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AutoRoute Rapid Flood Inundation Model

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) demonstrates the flood modeling capabilities of the AutoRoute model. The AutoRoute model has been developed to support the Military Hydrology Program at the Coastal and Hydraulics Laboratory (CHL) as part of their mission to determine route vulnerability caused by flooding over large land areas. Through several tests the AutoRoute model showed that it quickly and effectively simulates the flood extent of high flow volumes where adequate Digital Elevation Model (DEM) data is available.

INTRODUCTION: The Military Hydrology Program at CHL fields numerous requests for information (RFI) from the military regarding route vulnerability caused by hydrologic factors, such as flooding. Currently, completing these route vulnerability studies includes the use of the AutoRoute model developed by CHL personnel in 2011. The model is computationally efficient and versatile, allowing for large sections of routes to be analyzed in a timely fashion. The model results can also link to existing mobility models to determine the risk that flooding has on the mobility of vehicles.

The AutoRoute model is a one-dimensional, raster-based program developed to determine flood extent and stream cross sections efficiently over large areas. The model uses a Digital Elevation Model (DEM) and a computed stream mask to determine the location and cross section of each stream cell within the domain. As in most modeling cases, the finer the resolution of the DEM data, the more accurate and defined the results will be.

The goal of AutoRoute is to compute the inundated area and spatially explicit depth of inundation for a given flow value. For a given flow Q we wish to derive the flood depth h, flood extent, cross-section profile, cross-section area A, and average flow velocity ($V = Q/A$). Unlike typical flood models, the AutoRoute model neglects the flow in highly detailed channels. The target application of AutoRoute is in data-sparse regions where DEM data are the primary source of data and stream cross-section data does not exist. As such, the AutoRoute model is not meant to be as accurate as models such as HEC-RAS (U.S. Army Engineer Hydrologic Engineering Center 2010) or AdH (Berger and Tate 2007). It is also not meant to be as computationally complex and thus is much more rapid. The hypothesis of the AutoRoute model design is that, for significant flooding return periods in areas of limited river engineering, the primary channel can be sufficiently approximated by a cross section based on the DEM. Thus the spreading of the floods can be sufficiently approximated by directly computing flow across cross sections based only on the DEM. It would be expected that AutoRoute would be less successful at predicting flow in areas of significant river engineering, such as areas with levees and floodwalls.

A validation study of the AutoRoute model was briefly completed during development in 2011, but no official validation study has been completed to date. This technical note will describe the processes that AutoRoute employs as well as validate the model by demonstrating its capabilities to (1) create accurate flood inundation maps, and (2) create cross-sectional profiles that are useful to existing mobility models. These capabilities will be demonstrated using existing flood inundation data collected by the U.S. Geological Survey (USGS) after historical floods within the continental United States.

DATA SOURCES: The AutoRoute model is raster-based and depends on the DEM of the river corridor and adjacent areas, as well as products derived from the DEM to determine both the locations of stream cells and the cross-section profile affiliated with each stream cell. The flood extent, depth, and velocity at each stream cell can be determined based on the cross-section profile, flow value (described below), and information derived from the DEM.

As discussed below, the main inputs into the AutoRoute model are the following:

1. High-resolution DEM
2. Stream mask derived from the DEM
3. Estimate of flow through river

DEM. AutoRoute works by looking at every stream cell within the domain and calculating the parameters needed to compute the flows, including the longitudinal slope S along the stream and the perpendicular cross-section. The cross section is perpendicular to the general stream direction and is sampled from the DEM. For this project the AutoRoute model looked only at the adjacent upstream and downstream stream cells to determine the general stream direction, but it has the capability to look at stream cells further upstream and downstream to determine the general stream direction. The resolution of each stream cell cross section is entirely dependent on the resolution of the DEM.

Stream Mask. The stream mask is based on the DEM and is created using a raster-based flow accumulation regime. There are many flow direction/accumulation regimes to choose from (Freeman 1991; Quinn et al. 1991; Costa-Cabral and Burges 1994; Tarboton 1997; Schäuble, Marinoni, and Hinderer 2008), but the one found in ArcHydro of ArcGIS 10.0 (ESRI, 2011) was used in this project. A flow accumulation regime determines how many cells hydraulically contribute to each raster cell within the domain. The resulting flow accumulation map has the number of cells that hydraulically contribute to each raster cell, also known as the flow accumulation value, or FAC. Higher FAC values indicate that the drainage area to that cell is larger and a stream is more likely to be present. More information on the flow accumulation map and the regime utilized in ArcHydro of ArcGIS 10.0 to compute the flow accumulation map can be found at *http://resources.arcgis.com*.

The flow accumulation map is post-processed to eliminate all FAC values that do not meet a certain threshold FAC value; typically equivalent to 1 km^2 but can be adjusted to match known stream locations. Figure 1 shows a flow accumulation map and a stream mask for the same area. All cells within the flow accumulation map have a value while only cells that are likely streams have values in the stream mask. An example of a stream mask with a DEM background is shown in Figure 2.

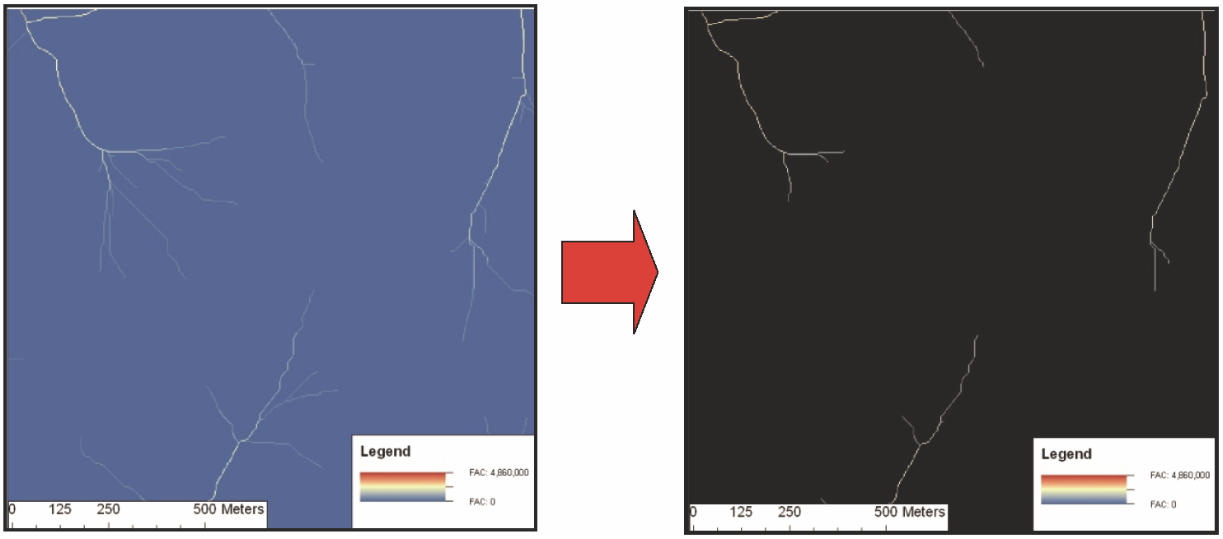

Figure1. Example Flow Accumulation Map and Stream Mask (NULL Values in Black)

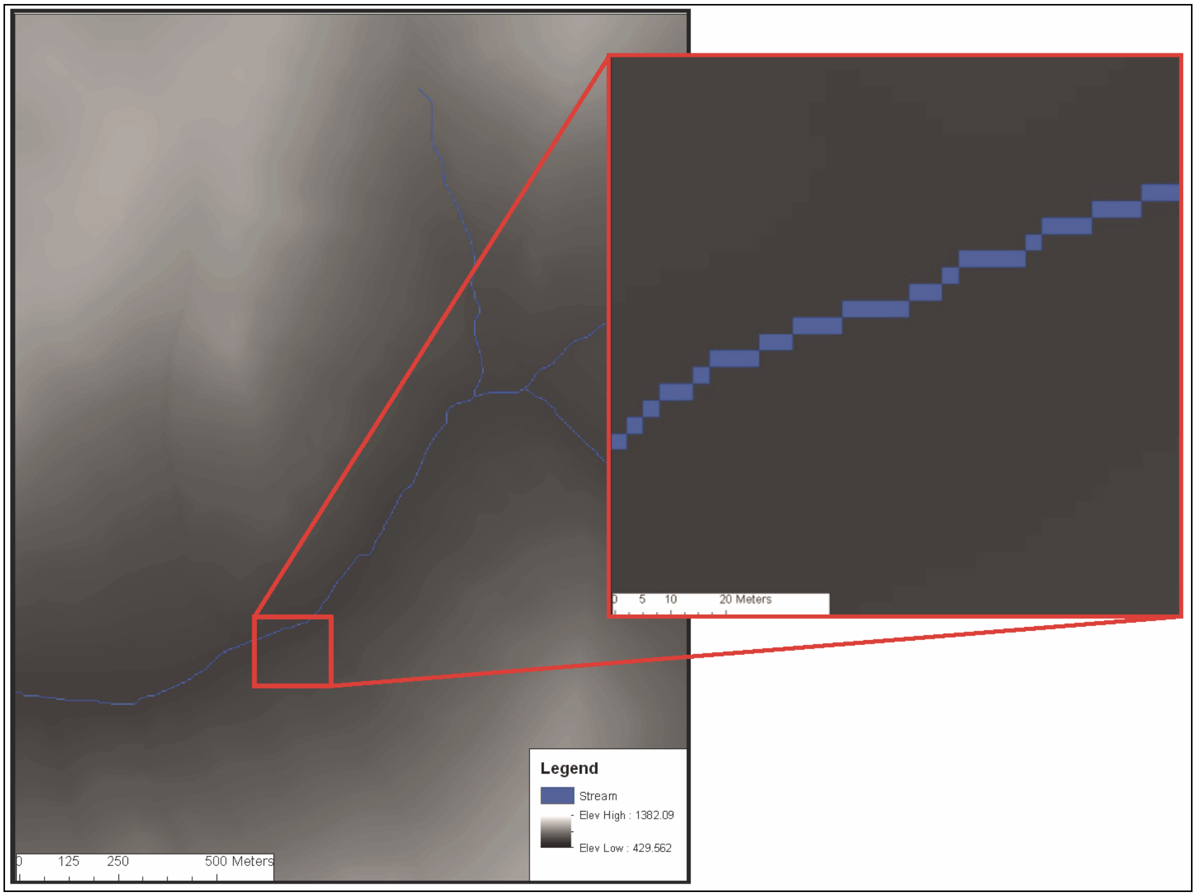

Figure 2. Example Stream Mask with DEM

Flow Value. The AutoRoute model requires a flow value for each stream cell and can input the flow value(s) three ways: uniform flow, proportional flow, or the rational method. Uniform flow, as used in this technical note, assigns a uniform flow to each stream cell within the domain. The proportional flow method bases the flow at each stream cell on a user-defined proportional flow value and the FAC value at the stream cell (taken from the stream mask). The flow at each stream cell is then calculated by multiplying the FAC of the cell by the proportional flow value. The rational method calculates flow at each stream cell using a simplistic rational method. The contributing drainage area is assumed to be the flow accumulation value at the stream cell while the precipitation and uniform area curve number are user-defined inputs. Use of the rational method is constrained by drainage area limitations and in situ soil assumptions (Maidment 1993).

AUTOROUTE HYDRAULIC CALCULATIONS: For each cross section within the domain, the flow velocity, depth, and extent are iteratively calculated using a user-defined flow value and a volume-fill method. The depth of the flow is incrementally increased within the cross section until the flow calculated using Manning's equation (1) is within a predefined percentage of the flow specified by the user. Figure 3 displays the process completed for each stream cell within the domain.

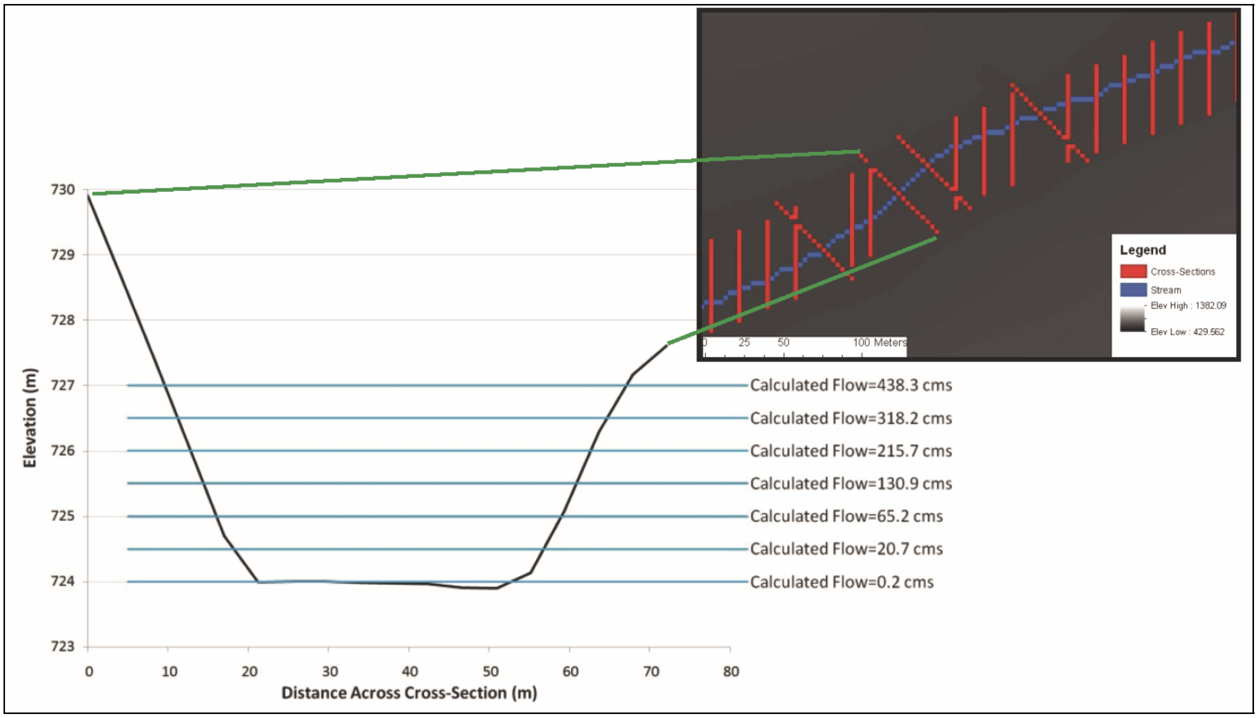

Figure 3. Cross-Section Profile with Incremental Flows

$$Q = \frac{Cu}{n} * A * R^{\frac{2}{3}} * S^{\frac{1}{2}} \tag{1}$$

where

Q = flow through channel
Cu = unit constant
n = Manning's roughness coefficient
A = hydraulic area
R = hydraulic radius
S = longitudinal slope of channel

Model Outputs. A raster-based flow depth file, as seen in Figure 4, is created for every simulation of AutoRoute. A flood inundation shapefile can be created by using ArcGIS 10.0, or an equivalent program, to post-process all of the flood extent results from AutoRoute. A file containing all of the cross sections with cross-section profiles, water elevation, and flow velocity is created for every simulation as well. This file can be input into mobility models to determine the impact of flooding on the mobility of vehicles to ford each cross section.

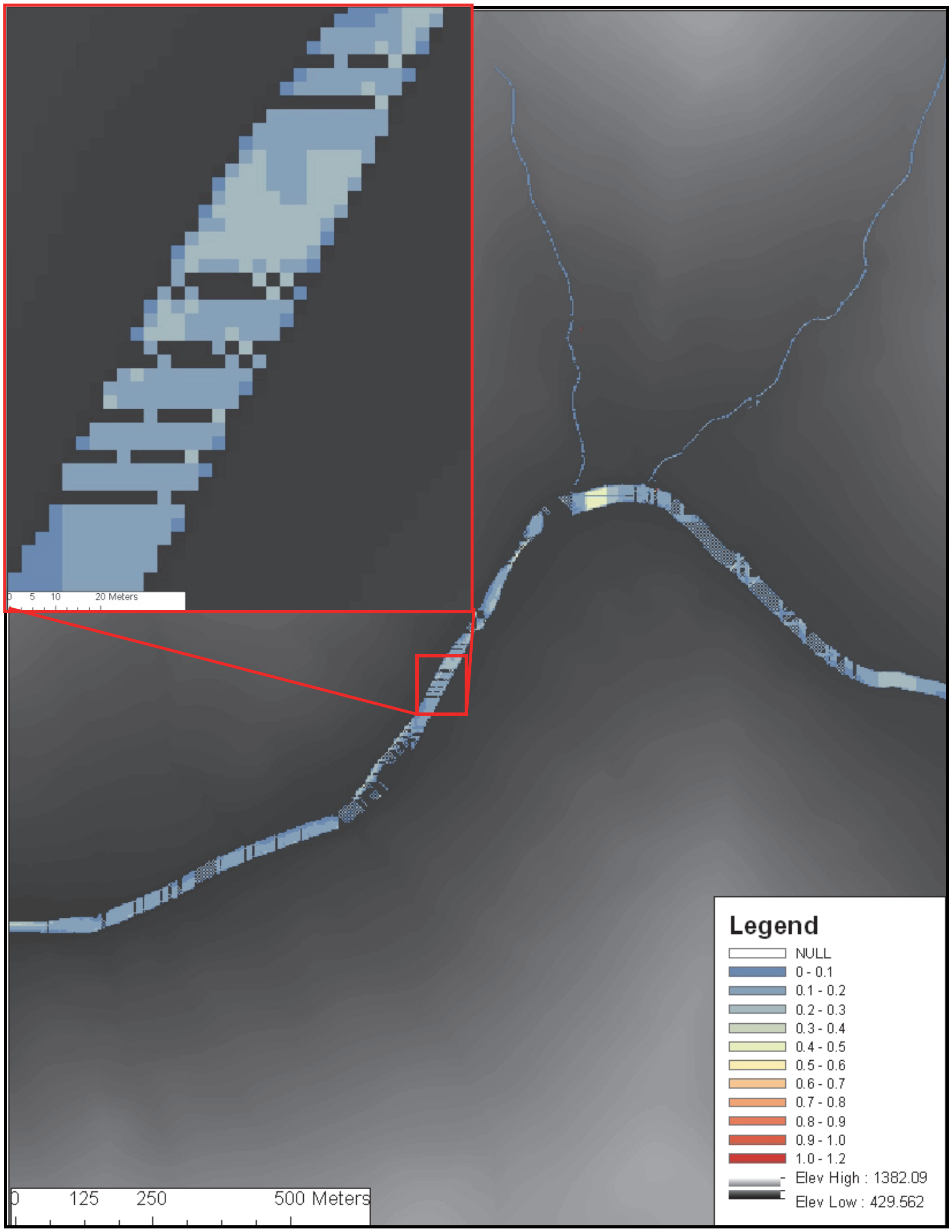

Figure 4. Example Flow Depth Output from AutoRoute

MODEL VALIDATION: Testing was conducted to validate the approach that AutoRoute takes to simulate the flow dynamics of a stream. Generally speaking, if the flood extent of a simulation is correct, the contributing hydraulic characteristics, such as depth and velocity, are also correct. To validate the model, simulations were run on areas with known flow values and known flood extents.

In June of 2008, a heavy rain event occurred over central and southern Indiana and southern Wisconsin. The rain event resulted in extreme flooding, culminating in loss of life and millions of dollars in damages. In response to these flooding events, the USGS determined high-water marks in several communities using global positioning systems (GPS). Flood-peak inundation maps and water-surface profiles were generated by combining the high-water data (if available) with high-resolution (1- to 10-m) DEM data and flow data at nearby gage sites. For each area where a flood inundation study was completed, the USGS also estimated the peak flow that caused the flooding. This information as well as more description of the flooding events and how the peak flows were generated can be found in Fitzpatrick et al. (2008) and Morlock et al. (2008).

The AutoRoute model simulated the flood extent for four locations studied by the USGS after the June 2008 flood events. The locations were selected based on availability of high-resolution DEM data, and simplicity of the stream network (i.e., limited tributaries within modeled area). A simple stream network was desired to assure that the peak flow was assigned to the correct channel. The AutoRoute model is tested by comparing the flood extent area determined from the AutoRoute simulation and the flood extent area measured by the USGS.

DATA COLLECTION: Data were collected for four locations. The location, peak flow, estimated recurrence interval of peak flow, and resolution of DEM data collected at each location are shown in Table 1. An overview of sources and data collected are described in the following paragraphs.

Table 1. Model Location, Peak Flow, and Resolution

Location	Peak Flow (m^3/s)	Estimated Recurrence Interval (yr)	DEM Resolution (m)
Gays Mills, WI	623	100 - 500	~10
Beloit, WI / IL	368	25 - 500	~10
Newberry, IN	3,907	>100	~3
Spencer, IN	1,798	25 - 50	~3

DEM Data. All DEM data were collected from the USGS Seamless server site (*http://nationalmap.gov/viewer.html*). The data were collected at a resolution of 1/3 Arc Second (~10 m) and 1/9 Arc Second (~3 m) where available. The data were reprojected from a geographic projection to a local Universal Transverse Mercator (UTM) coordinate system.

Stream Mask Creation. As discussed previously, the stream mask for each location was created using the DEM and functions within the ArcHydro program of ArcGIS10.0. The threshold values used to create the stream masks varied among the locations. The threshold values were set to values that made the stream mask match a geographic map (as seen in Figures 5-8). Because of issues with stream locations using the 10-m resolution DEM data, the stream mask for the Beloit, IL/WI, site was manually created within ArcGIS 10.0 to match a geographic map. All stream locations are shown in black in Figures 5-8.

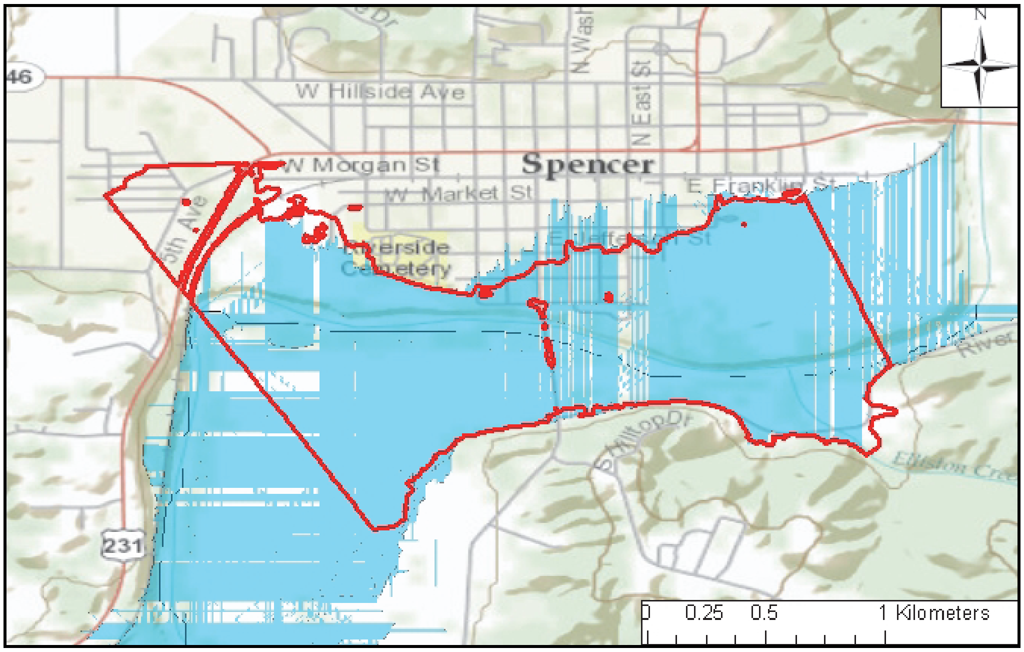

Figure 5. June 2008 Flood of Spencer, IN, 3-m DEM, peak flow=1,798 m^3/s

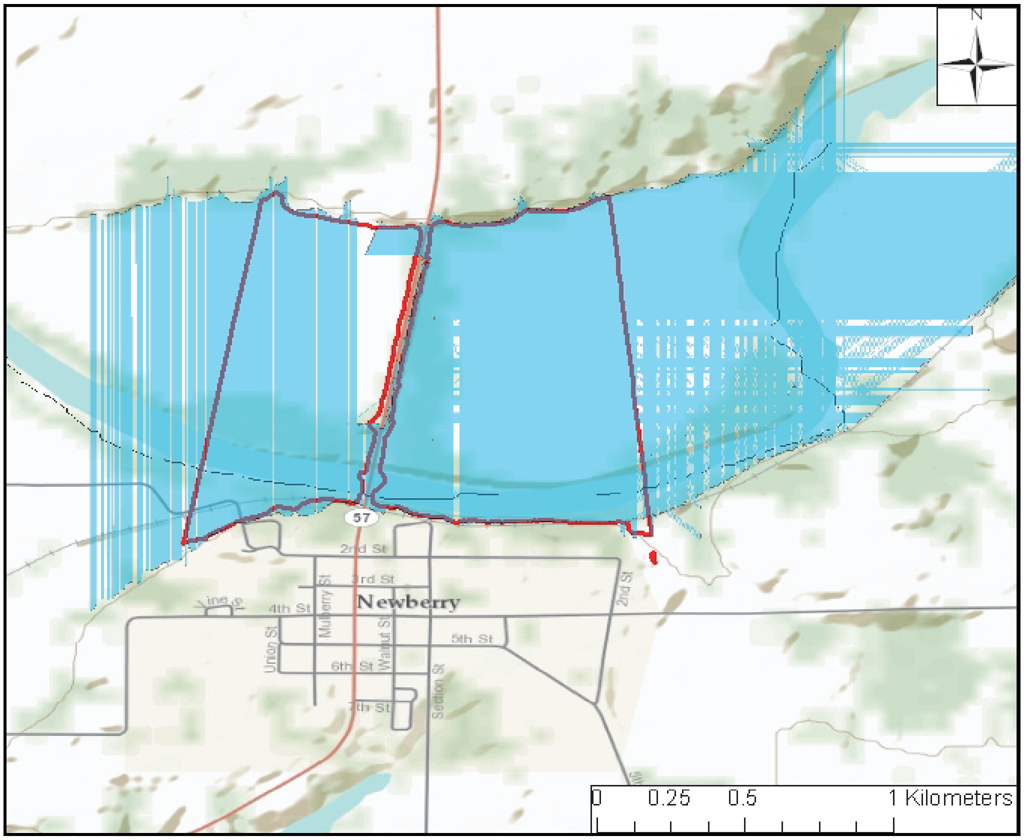

Figure 6. June 2008 Flood of Newberry, IN, 3-m DEM, peak flow=3,907 m^3/s

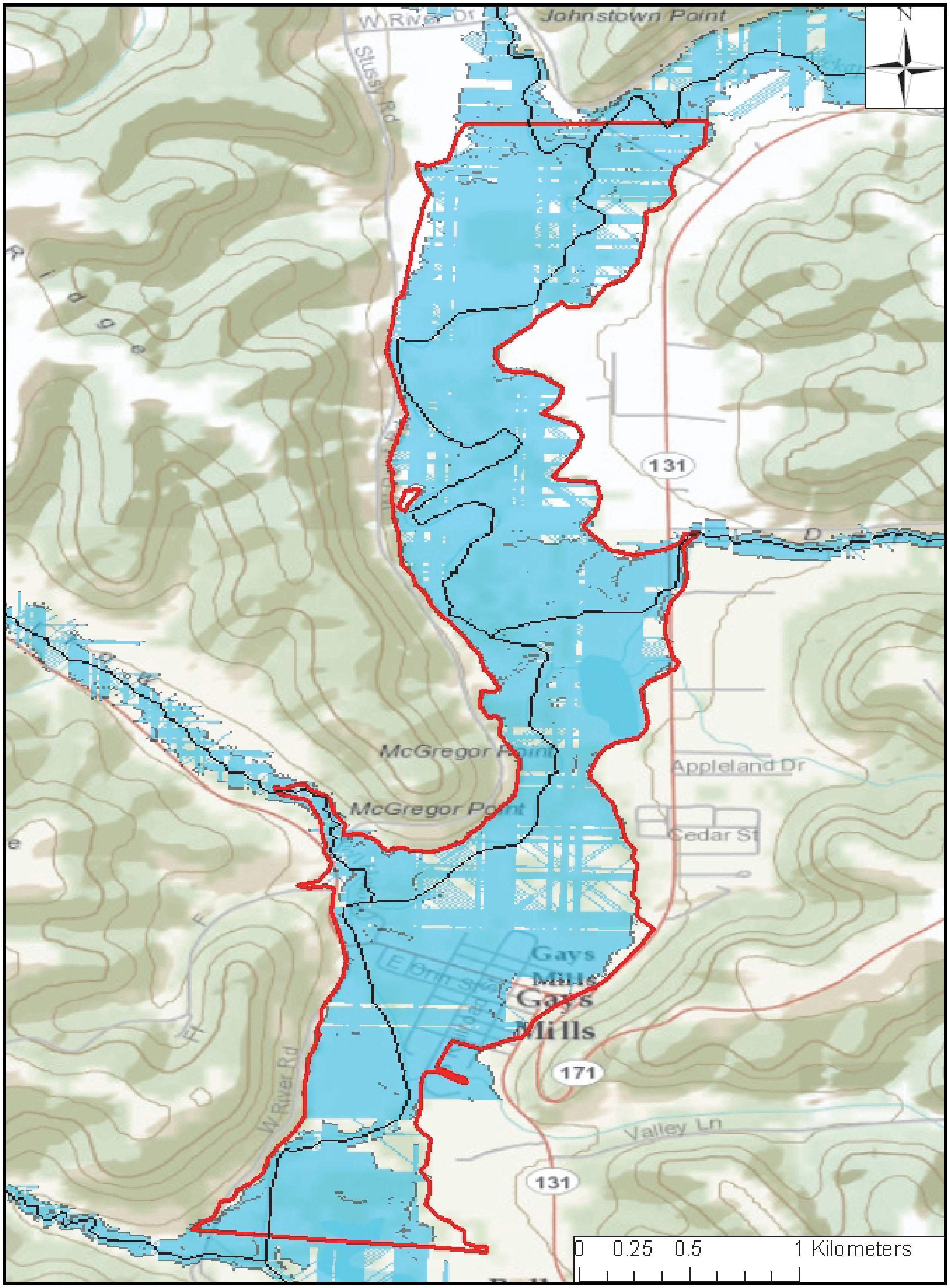

Figure 7. June 2008 Flood of Gays Mills, WI, 10-m DEM, peak flow=623 m^3/s

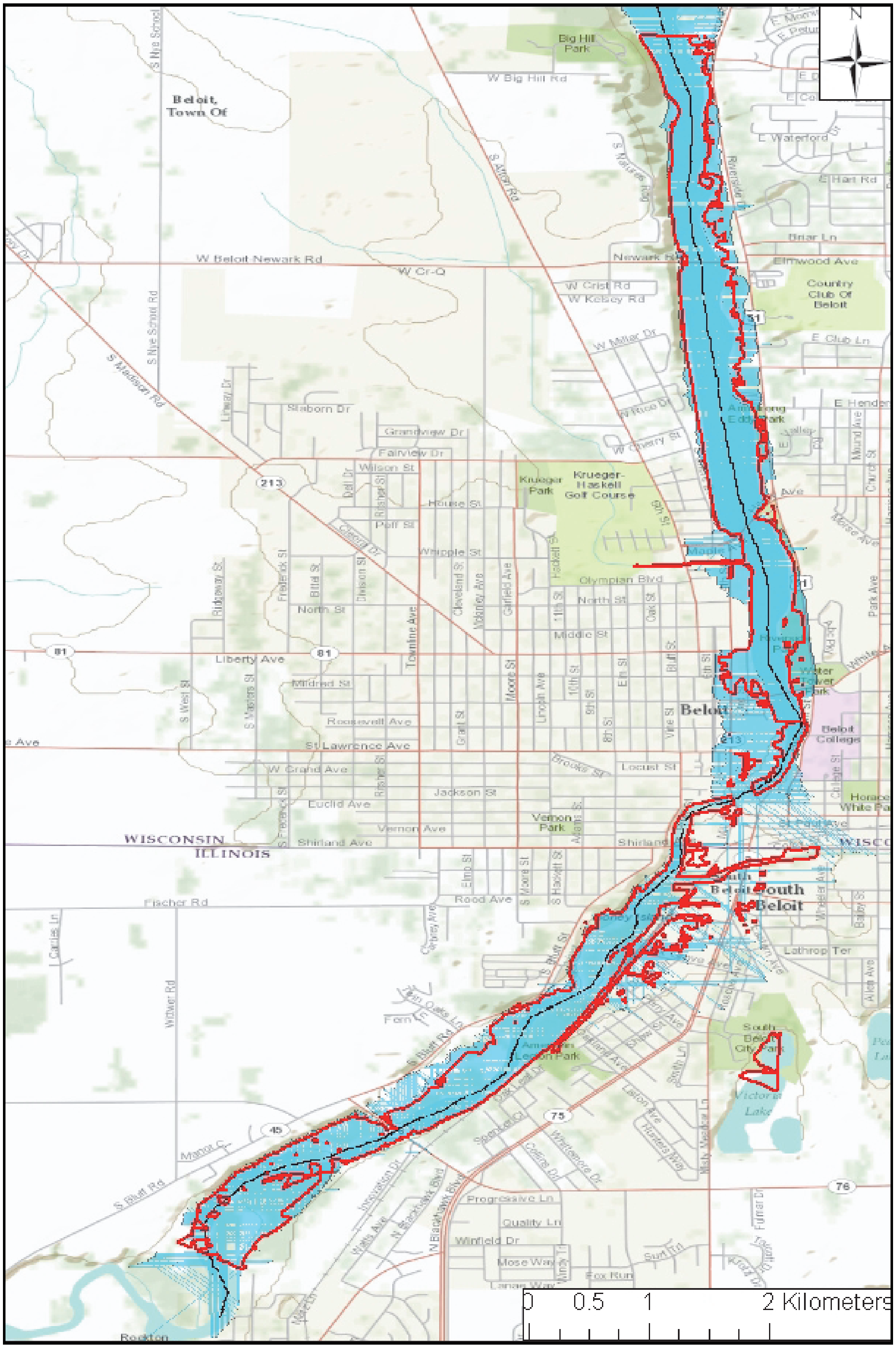

Figure 8. June 2008 Flood of Beloit, WI/IL, 10-m DEM, peak flow = 368 m^3/s

Flow Values and Flood Extent Data. Flood extent as well as flow values associated with the flood extent were collected for each area simulated. The data were obtained from USGS reports (Fitzpatrick et al. 2008 and Morlock et al. 2008) and the USGS website (*http://www.usgs.gov/*). The peak flow values for each flood event are shown in Table 1.

RESULTS: Observed flood extent (red) and simulated flood extent (light blue) results using the AutoRoute model are shown in Figures 5-8. A uniform Manning's roughness coefficient of 0.035 was used in each simulation. During simulation, the depth of each cross section was incrementally increased until the flow calculated using Manning's equation (1) was within 1 percent of the observed flow (peak flow of the flood).

The simulated flood extent (light blue) results are rasters based on the numerous cross sections analyzed within the domain. Because of the one-dimensional cross-section nature of the algorithms, there are frequently patches within the simulated results that show no flooding. These patches are not perpendicular to a stream cell and therefore do not show up in the raster results. These areas are accounted for if the results are post-processed into shapefiles. The shapefile boundaries represent the area of flooding by connecting the flood extent of each cross section within the domain into a single area of inundation, thereby encompassing the patches that show no flooding.

The Spencer, IN, flood map (Figure 5) shows excellent fit between simulated (AutoRoute) and observed (USGS) flood extents along the southern boundary of the White River and less accuracy along the northern boundary of the White River. The simulated flood extent overestimated flooding near downtown Spencer. This may be due to the area's being residential and urban with man-made structures that can affect one-dimensional hydraulic models, such as AutoRoute. The simulated flood extent did not capture the flooding in the northwest portion of the domain. This may be due to hydraulic structures, such as culverts which are not accounted for within the AutoRoute model, or flooding from waters flowing around topographic features, a characteristic requiring a two-dimensional hydraulic model to simulate accurately.

The Newberry, IN, flood map (Figure 6) also shows excellent fit between simulated (AutoRoute) and observed (USGS) flood extents. This is likely due to the White River at Newberry having a fairly well defined channel and few obstructions.

The Gays Mills, WI, flood map (Figure 7) shows excellent fit between simulated (AutoRoute) and observed (USGS) flood extents. Both methods (AutoRoute and USGS) utilized 10-m-resolution DEM data to develop the flood extents. Fitzpatrick et al. (2008) mentioned that some error was associated with the downtown area of Gays Mills, but it was likely associated with the coarse 10-m resolution DEM data. It is also likely that any error in the AutoRoute simulated flood extents is a result of using 10-m resolution DEM data instead of higher resolution DEM data.

Based on visual inspection the Beloit, WI/IL, flood map (Figure 8) has the least accuracy of the modeled areas. The AutoRoute simulation used 10-m resolution DEM data because it was the highest resolution DEM data publicly available for the entire area via the USGS Seamless server site (*http://nationalmap.gov/viewer.html*). The flood inundation map completed by the USGS utilized 1-m resolution DEM data derived from 2-ft contours of the Beloit area, and the final results were corrected by the Beloit, IL, city engineer (Fitzpatrick et al. 2008). The corrections made by the city engineer took into consideration floodwalls and sand bags deployed during the flooding. It is likely that differences between the two methods (AutoRoute and USGS) are results of the different resolutions of DEM data used to derive the flood extents as well as the effects of man-made structures that were accounted for within the USGS results.

The AutoRoute model typically performed well in areas where few or no man-made structures were present. Flood structures such as floodwalls and sandbags cannot be adequately captured at the resolutions (approximately 3 and 10 m) used within this study. Therefore, errors in simulations were evident, especially in the Beloit, WI/IL, model results (Figure 8). Areas that could not be reached by cross sections because of topographic features were also missed by the AutoRoute model. Examples of this include the northwest portion of the Spencer, IN, model results (Figure 5), and the thin, meandering flooded sections found in the Beloit, WI/IL, model results (Figure 8). One-dimensional models such as HEC-RAS assume that the defined low point of cross sections must be connected. However, in this approach the channel is assumed to be defined between high points; thus, small backwater channels will be missed in the cross-section definition.

SUMMARY: As shown in Figures 5-8 it is evident that the AutoRoute model effectively portrays the flood extent that occurred at each of the four locations. The model performed especially well in areas more typical of natural drainages; whereas urban and residential areas with man-made structures have more significant inaccuracies in the simulated results. It is also evident that the resolution of the DEM data used has an effect on the results. It is expected that in flat terrains the resolution of the DEM data will be particularly important.

This technical note provides several test examples that show that the AutoRoute model is capable of accurately simulating the flood extent of historical flood events. By accurately simulating the flood extent, it is assumed that the model also reasonably captures the profile, depth, and velocity within each cross section used to create the flood extent.

ADDITIONAL INFORMATION: For additional information, contact Mr. Michael Follum at *Michael.L.Follum@usace.army.mil*. This CHETN should be cited as follows:

> Follum, M. 2012. AutoRoute Rapid Flood Inundation Model. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-IV-88. Vicksburg, MS: U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. An electronic copy of this CHETN is available from *http://chl.erdc.usace.army.mil/chetn*.

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