Approach to Digital Elevation Model Correction by Improving Channel Conveyance

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Abstract: Digital elevation models (DEM) are important inputs for topography in modeling floods for remote and inaccessible regions. DEMs often lack in accuracy near water bodies and rivers. The objective of this research is to present a DEM correction technique to improve the accuracy of flood simulation and inundation mapping. The key feature of this method is the variability in thalweg (deepest point along a cross section) locations and depth based on the river meandering, width, and side slope. The DEM correction technique is demonstrated by adjusting a national elevation dataset (NED) DEM along the Cumberland River near Nashville in Tennessee. The original (base DEM) and modified DEMs are used as main input of the 1D Hydrologic Engineering Center River Analysis System (HEC-RAS) model and corresponding performances were analyzed. The model using surveyed topography was calibrated for a high flood event (May 2010) and later validated for an intermediate flood event (2003), a high flood event (May 2010), and a low flood event (May 2013) using the modified DEM. It was found that the model with base DEM is capable of simulating at a very high stage but fails during low and intermediate stages. The applicability of base DEM is also limited for any event above 127 m and 3,000 m^3/s with specific biases. The model using modified DEM could be used for simulating large arrays of flow events. The root mean square error (RMSE) for simulated stage using modified DEM for 2003, 2010, and 2013 with the observed stage were 0.86, 0.23 and 0.52 m respectively. Comparison of simulated flood map for the May 2010 flood event using modified and base DEMs with observed flood extent showed errors of 2.66% (overestimate) and 13.38% (overestimate), respectively. The preliminary application of the DEM correction technique thus showed significant improvements in the quality of DEM data with corresponding increase of the HEC-RAS model accuracy. **DOI: 10.1061/(ASCE)HE.1943-5584.0001020.**

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Introduction

Flooding is the single most devastating natural calamity causing the most significant human and economic losses on a global scale. According to national weather services in the United States (U.S.), flood losses of up to $272 million and 89 deaths per year were estimated in the past 30 years (National Weather Service (NWS) 2014). In addition, ever-increasing global changes, including urbanization and climate change, are likely to increase the vulnerability to floods. Therefore, it is imperative to have a better understanding of floods for the safety and security of the global community. Flood modeling enables decision makers to envision probable scenarios and thier associated losses, and consequently to plan required mitigation and adaptation measures. The two main inputs of flood simulations are hydrologic and topographic data. Hydrologic data is acquired through observed stream flow or by using hydrologic models. For engineering projects, topographic data is acquired for project specific areal extent, using various surveying techniques such as GPS, LiDAR, and bathymetric surveys. It is not only time consuming and expensive to obtain topographic data through surveying but also sometimes impossible for remote areas. For instance, Casas et al. (2006) reported that the approximate cost per km^2 to perform GPS survey, LiDAR survey, contour map generation, and bathymetric survey were around US $800, $1,200, $17, and $30,000 respectively, making these approaches cost prohibitive especially if working at a large scale. Online repositories have become a common source of digital elevation models (DEM) and other topographic data as an alternative to these project-specific data gathering techniques. Available DEMs have resolution of 10, 30, and 90 m, and so on. Some areas in the United States, especially metropolitan and surrounding areas, have DEMs available at a finer spatial resolution of up to 3 m. Although tremendous improvements have been made in DEM resolution and availability, the accuracy of elevation data is still a major issue. For instance, Fig. 1 presents the cross sections across the American River near the city of Sacramento that were derived using conventional surveying, national elevation dataset (NED), and LiDAR, data respectively (Kalyanapu et al. 2013). It is evident from the figure that the cross sections derived from digital data including NED sources have errors in depicting the channel geometry. The geometry data used in flood models that are based on these digital data will thus incorporate additional uncertainties in the accuracy of flood models.

DEMs, like other spatial data sets, have errors [Monmonier 1991; Nardi et al. 2008; U.S. Geological Survey (USGS) 1995; Wright 1942]. Errors associated with bed level of water bodies (e.g., ponds and rivers) is mainly due to shortcomings in data acquisition techniques of various digital data. Digital terrain data such as interferometric synthetic aperture radar (IfSAR) and Shuttle Radar Topographic Mission (SRTM) DEMs are based on interferometry, which

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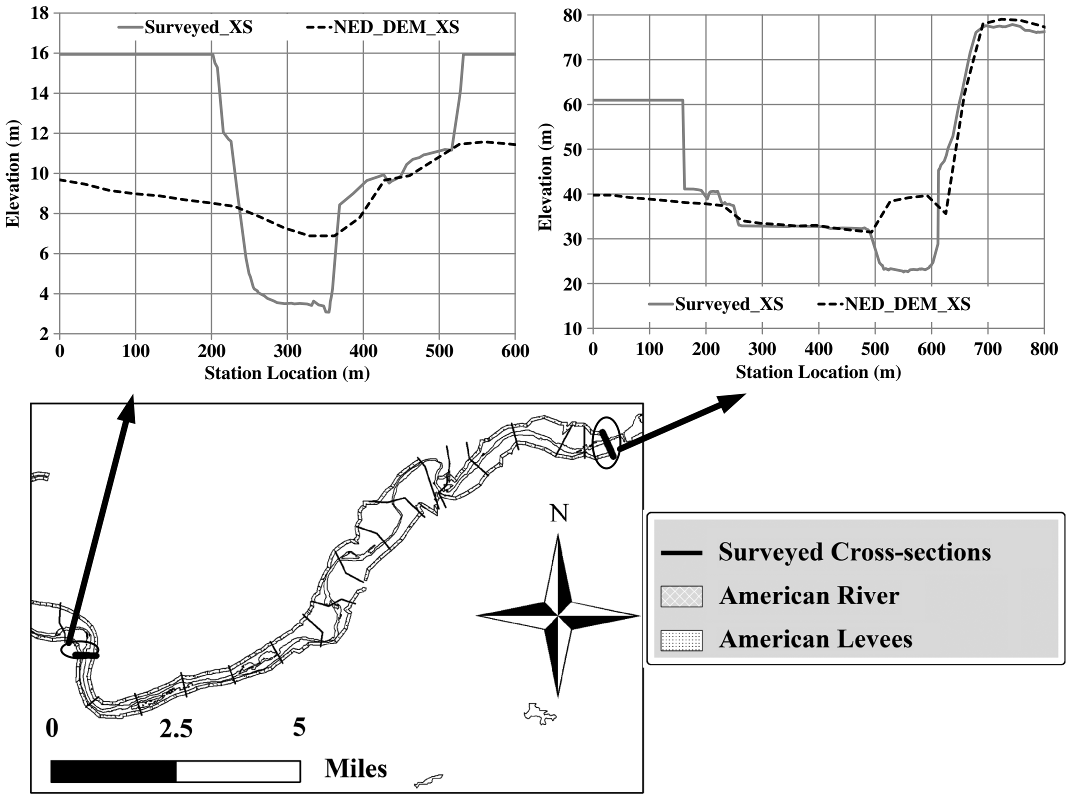


Fig. 1. Comparison of surveyed river cross sections with NED-derived cross sections along the American River, California [adapted from Kalyanapu et al. (2013), American Meteorological Society used with permission]

uses reflections from the ground surface to measure elevation. On the other hand, NED is generated based on processed data ranging from quadrangle maps to LiDAR surveys. NED presents DEM as bare earth and the root mean square error (RMSE) is 2.44 m (Gesch 2007; Gesch et al. 2002). Usually NED DEMs represent a flat surface over the water bodies (Fig. 1). So inaccuracies in representing river beds introduce unexpected errors into simulated results. To address these inaccuracies, studies such as Merwade and Maidment (2004), Price (2009), and Gichamo et al. (2011), have used synthetic cross sections. Most existing approaches use prismatic cross sections and tend to provide adequate conveyance for the flow to pass, but lack in representation of local morphological features such as side slope, thalweg location, expansion, and contraction. The following paragraphs present a brief literature review on the DEM correction approaches that were developed to improve the topographic representation in flood modeling.

The DEM correction approach applied by Yamazaki et al. (2012) eliminates errors and improves connectivity among the channels. This approach distributes the channel/stream into a number of streamlines. The algorithm removes all the pits in the spaceborne DEM caused by vegetation canopies, sub-pixel-sized structures, and random radar speckles. Once the streamlines are corrected, the individual streamlines are aggregated to produce a complete channel. This method considers the rivers to have accurate bed-level representation in DEM. It also assumes the river has similar cross section widths all through. This approach targets to ensure better flow connectivity within the channels. This method will be applicable if the DEM represents bed elevation accurately.

Gichamo et al. (2011) applied synthetic cross sections as described by Price (2009) for one dimensional flood modeling. After the cross sections were plotted for the upstream and downstream ends, the intermediate sections were obtained by interpolation. This approach may not represent the local features due to planform irregularity such as meander and constriction. Interpolating in between larger length may not be a good solution to represent the river bed.

Merwade and Maidment (2004) used planform-based analysis to derive thalweg and bathymetry. They used meandering (sinuosity) of a river to estimate thalweg locations and a probability distribution function to approximate the bed level elevation along the cross sections. This approach requires surveyed bathymetry points to define the channel morphology. Therefore, it may be applicable only areas where a certain amount of surveyed data is already available.

Following the challenges involved in DEM adjustment approaches as evident from the literature, in this study, an approach is presented that uses the available DEM data and the classical equation of uniform flow (Mannings' equation) to resolve the limitations regarding overestimation of flood stages and flow connectivity. The targeted issues were (1) to approximate the location of thalwegs (2) to eliminate random irregularities along the long section that connects the thalwegs, and (3) estimate required channel conveyance. The objective of this study is to provide a geospatial technique to improve DEM with synthetic cross sections for flood modeling applications. It is also expected that the synthetic cross sections will provide better outputs of velocity distribution along with flow and stage if used in a two-dimensional model.

Methodology

This section presents the methodology adopted in this research. The major processes involved in this geospatial technique are: (1) raster processing, (2) hydrologic processing, (3) three-point cross section generation, and (4) raster modification. Following these steps, the DEM is adjusted and synthetic cross sections are generated that are used in flood models. The study uses an unconditioned DEM, which is hereafter called the base DEM. The inputs needed for

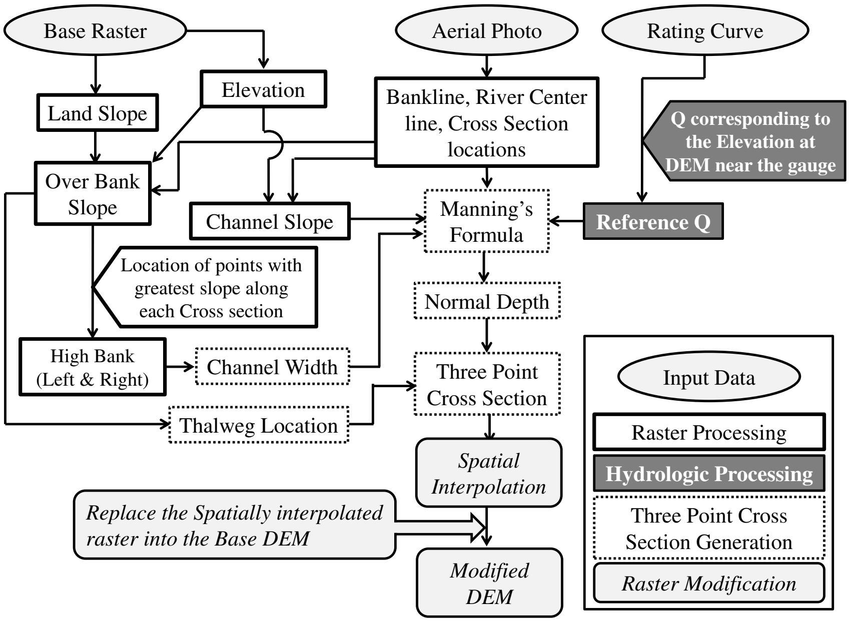


Fig. 2. Flow chart of the DEM modification algorithm

applying this technique are a river centerline, cross section lines, bank lines, the base DEM, and historic stream flow data. The river centerline is a streamline that is manually drawn using satellite images (i.e., Google Earth). The algorithm developed is presented in a flow chart in Fig. 2. The essential assumptions of the method are as follows:

1. The river is single channel stream;
2. The elevation available in the base DEM along the channel represents the water surface instead of the stream bed;
3. Each river cross section is composed of two half-parabolic segments. Each segment is the area between the parabola and the vertical line through the vertex; and
4. The intersection of the two side slopes at each cross section is the thalweg location.

Raster Processing

River planform features (i.e., the river centerline, banklines, and alignment of cross sections) are manually delineated using a satellite image or aerial photo (i.e., Google Earth). Chainage points along the river centerline and station points along the cross sections are generated at spacing equal to the DEM cell size. Using the base DEM, a percent rise slope raster is generated in an *ArcGIS 10.0* environment. The elevation and slope values are extracted from the base DEM and assigned to the chainage points and station points. Average channel slope was calculated from the elevation at the chainage points.

The extracted station points at each cross section were then classified as left section points and right section points based on the river centerline. Each section represents a portion of the river cross section falling on that side of the river centerline. The point with steepest gradient in the left section is determined and assigned as the left high bank. The process is repeated to get the right high bank. Thus two high bank points (left and right) are identified for each section. These points are hereafter called high bank points and are later used for three-point cross section generation.

Hydrologic Processing

Historic data from a gauging station within the reach is used as the reference for flow and stage. The elevation available in the base DEM near this station is considered as the reference stage. The corresponding flow is estimated from the rating curve prepared from these data. This flow is hereafter called the reference discharge.

Three-Point Cross Section Generation

The modified cross sections are conceptualized as parabolic for which the side slopes at two banks should become zero at the point of intersection. Using the slope assigned at high bank points, the intersection points for each cross section are determined and assumed to be the approximate location of thalweg (location of the deepest point—the intersection of dotted lines in Fig. 3). For a single channeled river, the side slope gradually reduces to zero at thalweg from a maximum at the high bank point. Once the thalweg location is fixed, then each cross section is the sum of two individual segments (i.e., a left segment and a right segment). Each segment is equivalent to the area within the parabola and axis of symmetry, which is a vertical axis along the location of the thalweg. The conceptual cross section will have a cross-sectional area two-thirds of a rectangle (represented by firm dash line in Fig. 3). The horizontal and vertical distances between the edges of the rectangle are equal to the top width (B) and uniform flow depth (y), respectively. The mathematical equation for geometric properties of the modified cross section is as follows:

$$\text{Top Width, } B = \text{Channel Width } (B')^{*}(y/y1)^{1/2} = B'^{*}\sqrt{\frac{y}{y+\text{Dem Elev. at High Bank}-\text{DEM Elev at Thalweg}}} = B'^{*}\sqrt{\frac{y}{y+Z_i-Z_T'}}$$

$$\begin{aligned}\text{Area} = A = \sum A_i = A_l + A_r &= 2/3 * y * B_l + 2/3 * y * B_r\\ &= 2/3 * y * (B_l + B_r) = 2/3 * y * B\end{aligned}$$

$$\text{Wetted perimeter} = P = \sum P_i = Pl + Pr,$$

where $Pi = (2Bi/2)[(1+d^2)\langle SpI\rangle^{1/2} + (1/d)\ln(d + (1 + d^{1/2})\langle SpI\rangle^{1/2}]$; and $d = 4y/2Bi$.

Hydraulic radius, $R = A/P$

Using the Manning's equation [shown in Eq. (1)] for top width and channel slope, the Manning's roughness for channel and slope of the channel uniform depth for each section is determined. This is

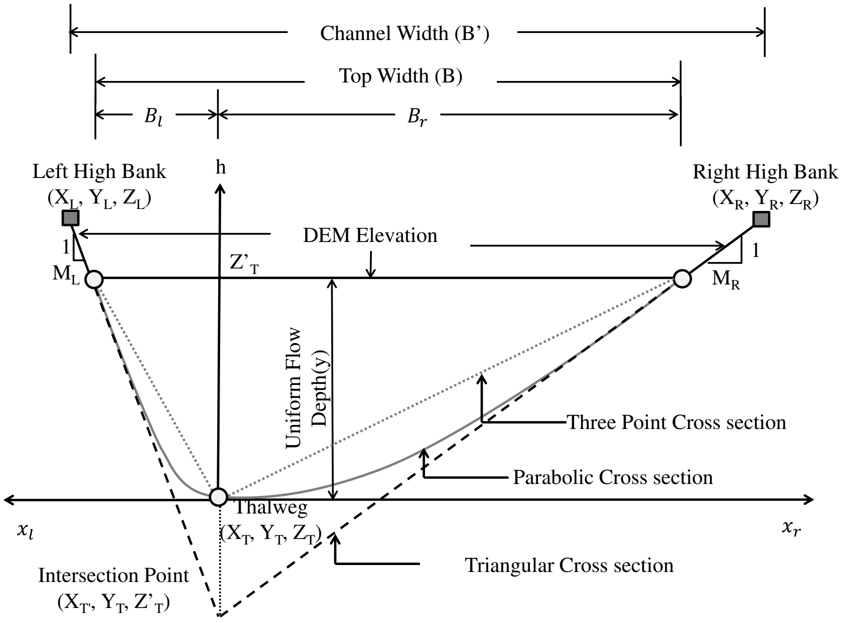


Fig. 3. Schematic of a three-point cross section

an iterative process to arrive at the exact solution of uniform flow depth for the reference discharge. Channel slope is determined from elevations available on the DEM along the river centerline. The roughness factor applied is determined considering the local features and terrain. The target is to achieve a minimum difference between the longitudinal slope from the estimated thalweg points and the applied value of the channel slope. Subtracting the uniform depth from the DEM elevation gives the thalweg elevations. Thus, a simplified three-point cross section for individual sections will be generated. Fig. 3 shows a schematic three-point cross section where circular marks indicate the three points.

$$\text{Manning's equation, } Q = \frac{1}{n} A R^{2/3} \sqrt{S} \tag{1}$$

where Q = reference discharge; n = channel roughness; and s = channel slope.

Raster Modification

The elevation for points along the cross section are calculated using the Parabolic equation $Z = y/B_i^2 * x_i^2$. By merging the floodplain contour, stream centerline, and modified cross section points, a modified topography is generated. The values of base DEM along the river are then replaced by the values from the modified topography. The adjusted DEM now contains updated channel bathymetry and thus improved conveyance and can be used as input for topography in hydraulic flood modeling.

Case Study

The DEM correction technique is tested on Cumberland River in Tennessee, U.S.A. The NED is used as the primary DEM product due to its wide usage in the United States. A 10 m spatial resolution is used for Cumberland River in this study as it represents topographic details in urban environments at a higher scale compared to 30 m or coarser resolutions. In this study, a Hydrologic Engineering Center River Analysis System (HEC-RAS) model is employed to simulate the floods with DEMs provided from this approach.

Study Area

The study area is the lower Cumberland River in Tennessee, U.S. The reach lies within the Lower Cumberland Sycamore watershed (USGS Hydrologic Unit 05130202). It has an area of 1,678 km^2. The Lower Cumberland River in this watershed stretches from tail end of the Old Hickory Dam (OHD) to 46 km upstream of the Cheatham Dam. It also passes water from J Percy Priest Dam. Fig. 4 shows the study area along with the location of USGS stream flow stations.

A HEC-RAS 1D model was developed for the reach stretching from downstream of Old Hickory Dam to Cockrill Bend. The model was calibrated for a moderately high flood event and later validated for high flood and low flood events. A summary of the flood events is presented in Table 1.

Data

The primary data used in this study include geometric data, hydrologic data, and aerial photographs. A summary of data types is presented in Table 1. The 10 m resolution DEM for the study area was collected from the National Elevation Dataset (2014). The DEM was projected in the Universal Transverse Mercator (UTM) (NAD 1983, Zone 16 N) coordinate system. There are 22 stream flow stations available within the study area in the USGS Tennessee water science center website (USGS 2014). For simulation purposes, six stations listed in Table 2 were used. Time series data for 2003 and 2013 were readily available in the USGS archive (2014). Flow data for J. Percy Priest (JPP) dam for 2003 and 2013 were calculated from flow continuity at Nashville station (03431500). Total discharge from OHD in 2013 was estimated by converting the stages using a stage-discharge chart obtained from the observed stage-discharge for May 2010 event.

Flow data for the 2010 event were collected from a report on Cumberland River Basin May 2010 Flood Event by the United States Army Corps of Engineers (USACE 2010b). Aerial photograph for the study area was collected from Google Earth. Two photographs were collected for this study (August 2012 and May 2010). An August 2012 photograph were used for initial bankline and channel delineation and a May 2010 photo was used to estimate actual extent of the May 2010 flood. This is based on

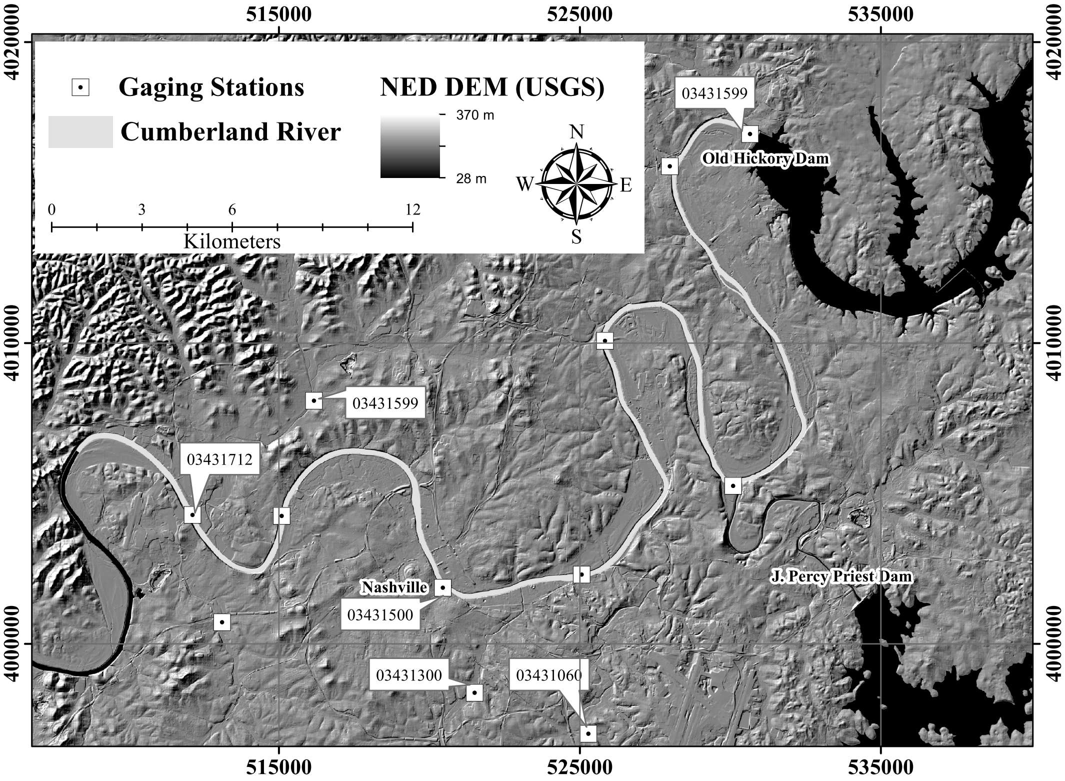


Fig. 4. Study area along with the available gauging stations (adapted from U.S. Geological Survey National Map 2014)

Table 1. Summary of Flow Events

Year	Period	Event	Remarks
2003	April 29–May 23	Moderately high flood	Validation
2010	April 29–May 7	High flood	Calibration,validation
2013	April 15–May 31	Low flood	Validation

a fixed bed model, i.e., no morphological change occurred within the tenure of the events. The three events were simulated on single set of topographic data derived from the modified DEM; hence planform change of the river is neglected. Stage data for downstream station (03431712) was not available for the 2003 and 2010 events. Eq. (2) shows the correlation equation for stage at downstream station that was developed using the observed stage from October 2012 to July 2013 and channel slope from station 03431500 to model downstream. The Nashville station (03431500) was used as the location of calibration and hydrologic comparisons. All the elevations used in this study are above NAVD 88 (North American Vertical Datum of 1988) and projected to UTM 1983 (Zone 16N)

$$\begin{aligned}\mathrm{WSEds} &= \mathrm{WSE03431500}\\ &\quad - (0.05 \times \text{Distance from Nashville in km})\mathrm{m}\end{aligned} \tag{2}$$

The HEC Geo RAS tool (USACE 2012) was used to prepare geometric data. Fig. 5 demonstrates the model's extent along with graphical comparison of cross sections extracted from base DEM and modified DEM with surveyed cross sections. The distances in the horizontal axis are plotted as looking downstream to the channel.

Calibration

The 1D Hec-RAS model was calibrated using surveyed cross-sections for the 2010 event. Manning's roughness coefficient n was selected as the calibration parameter. Stage and discharge at the station near Nashville were used for calibration. Different set of roughness factors were tested and their efficiency was calculated. The efficiency of the calibration simulations is shown in Fig. 6, where values in the horizontal axis are the Manning's roughness. The minimum RMSE for simulated flow and stage were found at 0.018 and 0.03, respectively, but minimum error in predicting the peak was at n = 0.024. Hence channel roughness $n = 0.024$ and floodplain roughness $n = 0.04$ were selected for optimum efficiency. Here the roughness factors are different from those used for estimating uniform depth because the purpose is to calibrate the model setup for simulation of certain hydrologic events with reasonable calibration parameters. Although the location and depth of the thalweg could be predicted, the modified channel still lacks in conveyance as compared to the actual channel.

Table 2. Data Used for the HEC-RAS Model

Data	Period	Source	Remarks
DEM		National elevation dataset (NED)	Resolution: 1/3 arc s (10 m)
Hydrologic data	April 29–May 23, 2003 (daily mean) April 29–May 07, 2010 (3-hourly) April 14–May 31, 2013 (daily mean)	USGS, USACE	USGS stations: 03426310, 03431060, 03431300, 03431500, 03431599, 03431712
Aerial Photograph	May 2010, August 2012	Google Earth	—

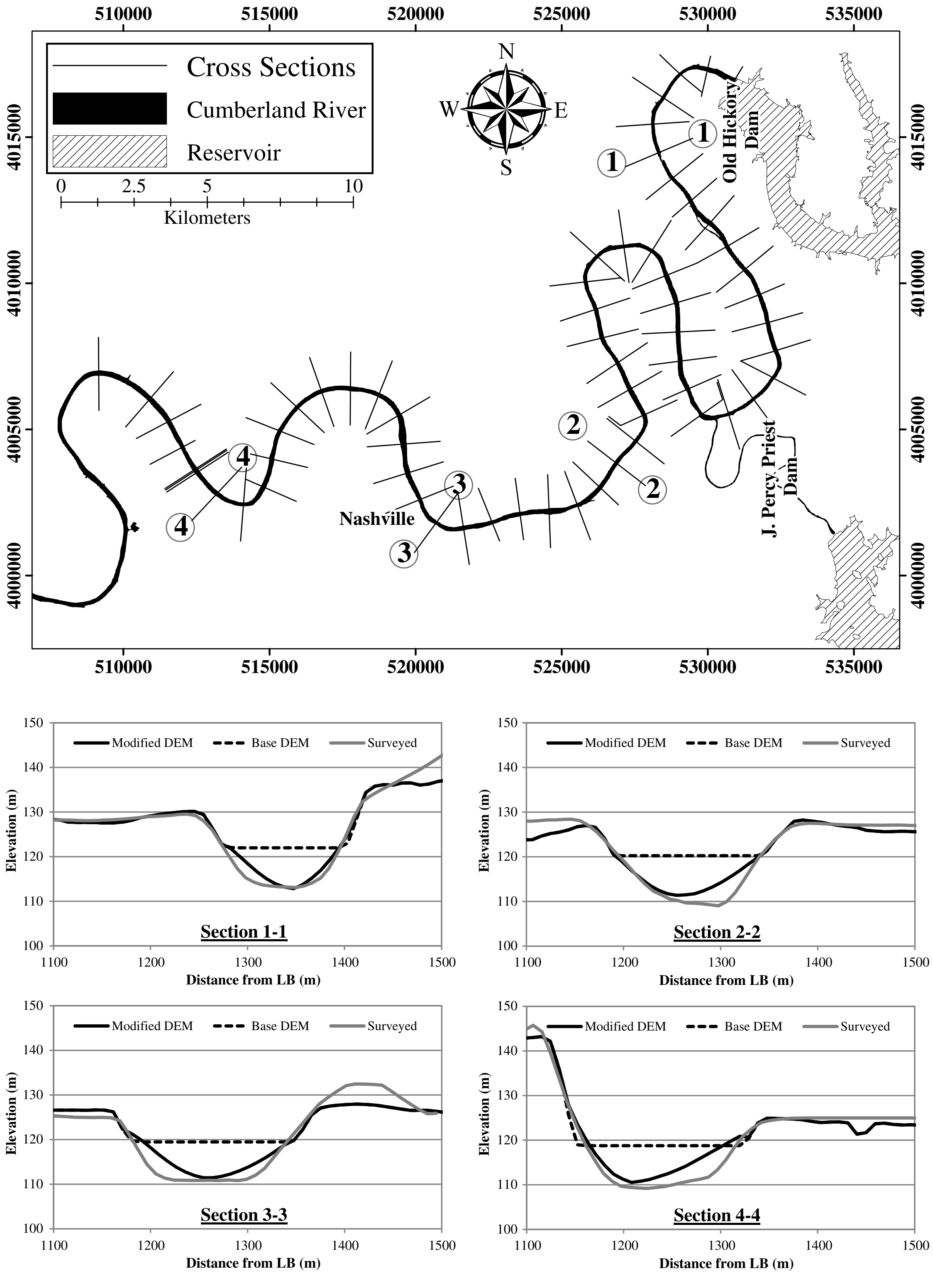


Fig. 5. One-dimensional model extent and comparison of the cross sections before and after modification with surveyed cross sections

Validation

The model validation was performed by simulating three flow events using cross section derived from the modified DEM. The validation events represent a high flow event (2010), an intermediate flow event (2003), and a low flow event (2013). The maximum discharge (daily mean) for 2003, 2010, and 2013 are 3,700, 5,000, and 1,800 m^3/s, respectively, at the same location. Three-hourly instantaneous data was used for simulation of 2010. Therefore the peak discharge in the 2010 event (5,600 m^3/s) for the simulated hydrograph is higher than the maximum discharge (daily mean). The efficiency of simulation for both events is summarized in Table 3. The validation plots for 2003, 2010, and 2013 events are shown in Figs. 7–9, respectively.

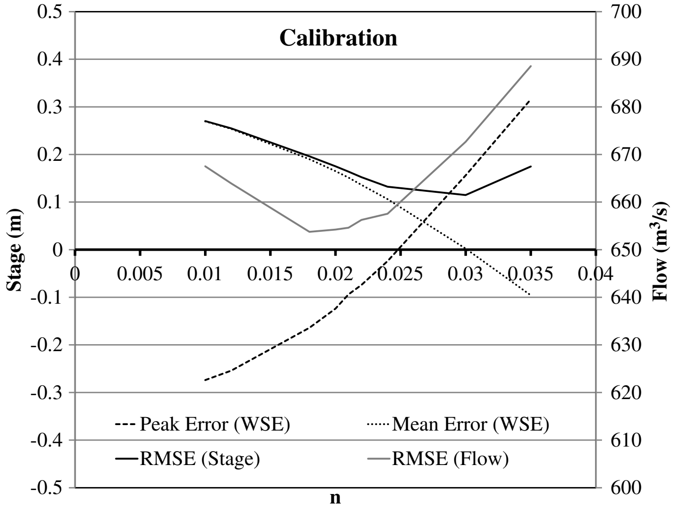


Fig. 6. Calibration efficiency plot for 2010 using surveyed topography at Cumberland River near Nashville; horizontal axis shows channel roughness

Results

Error Analysis

The three hydrologic events (2003, 2010, and 2013) were simulated using the base DEM to analyze the relative error. The focus was to see if there is any improvement after applying the modification algorithm. Initially, it was not possible to simulate the events with cross sections extracted from base DEM because the water surface elevation (WSE) at the downstream boundary were lower than the minimum bed level. Therefore, the simulations had to be curtailed to simulate only the crests of the hydrograph. The model simulations tend to produce abrupt flow depths as they approached lower stages. This is due to the lack in sufficient conveyance that makes the model unstable. Fig. 10(a) shows the error in simulated WSE with respect to the observed WSE, and Fig. 10(b) shows the comparison of observed and simulated WSEs for all six simulations. For the base DEM, the minimum bed elevation at the downstream cross section was 118.77 m. Therefore it is theoretically not possible to simulate any flow with this DEM that has an elevation lower than 118.77 m. The error in simulated WSE for base DEM and modified DEM start to converge near 127 m. After this threshold, the error in model using the base DEM becomes consistent as an indication of the dominance of flood plain flow.

A comparative plot for simulated and observed discharge is given in Fig. 11(a). The simulated discharge for the base DEM is mostly lower than the observed discharge. The error is significant below discharge 3,000 m^3/s. The observed and simulated stage discharge plot is shown in Fig. 11(b). This shows that the modified DEM is able to follow the observed pattern whereas the simulation deviates significantly below 3,000 m^3/s for the base DEM.

Flood Mapping

A flood extent map for 2010 was delineated from a Google Earth image dated May 04, 2010. This map is considered as the periphery of the flood extent. Simulated flood inundation map for 2010 was generated using RAS Mapper tool (USACE 2010a). Three simulated flood inundation maps were generated. One simulation used the topography derived from surveyed data and the other two used the base DEM and modified DEM respectively. All simulated flood maps were then compared with the observed map. Comparisons were conducted for the stretch where observed map was available. Fig. 12 shows the comparison of simulated and observed flood maps. The simulated flood map using the survey data shows underprediction of about 3.3% whereas the modified DEM and the base DEM show overprediction of 2.66 and 13.4% areas.

Table 3. Summary of Validation Simulations

		2003		2010		2013	
Topography	Parameter	Mean error	RMSE	Mean error	RMSE	Mean error	RMSE
Modified	Stage	0.77	0.86	0.20	0.23	0.51	0.52
Base	Stage	9.36	10.63	2.00	2.24	18.34	19.97
Modified	Flow	−9.94	92.22	−181.34	453.96	78.76	126.35
Base	Flow	−289.03	793.20	−226.50	521.02	−238.04	2511.35

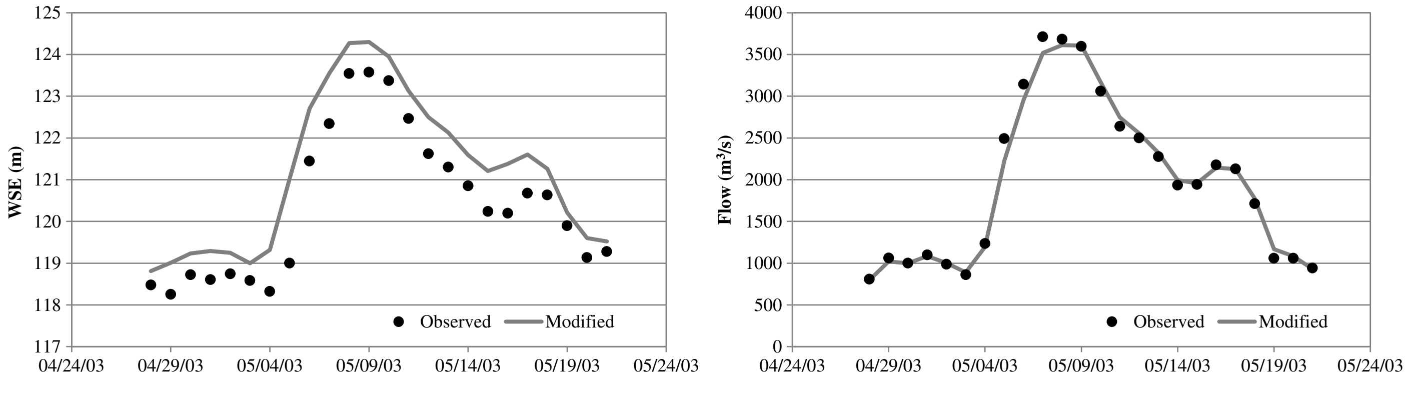


Fig. 7. Observed versus simulated plots for 2003 at Cumberland River near Nashville

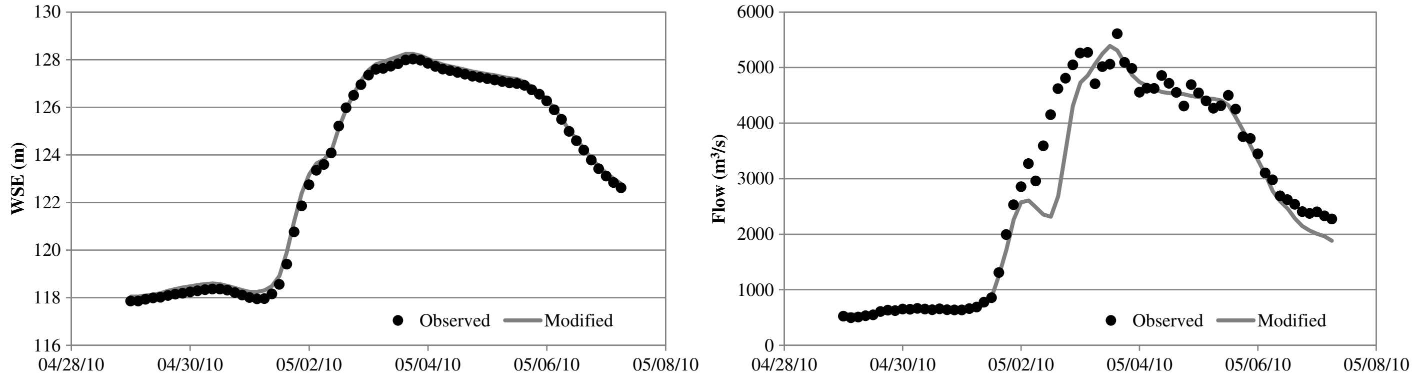


Fig. 8. Observed versus simulated plots for 2010 at Cumberland River near Nashville

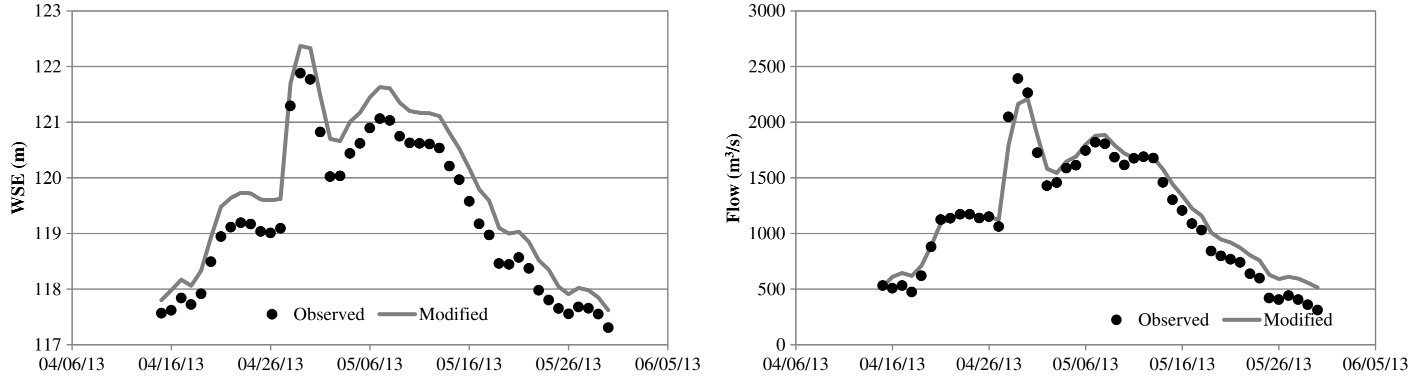


Fig. 9. Observed versus simulated plots for 2013 at Cumberland River near Nashville

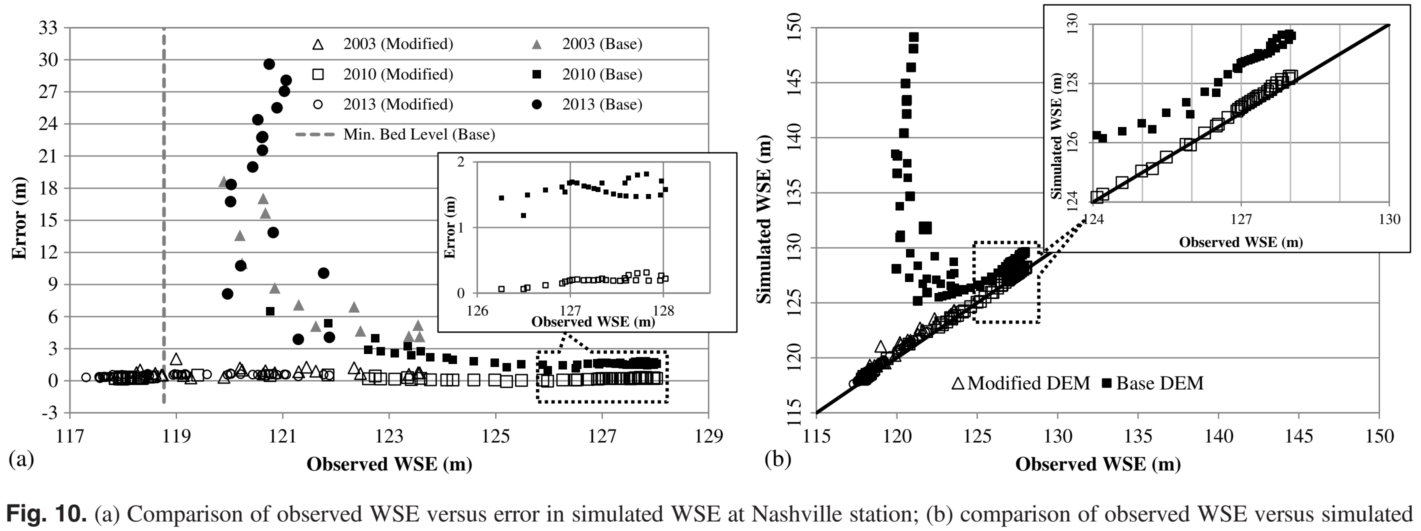


Fig. 10. (a) Comparison of observed WSE versus error in simulated WSE at Nashville station; (b) comparison of observed WSE versus simulated WSE at Nashville station for all six simulations

Discussion

The synthetic cross sections have thalweg depths close to those of the surveyed sections but still lack in required conveyance. The spatial interpolation method used here was generic Topo to Raster available in Arc-GIS. The interpolation method seems inadequate for inner banks where mild side slope is available. An improved interpolation method considering the slope stability and channel sinuosity may improve the prediction of cross section shape.

The method presented in this study is tested on Upper Cumberland Sycamore watershed in Tennessee. The DEM used has a resolution of 1/3 arc second (10 m). The initial assumption was the DEM has an acceptable level of accuracy for the terrain except for the portion that is under deep water. So the quality of the DEM for floodplain representation is also important. There is a strong

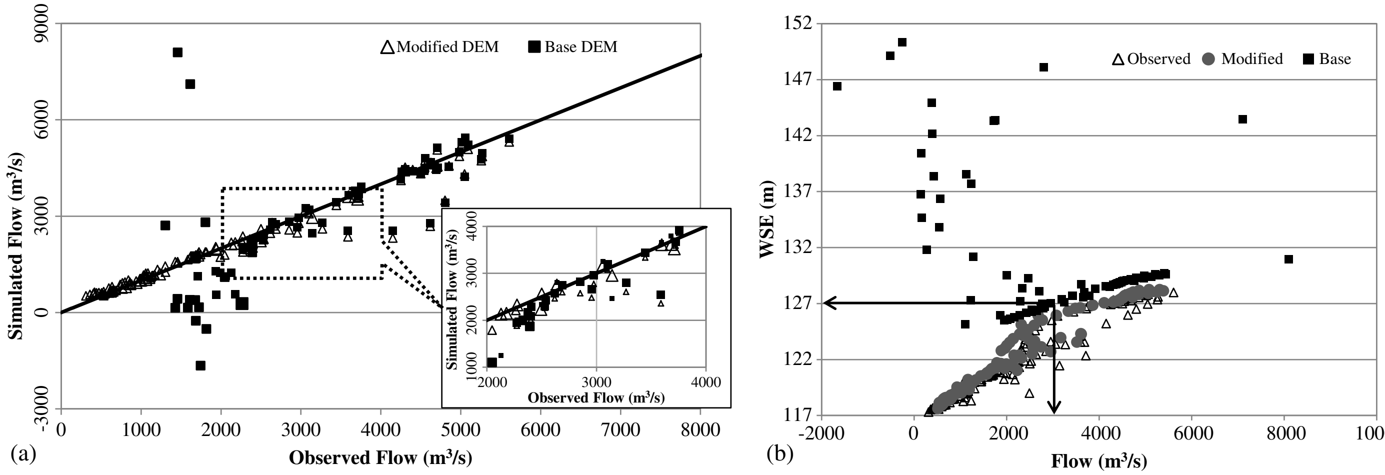
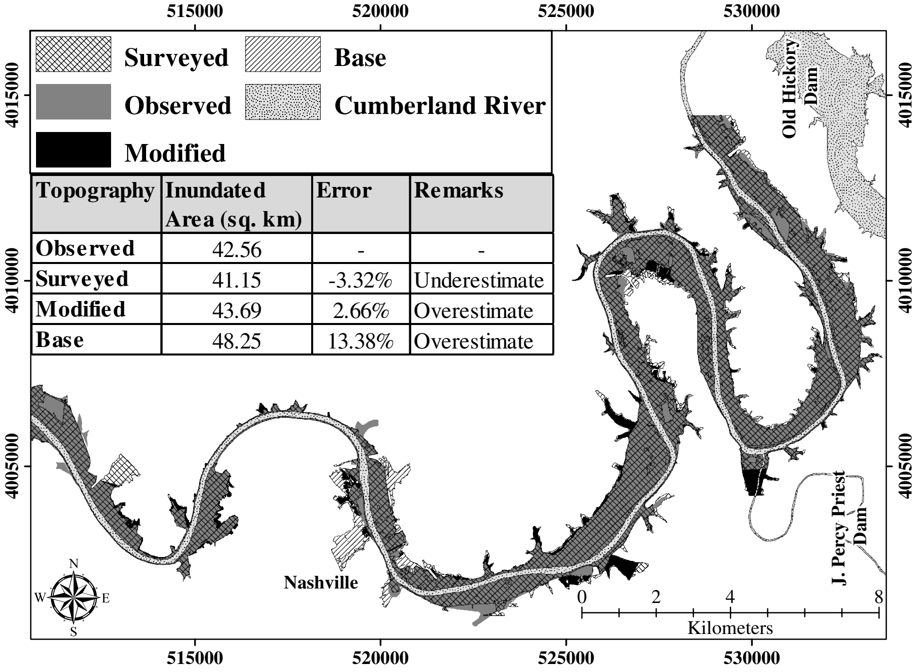


Fig. 11. (a) Comparison of observed discharge versus simulated discharge at Nashville station for all six simulations; (b) observed and simulated stage discharge plot at Nashville station

positive relationship between the quality of the DEM and the extent of the inundation (Brandt and Lim 2012). Accuracy of the approach depends on the cell size of the DEM. Therefore the applicability of this method for coarse-sized DEMs cannot be ascertained at this moment.

The roughness factors for the calibrations were slightly low for the main channel due to the lack in conveyance. This set of roughness factors could be used for this model setup considering the errors shown in Table 3. The errors for the simulated results using the modified DEM follow similar pattern for all three hydrologic events. This enables the limits of confidence to be ascertained for certain WSEs or discharges. Simulated results using the base DEM show good performances only for the higher stages. The errors are very high below WSE 127 m and discharge of 3,000 m^3/s at Nashville station. Above this threshold, the model with base DEM maintains a consistent bias, which is an indication of negligible channel flow compared to the floodplain flow. This DEM data could be used for simulating flow higher than this only if the bias is known. This model setup is inapplicable for rising and recession of a flood when flow remains mostly within the channel. This is important for real-time prediction of any hydrologic event. The 20 years annual peak discharge for Cumberland River (USGS 2014) at Nashville shows only five events having flows higher than 3,000 m^3/s. This implies the base DEM is not useful for most of the events. It is only applicable for a small portion of a catastrophic event like the May 2010 flood.

The inundation map for May 2010 using the modified DEM showed better agreement compared to the base DEM. The error in inundation area for surveyed DEM and modified DEM with the observed map is within 5% because in some places, it was not possible to delineate the flood boundary as precisely as the RAS Mapper could. Flood inundation is also related with overbank slopes. The simulated flood extent using the base DEM could produce large errors if applied in a flat terrain. Although



Topography	Inundated Area (sq. km)	Error	Remarks
Observed	42.56	-	-
Surveyed	41.15	-3.32%	Underestimate
Modified	43.69	2.66%	Overestimate
Base	48.25	13.38%	Overestimate

Fig. 12. Comparison of flood inundation map for 2010 flood event (adapted from U.S. Geological Survey National Map 2014)

overprediction introduces more safety, the target of flood management is to assure safety with cost effectiveness.

The major setback of this approach is its dependence on the quality of overbank data provided by the base DEM. It is also limited for use in single-channel rivers. If stage discharge data for any reach is available, then this method can be applied even if no surveyed cross section is available. This will help to simulate flood events in remote areas.

Future Research Directions

The method described in this study can be improved by incorporating a spatial interpolation method based on the morphological features of a reach. In particular, by integrating the presented work with terrain analysis approaches for DEM-based landscape feature (i.e., flooplain) characterization (e.g., Nardi et al. 2006, 2013), the presented geometric algorithm would be provided with a physically-based interpolating component that could enforce the flooding physics into the DEM correction methodology. In addition, while the method is tested on a single channeled river, a flow distribution ratio for anabranches in braided rivers could be also helpful to extend this methodology to multichannel rivers.

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