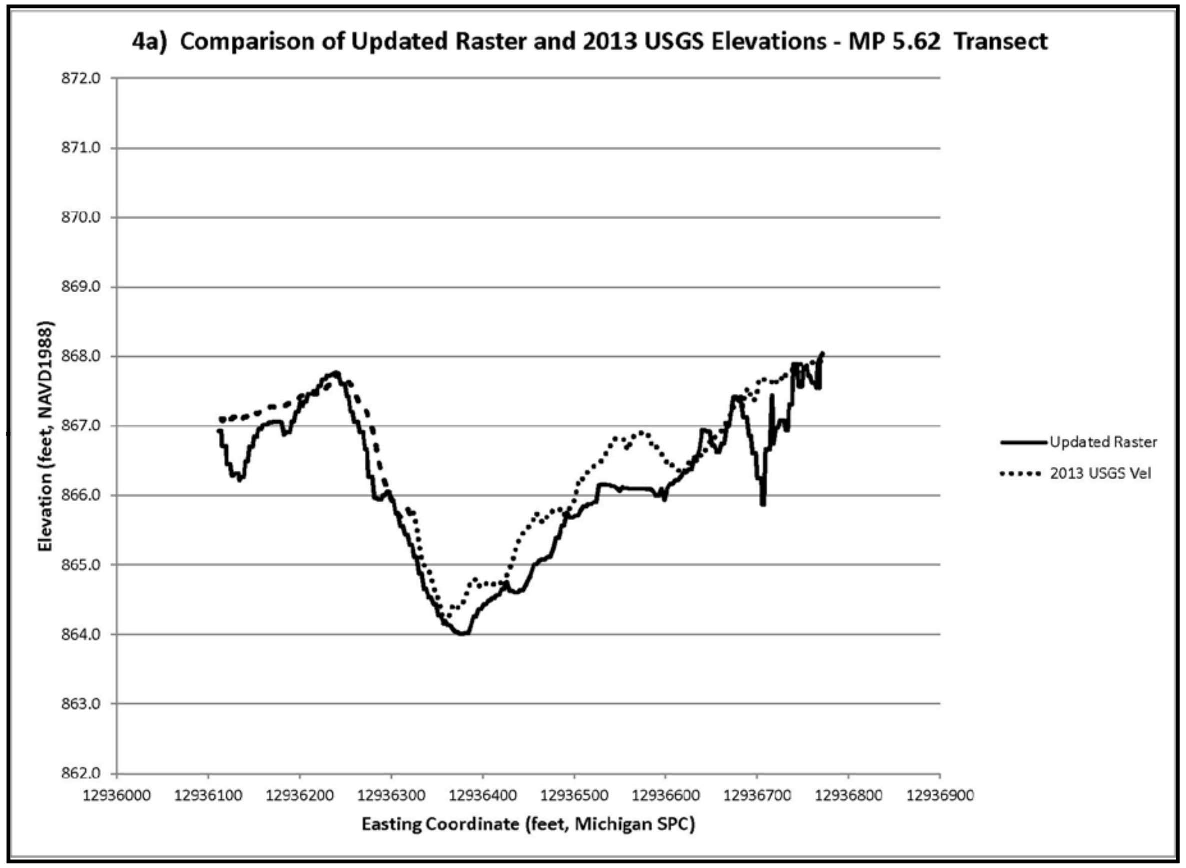

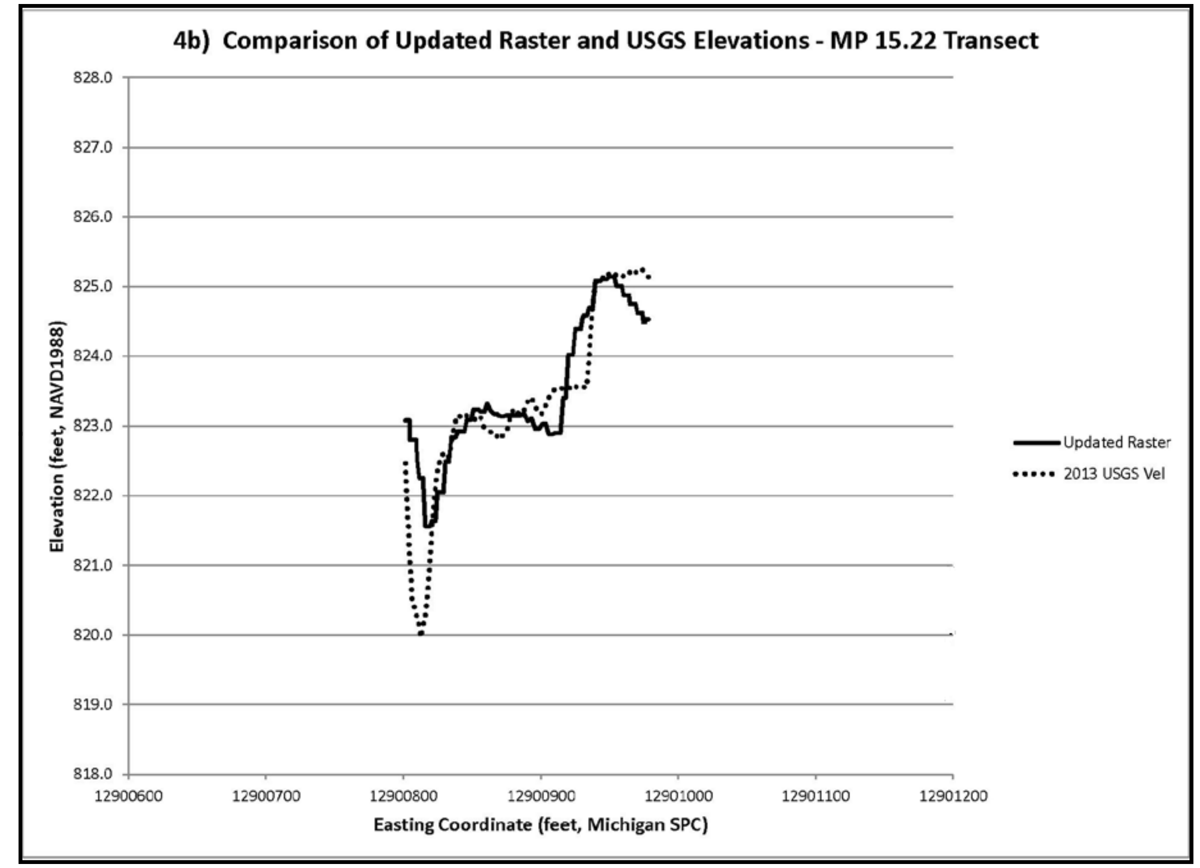

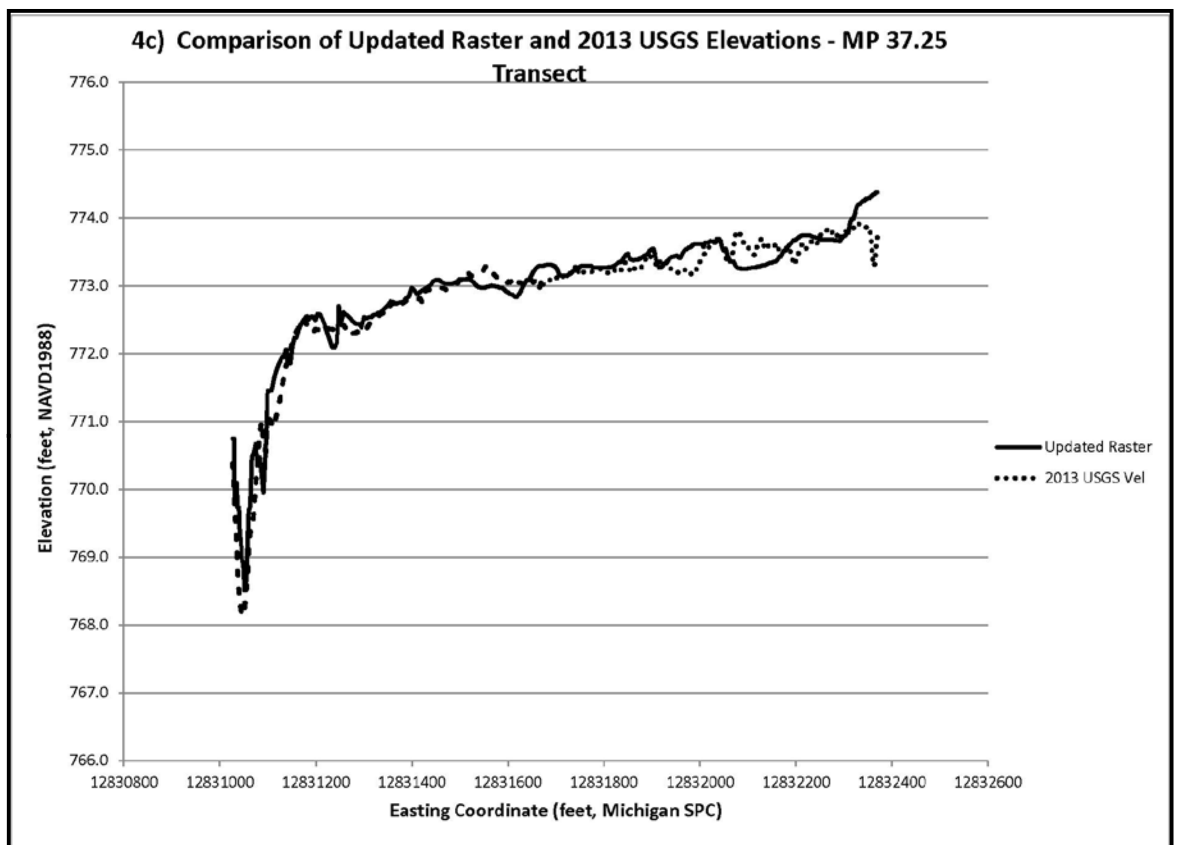

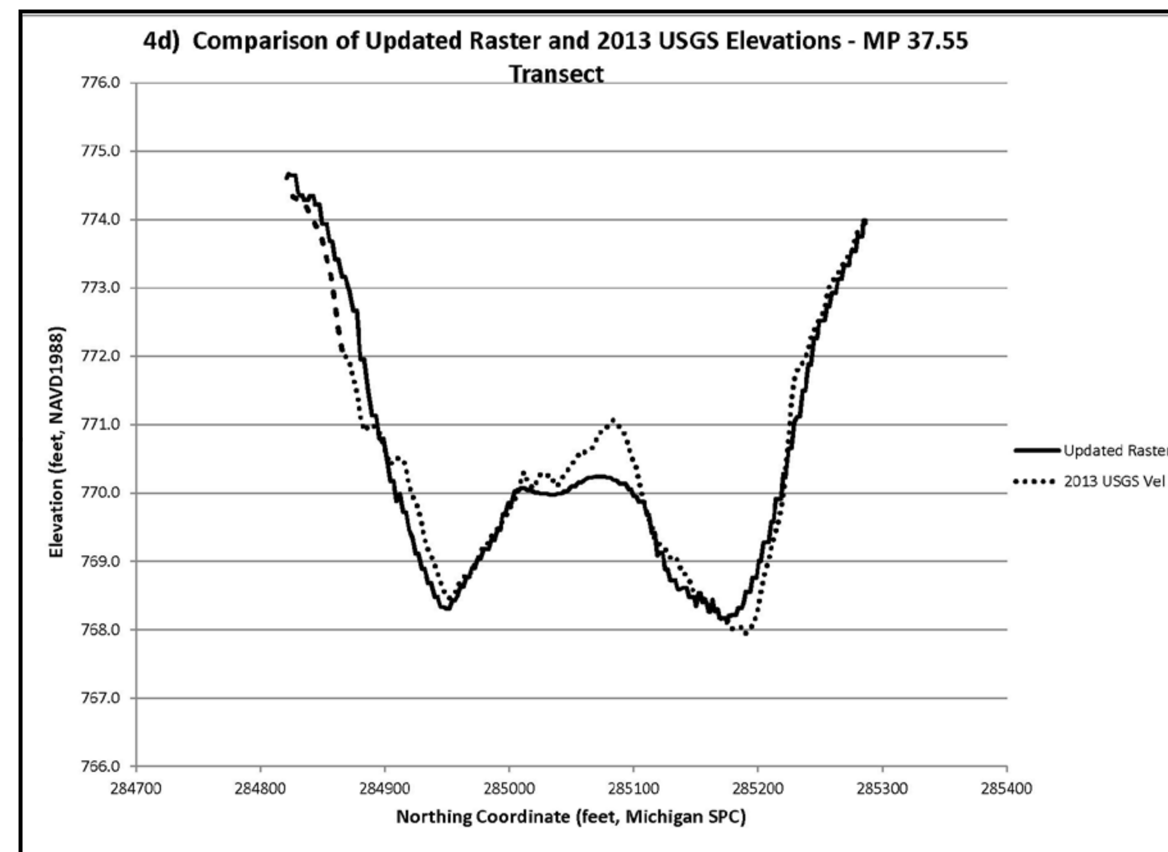

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FIGURE 4

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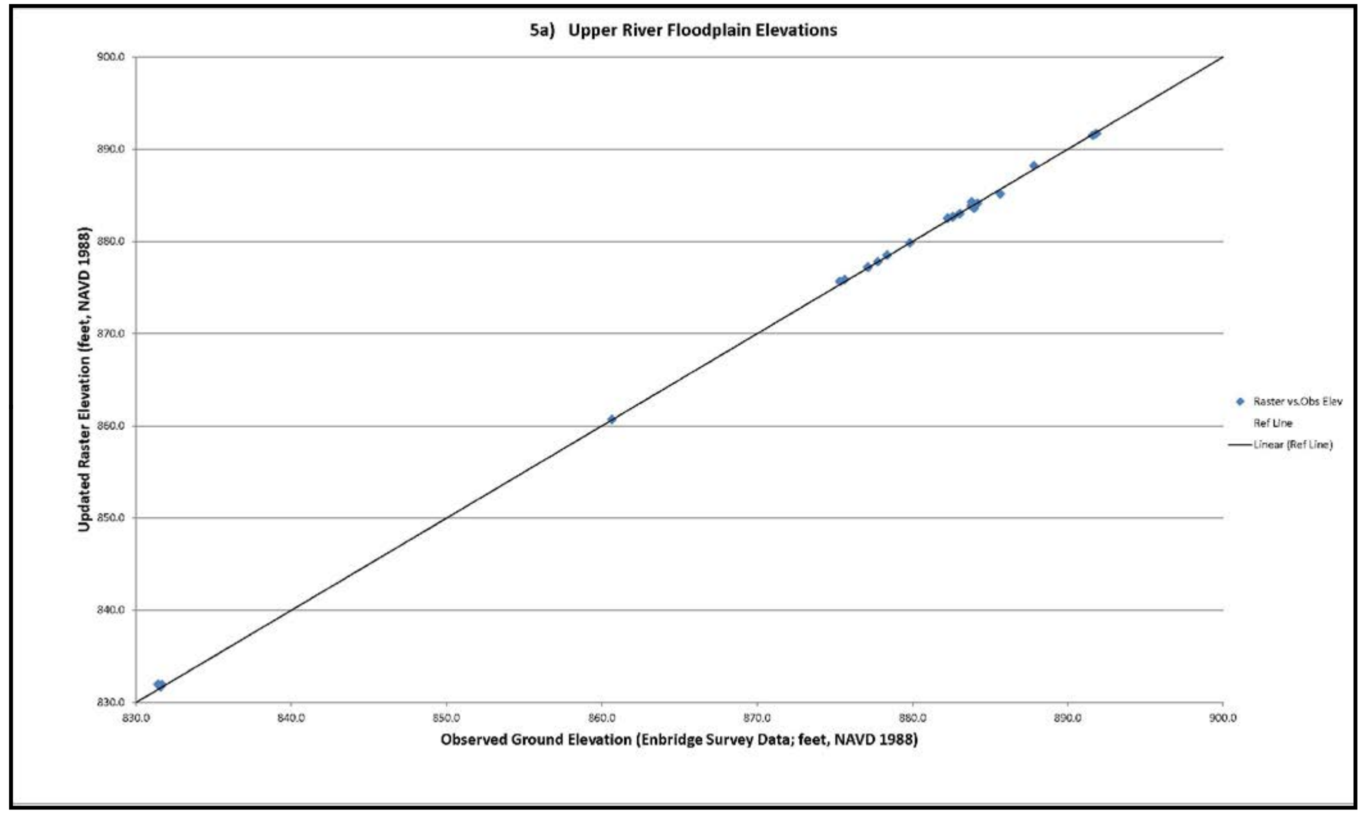

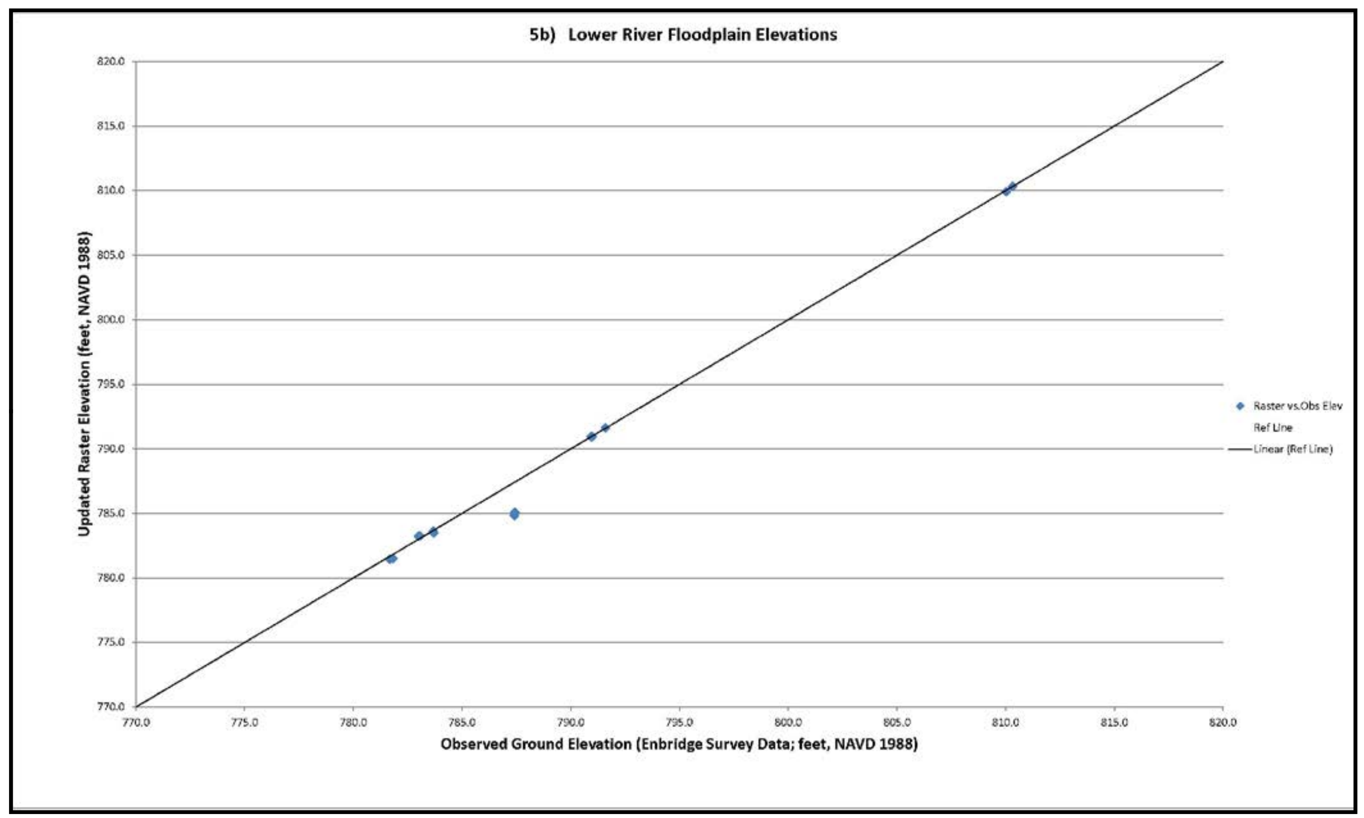

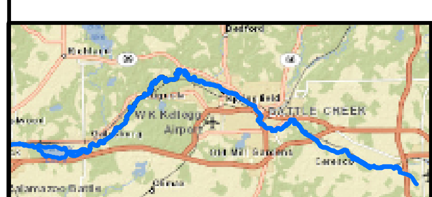

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FIGURE 5

MARSHALL, MI PIPELINE RELEASE
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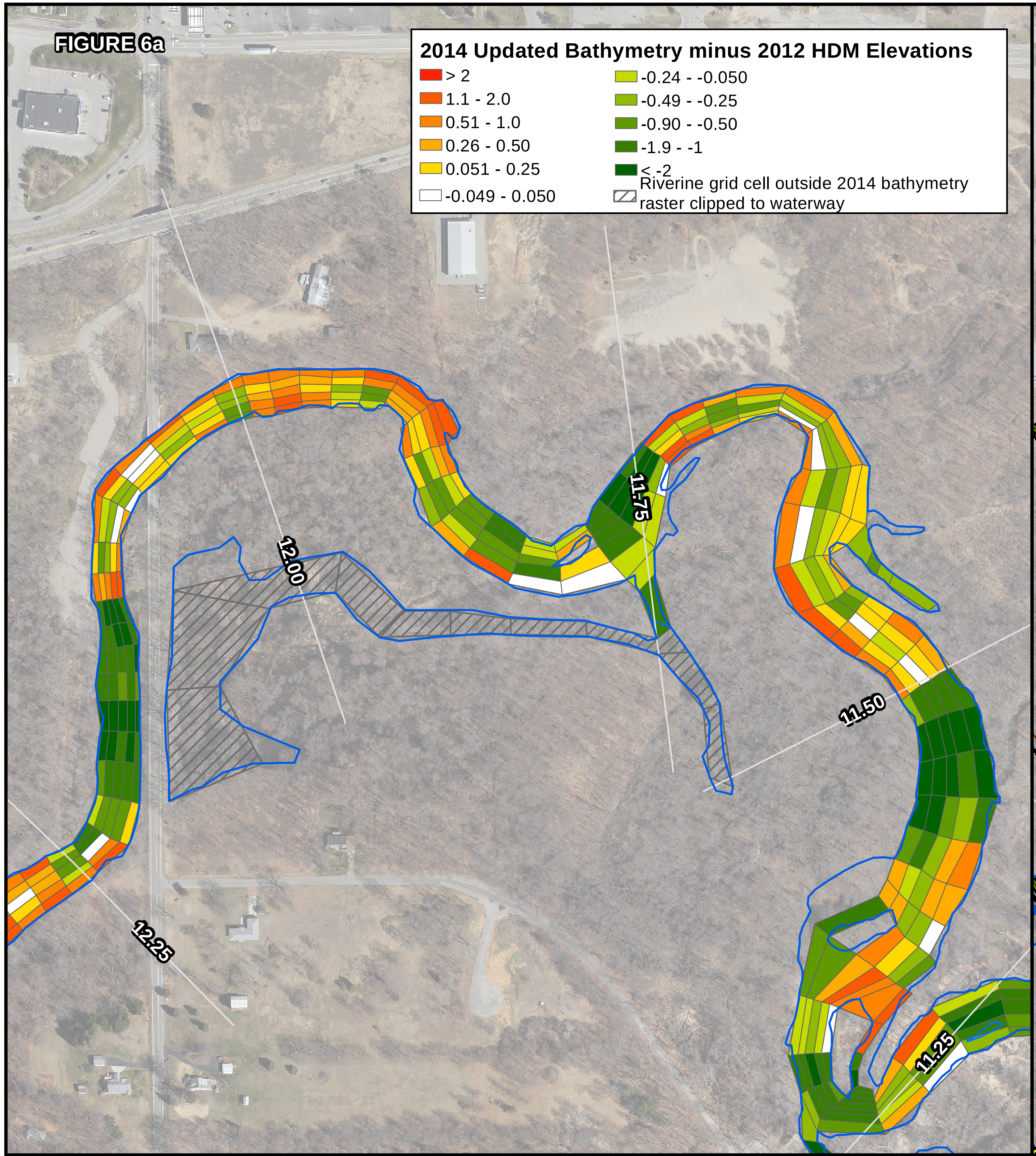

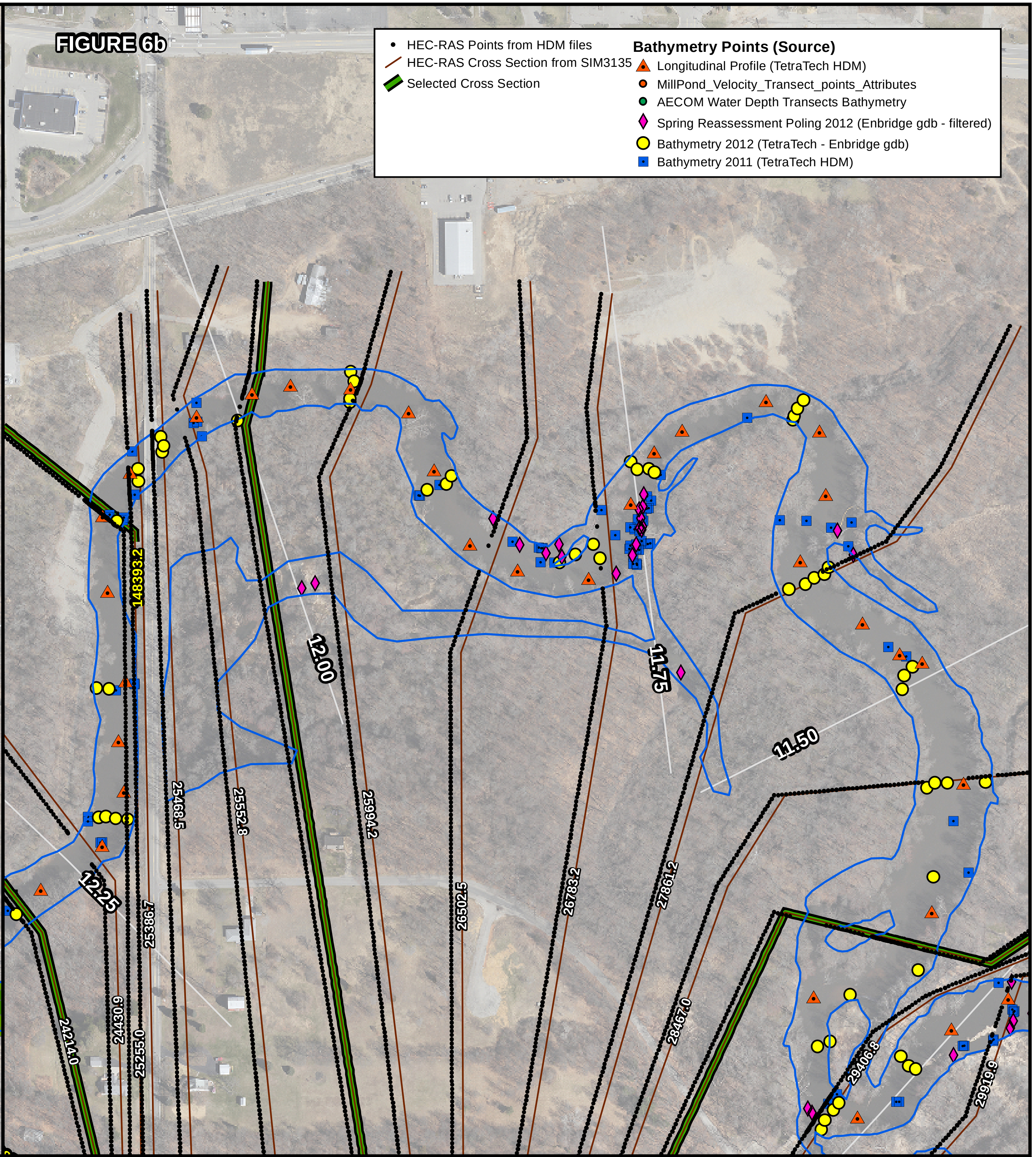

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0 150 300 Feet

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FIGURE 6

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KALAMAZOO RIVER, MI

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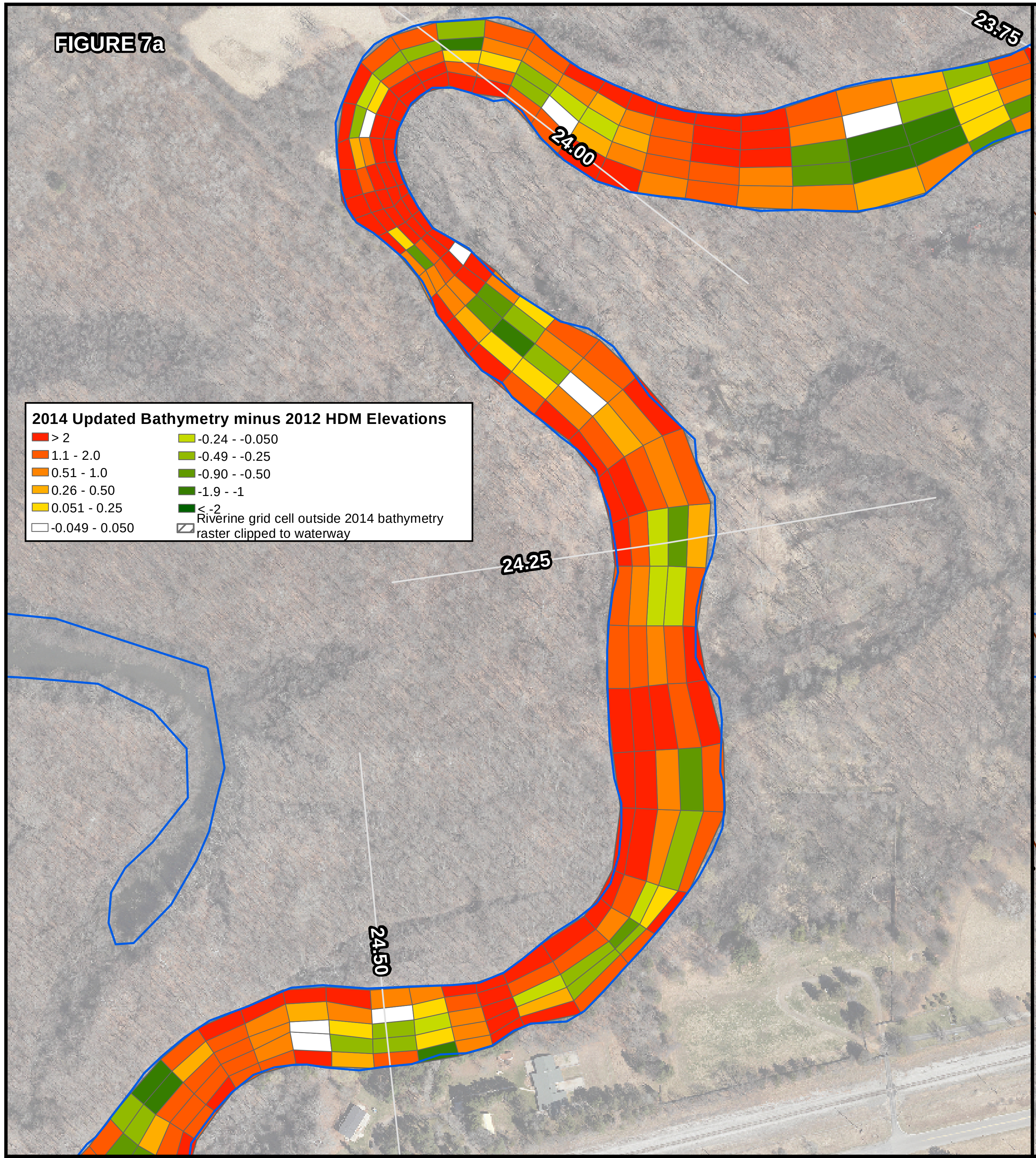

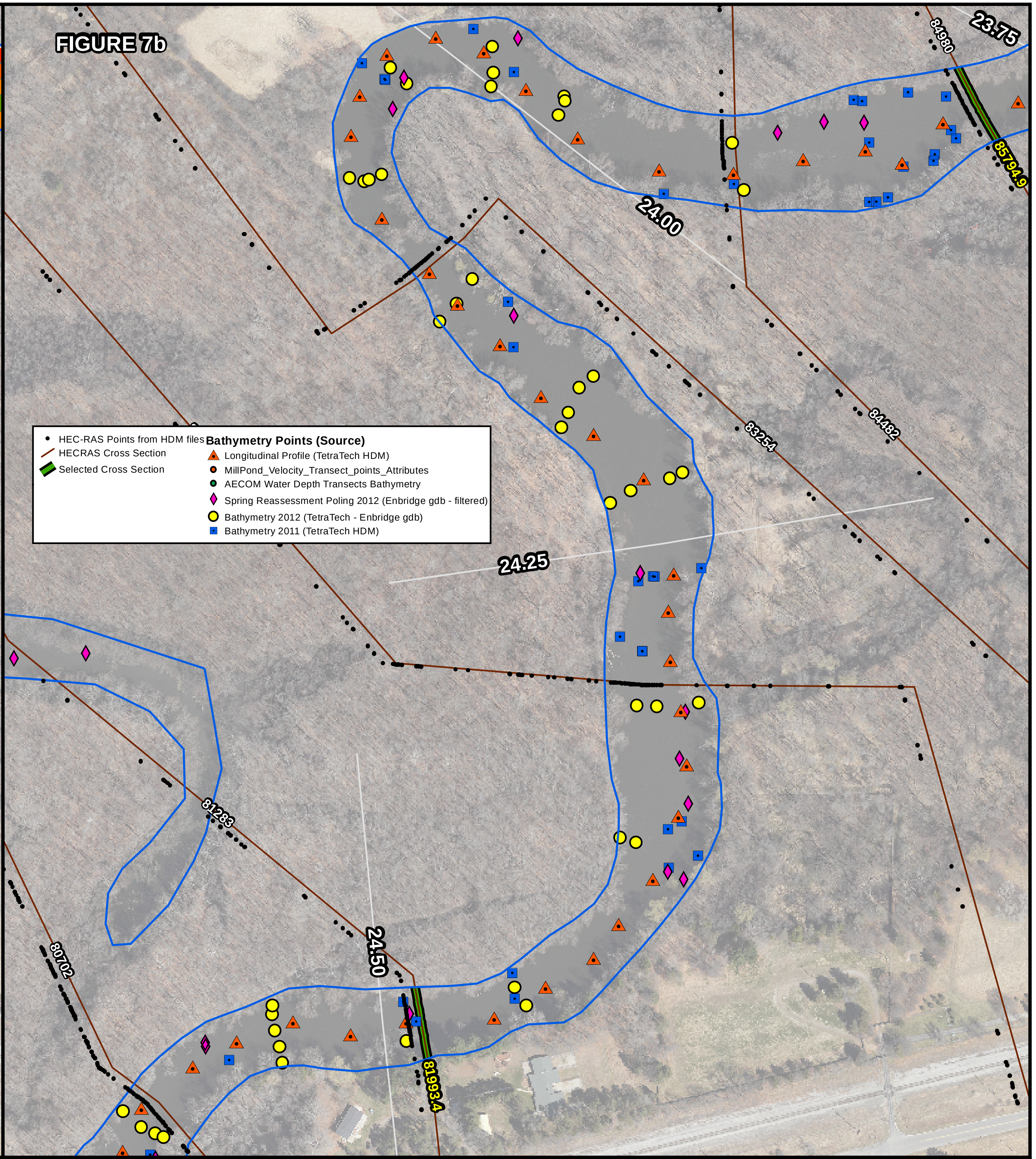

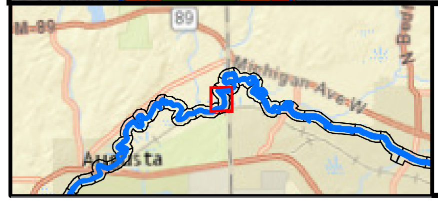

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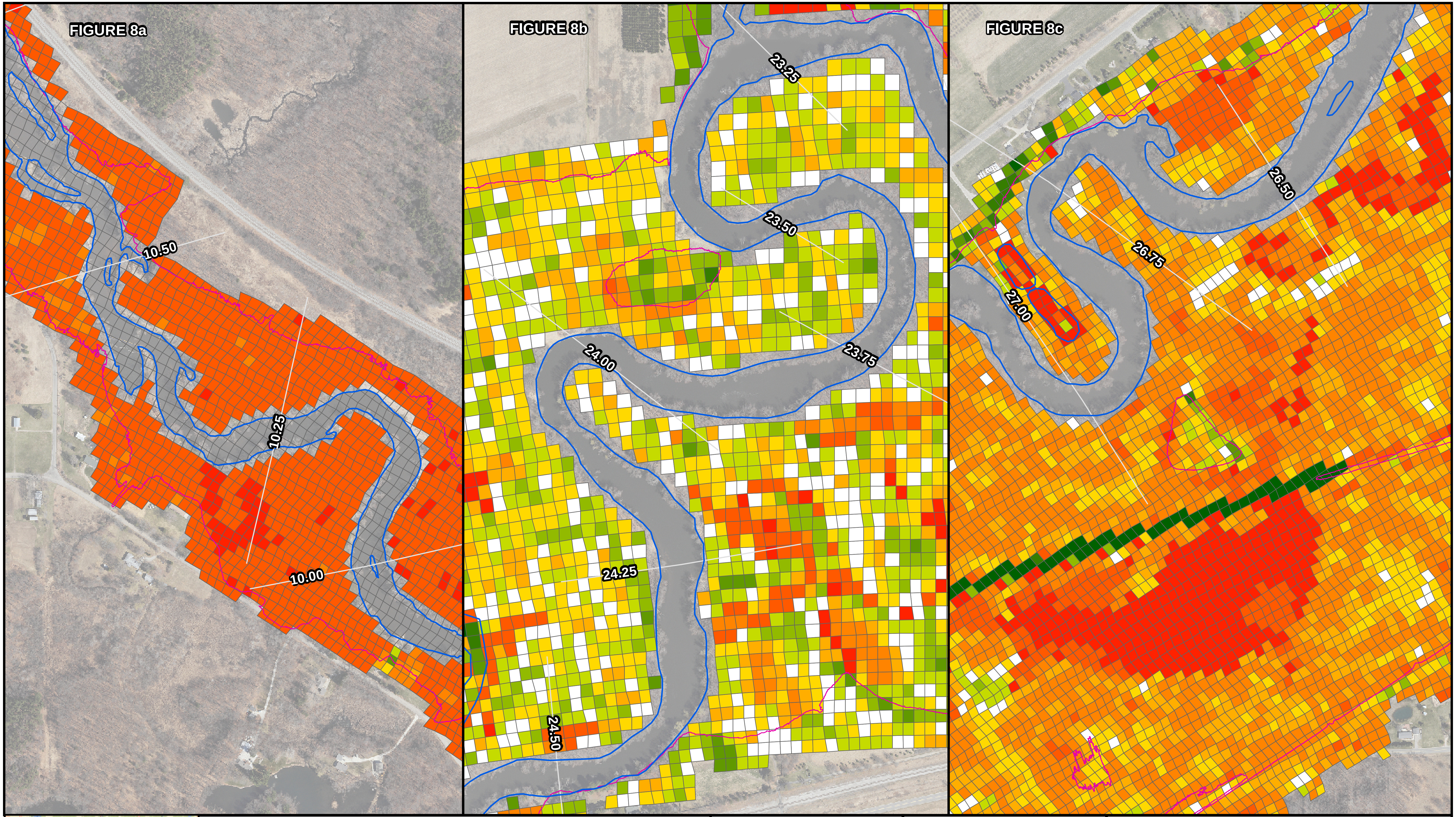
FIGURE 7

MARSHALL, MI PIPELINE RELEASE
KALAMAZOO RIVER, MI

Path: F:\Logistics\GIS_Data\Marshall_Oil_ER\GIS\MXD\20141212\Bathy_Memo\Fig7_Riverine_Grid_Comparison_Downstream_v20141215.mxd



2014 Mean Bathy minus 2012 HDM

- > 2
- 1.1 - 2.0
- 0.51 - 1.0
- 0.26 - 0.50
- 0.051 - 0.25
- -0.049 - 0.050
- -0.24 - -0.050
- -0.49 - -0.25
- -0.90 - -0.50
- -1.9 - -1
- < -2

Kzoo River Boundary (from Enbridge)
100 YR Floodline

N W E S

Feet 0 200 400

Prepared for:
U.S. EPA REGION V
Contract No.: EP-S5-06-04
TDD: S05-0005-1007-030
DCN: 1154-4D-AHMS

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FIGURE 8

MARSHALL, MI PIPELINE RELEASE
KALAMAZOO RIVER, MI

Map of

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Date of Aerial Photographs: April 2011