Water Resources Research

RESEARCH ARTICLE
10.1029/2020WR027477

Key Points:
- A lidar-based methodology reveals inherent variability in bankfull stage and bank elevations for three meandering river channels
- Mean variation in bankfull stage is 10% to 20% of the average channel depth
- The elevation range of mean variation in bankfull stage corresponds to the zone of high curvature in rating curves

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Citation:
Lindroth, E. M., Rhoads, B. L., Castillo, C. R., Czuba, J. A., Güneralp, İ., & Edmonds, D. (2020). Spatial variability in bankfull stage and bank elevations of lowland meandering rivers: Relation to rating curves and channel planform characteristics. *Water Resources Research*, *56*, e2020WR027477. https://doi.org/10.1029/2020WR027477

Received 12 MAR 2020
Accepted 19 MAY 2020
Accepted article online 25 MAY 2020

Spatial Variability in Bankfull Stage and Bank Elevations of Lowland Meandering Rivers: Relation to Rating Curves and Channel Planform Characteristics

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Abstract Mutual adjustment between process and form shapes the morphology of alluvial river channels, including channel banks. The tops of banks define the transition between the channel and adjacent floodplain, which corresponds to the level of incipient flooding. Despite the geomorphological and hydrological importance of this transition, few, if any, studies have extensively examined spatial variability in bank elevations and its influence on bankfull stage. This study uses an objective method to explore this variability at two spatial resolutions along three alluvial lowland meandering rivers. Results show that variability in bankfull stage is inherent to all three rivers. The mean variability of bankfull stage about the average downstream gradient in this stage is 10% to 20% of mean bankfull depth. Elevations of channel banks exhibit similar variability, even after accounting for systematic variations in heights of inner and outer banks associated with river meandering. Two-dimensional hydraulic simulations show that the elevation range of mean variability in bankfull stage overlaps considerably with the elevation range of high curvature on rating curves, confirming that variability in bankfull stage influences the shape of these curves. The simulations verify that breaks in channel banks allow flow to extend onto the floodplain at stages below the average bankfull stage. The findings provide fundamental insight into the variable nature of bankfull conditions along meandering rivers and the role of this variability in channel-floodplain connectivity. The results also inform river-restoration efforts that seek to re-establish the natural configuration of channel banks.

1. Introduction

Bankfull flow and the bankfull characteristics of river channels are important both geomorphologically and hydrologically. From a geomorphological perspective, bankfull discharge is often viewed as the primary flow shaping the form of river channels (Leopold et al., 1964; Rhoads, 2020; Williams, 1978). It has been referred to as the dominant discharge (Knighton, 1987; Rhoads, 1991; Wolman & Leopold, 1957) and has been equated to the effective discharge, defined as the flow that transports the greatest amount of sediment (Wolman & Miller, 1960). In meandering rivers, bankfull discharge typically is seen as a representative flow driving lateral channel migration (Güneralp & Marston, 2012). This migration, along with associated overbank deposition, regulates the elevation of the floodplain (Lauer & Parker, 2008a; Wolman & Leopold, 1957). During lateral migration, floodplain material is eroded from the outer bank and deposited on point bars along the inner bank. Overbank flows that exceed the bankfull discharge are no longer confined, resulting in diffusive and advective transport of suspended sediment out of the channel and deposition of this material onto the floodplain surface (Bathurst et al., 2002; Johnston et al., 2019; Pizzuto, 1987). The bankfull morphological characteristics of river channels are defined by the identification of a bankfull stage, which demarcates the upper boundary of the river channel. Of importance is whether bank elevations marking the upper boundary of the channel differ on the two sides of a river. The traditional perspective is that these elevations are relatively equal but the extent to which this perspective holds has not been thoroughly examined. In meandering rivers, bank elevations often are unequal with inner banks lower than outer banks (Lauer & Parker, 2008b). In such cases, bankfull stage corresponds to the elevation of the lowest bank.

From an applied geomorphological perspective, bankfull discharge and its relation to channel morphology now plays a central role in practical efforts to restore degraded rivers (Copeland et al., 2001; Rosgen, 1996; Shields et al., 2003; Soar & Thorne, 2001). The designs of restored channels and the connectivity of channels to adjacent floodplains are often guided by the notion that properly functioning river systems maintain a balance between their morphological characteristics and fluvial processes that occur during bankfull flows. Applied practice seeks to link channel designs with morphological characteristics of natural channels adjusted to bankfull flow (e.g., Rosgen, 2011), and this practice is also informed by scientific research linking morphological characteristics (e.g., bankfull width and depth) of alluvial river channels to bankfull flow (e.g., Parker et al., 2007).

From a hydrological perspective, bankfull flow defines an important transition between two discrete morphological components of alluvial river systems: the floodplain, formed through deposition of alluvial material within the valley bottom, and the channel, carved into the floodplain (Dury, 1961; Nunnally, 1967; Williams, 1978; Wolman & Leopold, 1957; Wolman & Miller, 1960). Bankfull flow establishes the level of incipient flooding (Copeland et al., 2001; Kilpatrick & Barnes, 1964; Knight, 2006; Navratil et al., 2006; Pickup & Rieger, 1979; Riley, 1972; Williams, 1978; Wolman & Leopold, 1957). In the traditional view, at or below bankfull stage, flow occurs within the channel, whereas above bankfull stage, flow spills onto the floodplain and flooding begins (Riley, 1972; Figure 1; Wolman & Leopold, 1957). Although bankfull flow occurs on some rivers at a fairly consistent frequency, often with a recurrence interval of about 1.5 years on annual flood series (Leopold et al., 1964; Wolman & Leopold, 1957), this frequency does not hold for all rivers (Harvey, 1969; Kilpatrick & Barnes, 1964; Williams, 1978). Given its importance in defining the distinction between channels and floodplains as well as within-channel flow versus flooding, bankfull stage clearly represents an important geomorphic and hydrologic threshold in river systems (Williams, 1978).

Despite established definitions for determining bankfull stage, the identification of this important reference level in natural rivers remains challenging (Copeland et al., 2005; Navratil et al., 2006; Williams, 1978). In many cases, determining bankfull stage relies on expert judgment (Harrelson et al., 1994; Williams, 1978). Of the various methods used to identify bankfull stage, two prominent categories of definition have emerged: morphologically and hydrologically based. Morphologically based definitions require surveyed data on channel cross-sectional form and rely on application of geometric criteria (Carling, 1988; Emmett, 1972; Harrelson et al., 1994; Harvey, 1969; Navratil et al., 2004; Osterkamp & Hedman, 1982; Pickup & Warner, 1976; Riley, 1972; Williams, 1978; Wolman, 1955). Hydrologically based definitions utilize changes in the slope of rating curves, requiring a gaging station and known stage-discharge relations (Dury, 1961; Emmett, 1972; Leopold & Maddock, 1953; Parker et al., 2007; Riley, 1972; Wilkerson & Parker, 2010; Williams, 1978; Woodyer, 1968; Yan et al., 2018). The composition and extent of vegetation have also been used in previous studies (Nunnally, 1967; Schumm, 1960; Speight, 1965; Woodyer, 1968), but they have been viewed as poor indicators of bankfull stage because vegetation can occur at irregular locations on channel banks, adapt to varied soil and water supply conditions, and consist of a variety of species, each with their own soil and water tolerance (Riley, 1972).

Even when objective criteria are used, bankfull stage is often defined based on survey data (morphological definition) or stage-discharge relationships (hydrological definition) from only one or perhaps a few locations along the river. This information may not be reflective of conditions even a short distance away from where data were collected (Copeland et al., 2005; Fonstad, 2003; Leopold et al., 1964), and thus, it is not sufficient for characterizing the whole channel or area of interest (Copeland et al., 2005; Navratil et al., 2006). When information on bankfull channel conditions is collected at multiple locations, these data are usually averaged to determine average bankfull channel dimensions (Navratil & Albert, 2010; Stewardson, 2005). Over long reaches, bankfull stage, the elevation at which flow overtops the banks, decreases systematically in the downstream direction in conjunction with decreases in the elevations of the channel banks as a river flows toward its base level.

Although past work has established that power-function relations between channel dimensions and bankfull discharge can include considerable scatter (Dodov & Foufoula-Georgiou, 2004; Jowett, 1998; Knighton, 1974; Leopold & Maddock, 1953; Park, 1977; Phillips, 1990; Richards, 1976), much less work has focused on the spatial variability of bankfull stage and bank elevations. For the most part, this

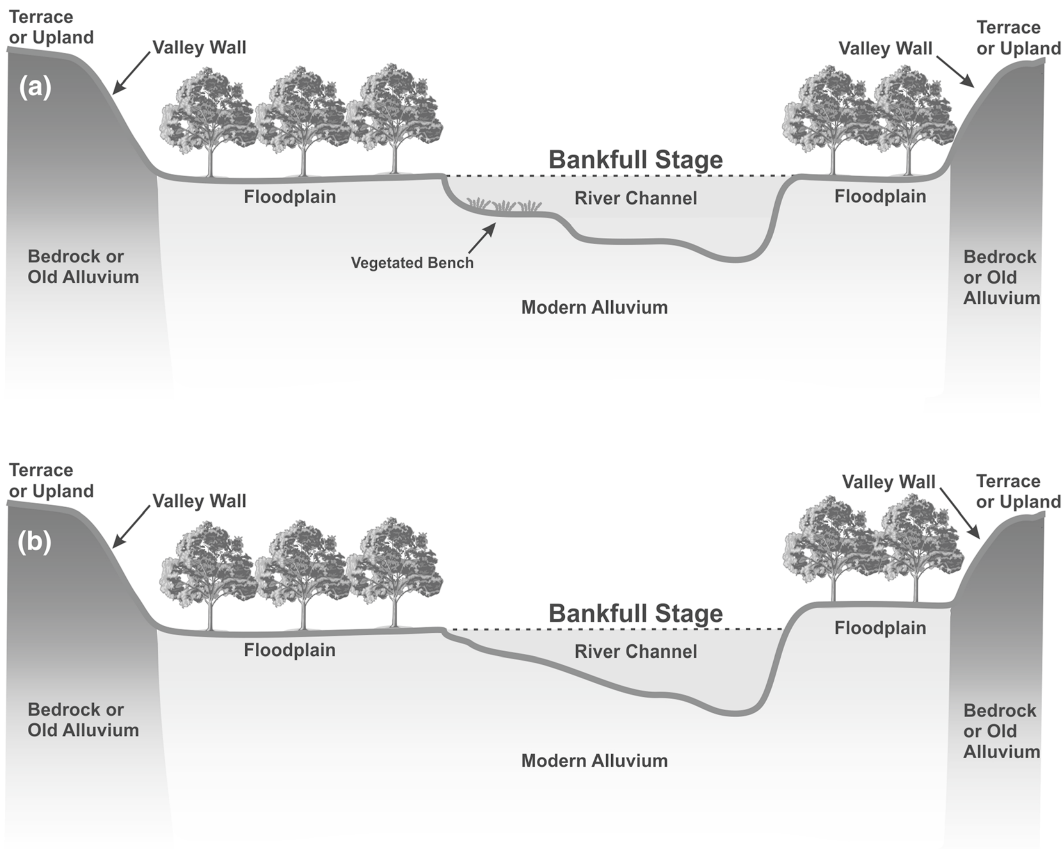

Figure 1. Schematic illustrating bankfull stage for (a) channel banks of the same elevation and (b) channel banks with different elevations. Bankfull stage is associated with the height of the lowest bank. Above this stage water in the river channel begins to inundate the floodplain.

variability has been ignored, despite recognition that considerable variation in bank elevations can occur along natural rivers (Williams, 1978). Few studies have explicitly examined the variability in bankfull stage and bank elevations defined on the basis of objective criteria (Fonstad & Marcus, 2010; Hudson et al., 2013). This variability is not only morphologically important for determining the extent to which rivers construct a uniform bankfull channel but also hydrologically important for determining the variability of floodplain inundation (Castillo, 2020; Czuba et al., 2019; Dzubakova et al., 2015). Highly variable bankfull conditions along a river should lead to highly variable flooding. This variability should be reflected in the shape of the stage-discharge relation and should be related to detailed patterns of inundation of the floodplain as stage increases.

The purpose of this work is twofold: (1) to develop an objective, morphologically based method for determining variability in bankfull stage and channel bank elevations at different spatial sampling intervals from lidar-based high-resolution digital terrain models (DTMs) and (2) to relate this variability to planform characteristics and rating curves for three lowland meandering rivers. The work focuses on the degree of spatial variability of bankfull stage and bank elevations. The degree of variability should have important hydrological implications for formative processes influencing the morphological relationship between river channels and their floodplains. Also, it should provide insight into channel-floodplain connectivity and stage-discharge relations as flow transitions from "in-channel only" to "in-channel and floodplain" flow. Variability in bank elevations should govern the timing and spatial pattern of floodplain inundation as water flows out of the channel onto the floodplain, which, in turn, should influence the shape of rating curves. Although hydrological methods for inferring bankfull stage from rating curves assume that these curves reflect the morphological relation between channels and floodplains, little, if any, direct evidence is available to confirm this assumption.

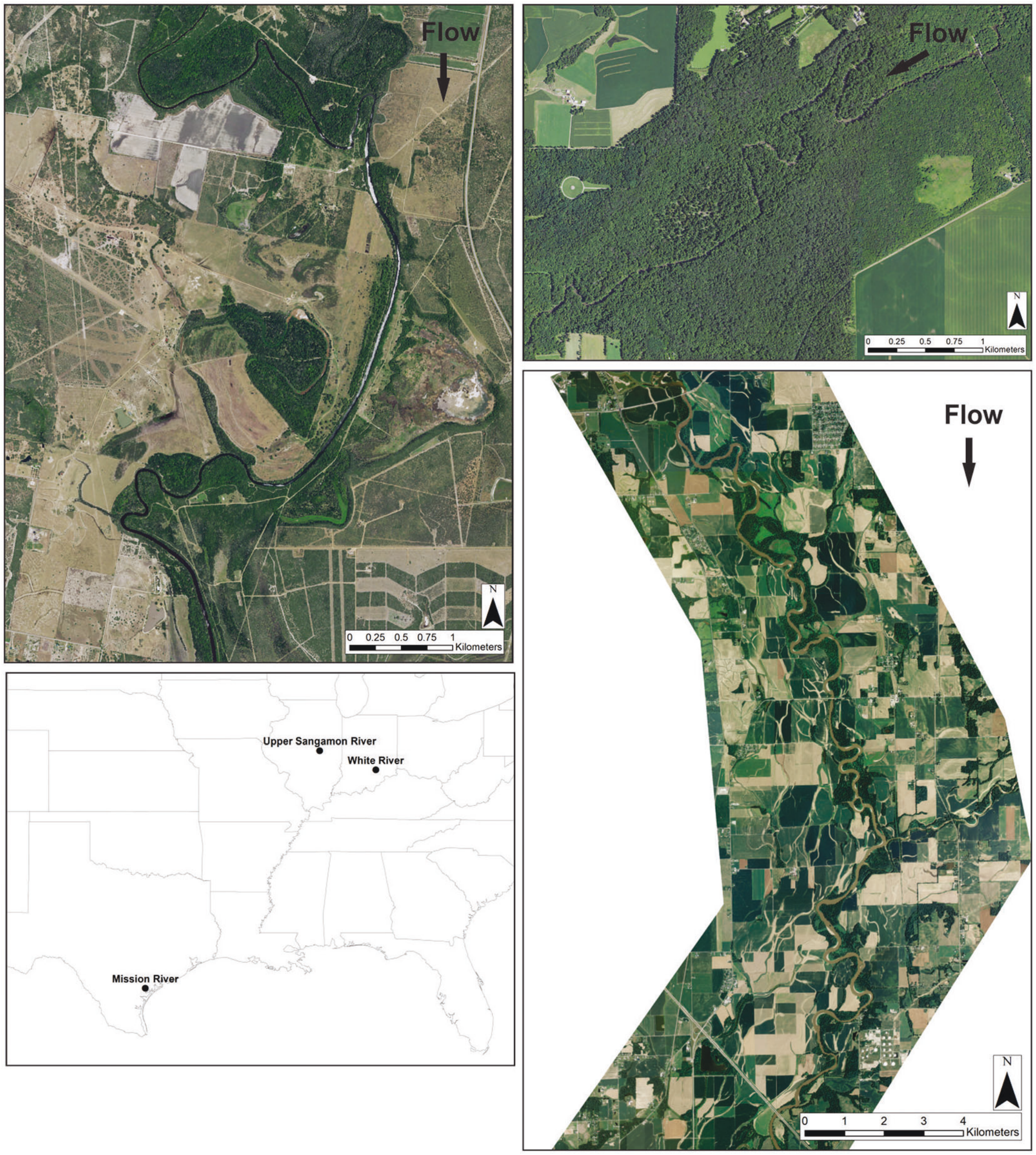

Figure 2. Location and overview of the three study areas. Clockwise from top left: Mission River, Upper Sangamon River, East Fork White River.

2. Study Sites

2.1. Upper Sangamon River

The study reach of the Upper Sangamon River (USR), located in East Central Illinois within Robert Allerton Park, a 607-ha tract of land owned by the University of Illinois, drains 1,500 km^2 and is 6 km long (Figure 2). The channel and forested floodplain in the park have not been disturbed directly by human activity. At bankfull stage, the channel is approximately 30 m wide and 3–4 m deep. The nearest streamgage is USGS 05572000 Sangamon River at Monticello, Illinois, located approximately 7 km upstream. The river system at the study area sits within a broad valley approximately 550–600 m wide bounded by distinct bluffs. The valley was likely carved by glacial meltwaters during the retreat of the ice margin during the Wisconsin glacial period 13,500–25,000 years ago (Illinois Department of Natural Resources, 1999). The tops of the bluffs are approximately 10–12 m above the surface of the floodplain within the valley bottom. The river meanders within the valley bottom, but detectable active migration of the river channel has not occurred during the past 80–90 years based on analysis of aerial photography (Rhoads et al., 2016). No distinct terraces exist within the valley bottom but are detectable elsewhere along the Sangamon River system (Yan et al., 2018).

2.2. East Fork White River

The study reach of the East Fork White River (EFWR), located in South-Central Indiana, drains roughly 5,800 km^2 and is approximately 24 km in length (Figure 2). The reach meanders through an agricultural floodplain and exhibits a dense, complex floodplain channel network as well as numerous oxbows and scroll bars (Czuba et al., 2019). Land cover along the reach, including the channel and floodplain, is approximately 76% agriculture, 13% forest, 7% open water, and 3% urban (Czuba et al., 2019). Average bankfull width is approximately 90 m, and bankfull depth ranges from 3.5 to 4.5 m. USGS Streamgage 03365500 EFWR at Seymour, Indiana, is located approximately 5 km downstream of the study area. Analysis of lidar data reveals that the floodplain of the EFWR displays abundant relict and secondary channels, some of which were likely formed by headcutting, indicating that the river is actively migrating and has a high frequency of flooding (David et al., 2017, 2018). Stream banks are overtopped and major low-lying floodplain channels are inundated roughly 19 days per year (Czuba et al., 2019).

2.3. Mission River

The study reach of the Mission River (MR), located in the Texas Coastal Bend, drains an area of approximately 1800 km^2, is approximately 9 km long (Figure 2). In the upstream part of the reach, where the river has incised into the historical floodplain, the modern floodplain is bounded by Quaternary terraces. In the downstream part of the reach, closer to the river mouth at Mission Bay, the river flows through a floodplain consisting of Quaternary alluvium. Flow in the downstream part is influenced to some extent by backwater effects associated with tides, but it lies upstream of major tidal influences. Floodplain features include numerous sloughs, secondary channels, and swales in the upstream part and oxbows and backswamps in the lower part. Land cover along the reach is predominantly coastal prairie (27%) and mesquite woodland (16%) in the uplands and bottomland hardwood forest (15%), floodplain grasslands (7%), bottomland live oak/mixed forest (6%), and riparian wetlands (4%) (Castillo, 2020; Elliott et al., 2014; Evans et al., 2012). The channel banks are lined with trees throughout the reach. Average bankfull width is approximately 60–70 m, and channel depth ranges from 7–8 m in the upstream part to 4–5 m in the downstream part. The nearest stream gage is USGS 08189500 MR at Refugio, Texas, located approximately 5 km upstream of the reach. The local landscape is predominantly rural, and topographic relief is relatively flat, with an average slope of approximately 0.038% (Uddameri & Kuchanur, 2007).

3. Methodology

To enhance objectivity, efficiency, and reproducibility, methods have been developed to determine elevations of channels banks from high-resolution, lidar-based DTMs (Hudson et al., 2013; Passalacqua et al., 2012). The representation of topography using lidar data has tremendous advantages over the representation based on traditional survey methods. Lidar data can be used to generate submeter resolution DTMs (i.e., topographic models with vegetation cover being removed digitally) over wide areas. Analysis of such DTMs provides the basis for accurately determining the morphological characteristics of river channels (Fisher et al., 2013; Hudson et al., 2013), terrace and floodplain features (Clubb et al., 2017; Stout & Belmont, 2014), and floodplain channels (David et al., 2017; Slatton et al., 2007). The present work builds on previous efforts to define bank elevations from lidar data (e.g., Hudson et al., 2013; Passalacqua et al., 2012) by identifying elevations of both banks rather than just the lowest one, by using accepted morphological methods to identify bankfull stage, and by allowing bankfull stage and bank elevations to be determined at different user-defined spatial sampling intervals. Multiple approaches to bankfull identification are included in the method to corroborate the determination of bank elevations and bankfull stage. The methodology for generating information on spatial variability in bankfull stage and bank elevations along lowland meandering rivers and for relating this variability both to planform characteristics of these rivers and to stage-discharge relations consists of three components: (1) identify bankfull stage at a user-defined spatial sampling interval from high-resolution DTMs generated from lidar data on floodplain and channel topography; (2) examine spatial variability in bankfull stage and bank elevations along the reaches of the selected rivers; and (3) relate the form of rating curves for each river to the variability in bankfull stage using two-dimensional (2-D) hydrodynamic modeling that has been calibrated to stream-gage data.

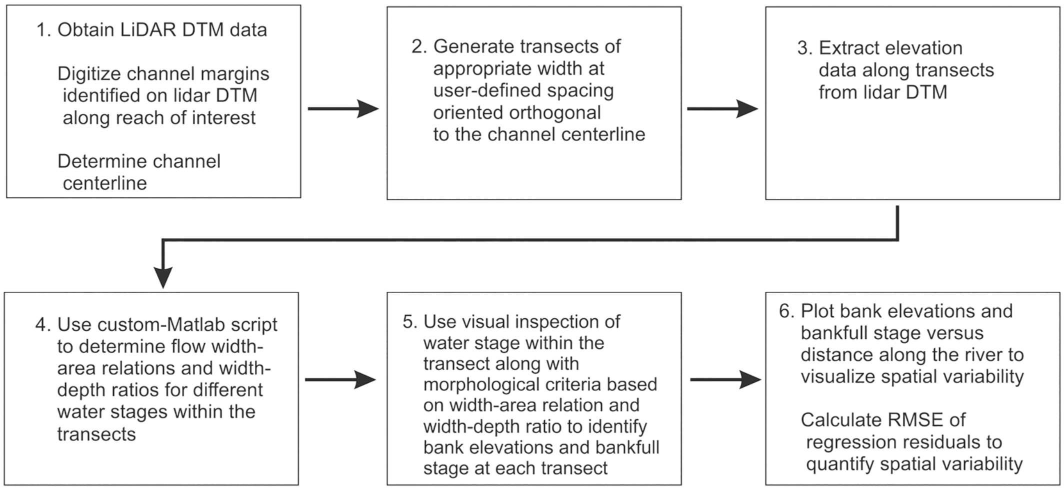

Figure 3. Flowchart of the steps required to obtain bank elevations and bankfull stage along a river reach.

3.1. Identification of Bank Elevations and Bankfull Stage

The workflow for the identification of bank elevations and bankfull stage from lidar data involves six steps (Figure 3). In Step 1, lidar data sets were acquired for each of the study areas (Güneralp & Filippi, 2019; Illinois State Geological Survey, 2012; IndianaMap, 2011). DTMs created from these data for each study area have horizontal resolutions of 0.3 m (USR), 1.5 m (EFWR), and 1 m (MR) and vertical resolutions of 0.06 m (USR and EFWR) and 0.03 m (MR). Visual margins of the river channel on the lidar imagery are digitized, and the path of the channel centerline is determined by locating center points between these margins using the Channel Planform Statistics Tool (Lauer, 2006). By determining the centerline from the midpoint of the margins, rather than manually digitizing it, error in the location of the centerline is reduced through averaging. Creating an accurate channel centerline is essential for establishing reference points from which transects can be constructed (Passalacqua et al., 2012).

In Step 2, transects orthogonal to the local path of the centerline are generated automatically at a user-defined spatial sampling interval based on spatial information on the local directionality of the centerline using a custom MATLAB script (Güneralp, 2007; Güneralp & Rhoads, 2008), which incorporates transformation algorithms similar to those described by Legleiter and Kyriakidis (2006) (Figure 4a). Two sampling intervals are used in this study to examine whether differences in this interval affect variability in bank elevations (Table 1), one three times the channel width (wide spacing) and the other one-sixth the channel width (narrow spacing). Analysis performed using the wide spacing extends over the entire length of the study reaches, whereas that using the narrow spacing focuses on subreaches within the study reaches. Transect length, defined by the user, must be great enough to extend past each bank. The DTMs are inspected to select a width adequate for identifying the distance between the river banks at a river's widest point. For all three study sites, transect widths are two to three times the average bankfull channel width (Table 1). In Step 3, the endpoints of the transects are determined from the MATLAB script, and tools in ArcGIS 10.7 (*Feature Vertices to Points, Points to Line,* and *Interpolate Shape*) are used to connect the endpoints by lines to define transects and then extract transect elevation data from the DTM.

In Step 4, elevation data for each transect are exported to a custom MATLAB script that determines geometric properties of the flowing water within the transects for different water-surface elevations. The vertical range of water-surface elevations extends from the lowest point in the transect to well above the top of the highest bank, increasing by a vertical increment (3 cm) similar to the vertical resolution of the DTM (Table 1). The lowest point in the transect corresponds to a flattened surface representing the water elevation in the channel at the time of lidar-data acquisition. The width, area, and mean depth of the inundated sections of the channel and floodplain are calculated for each increment of water-surface elevation on each transect. When performing these geometric calculations, the ends of the transects consist of imposed vertical boundaries to laterally constrain the domain of the calculations (see Figure 4b). The script generates three

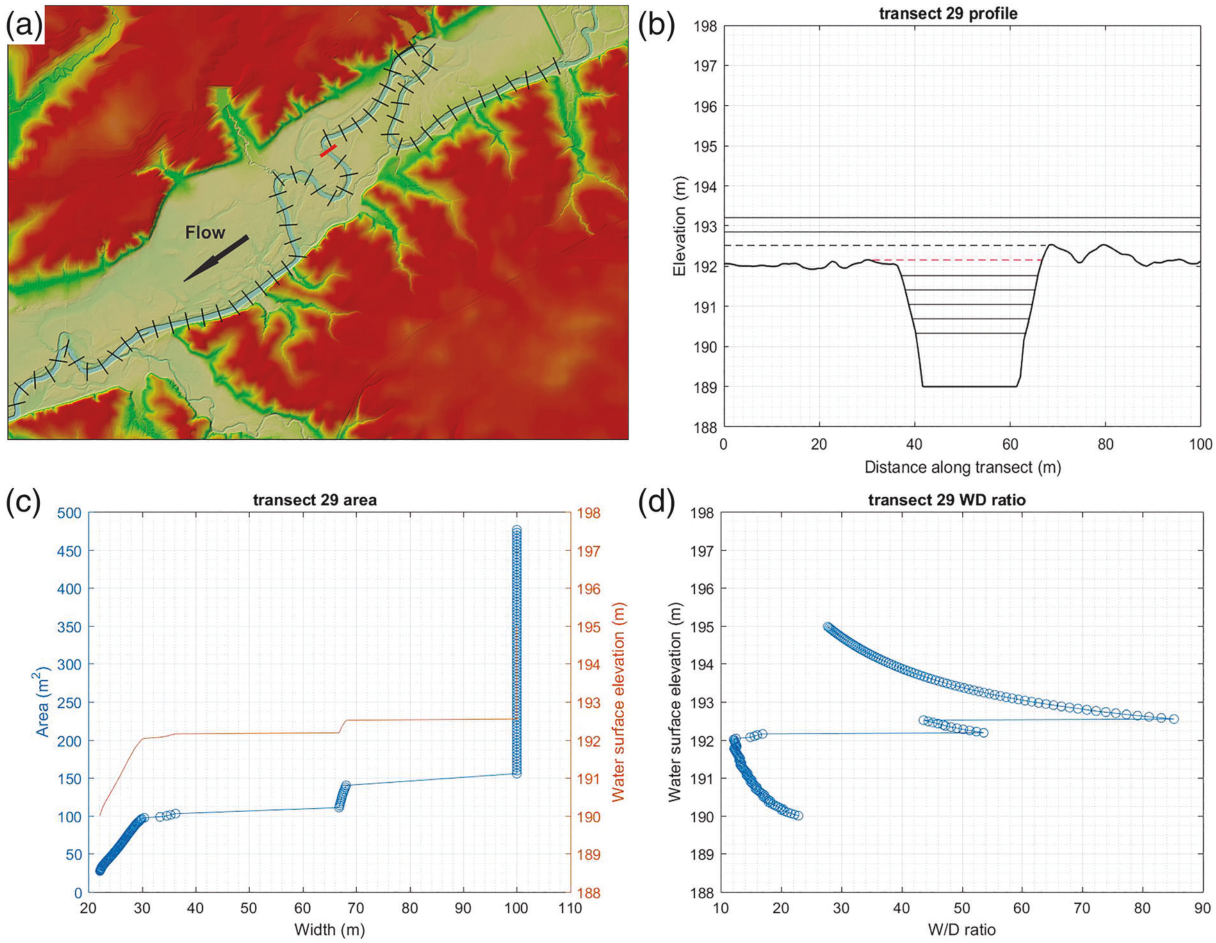

Figure 4. (a) Generated transects for the upper Sangamon River. Transect 29 is marked in red. (b) Tested water surfaces (solid black and dashed lines) plotted on the transect profile with surfaces at the tops of the left and right banks marked by red and black dashed lines, respectively (only ~10% of tested surfaces are plotted here to improve legibility). Sides of the plot represent vertical boundaries of the transects. (c) Width-area relation for water surfaces; (d) width/depth ratios for water surfaces. Breaks in plots c and d at about 192 and 192.5 m correspond to the water-surface elevations marking the tops of banks in plot b.

plots for identifying when the water surface has reached the top of banks as defined morphologically: (1) water surfaces plotted on the transect profile, (2) the relationship between the cross-sectional area of the flowing water and the top width (Williams, 1978) (Figure 4c), and (3) the relationship between the width/depth ratio and the water-surface elevation (Figure 4d).

In Step 5, the three plots are compared to well-established morphological criteria for determining the top of the channel banks: (1) the elevation at which the water surface corresponds to the transition from a relatively steeply sloping bank to an adjacent, nearly flat floodplain (Navratil et al., 2006); (2) abrupt change in the relationship between cross-sectional area and top width (Williams, 1978); and

Table 1
Spacing and Length of Transects and Vertical Increment of Water-Surface Elevation for Each River Reach

	3 × width reach length (m)	1/6 × width reach length (m)	3 × width spacing (m)	1/6 × width spacing (m)	Transect Width (m)	Vertical water-surface increment (cm)
Upper Sangamon	5,810	1,820	90	5	100	3
East Fork White	24,410	1,945	270	15	200	3
Mission	9,185	1,690	100	7	130	3

(3) minimum width-depth ratio for a particular water-surface elevation (Wolman, 1955). The three plots (Figures 4b–4d) are visually inspected to identify the elevation at which water overtops each bank. Once the top of the lowest bank is identified based on minimization of the width-depth ratio and major increase in the width-area relation, the process of raising the water surface continues until the next major break in width-depth ratio and area-width relation corresponding with top of the highest bank is encountered. Through this process, the elevations of the tops of both banks can be established. Once top-of-bank elevations have been identified at each transect, by convention, the elevation of the lowest bank is equated with the local bankfull stage (Passalacqua et al., 2012). Above this stage, water at that particular location will extend onto the floodplain, into secondary channels on the floodplain, or will produce backwater in tributaries (Figure 1).

To maintain objective consistency in selecting top-of-bank elevations, several selection criteria were adopted:

1. Top-of-bank positions correspond to elevations characterized by a distinct flattening of the slope of the channel bank as well as abrupt breaks in slope on width-area plots and minimums of width/depth ratios on plots of width/depth ratio versus water-surface elevation (Figures 4b–4d).
2. The extent of water beyond the position tentatively identified as the top of banks must spread laterally onto the adjacent surface, presumed to be the floodplain, for a distance greater than 1/30 of the channel width. This criterion was adopted to eliminate local shelves along the channel banks that produce distinct flattening of the bank slope but that occur well below the level of the floodplain. It also allowed inclusion of levees positioned a short distance away from flat areas near the top of banks.
3. If multiple vertical positions at a transect meet Criteria 1 and 2, bank elevation is determined from breaks in slope (width-area) and local minimums (width-depth ratios) that correspond to well-defined bank elevations at neighboring transects.

The locations and profiles of transects in relation to the topography depicted on lidar DTMs were also examined to ensure that the lowest bank elevations correspond to distinct topographic features such as sloughs, secondary channels, or entry of tributaries that result in an exceptionally low local bank height. Also, in situations where the channel abuts a valley wall, and no floodplain exists on that side of the channel, no bank height can be meaningfully identified based on topographic breaks. Thus, bank elevations remain undefined for these cases. At no location along any of the rivers, either for narrow or wide spacing of transects, was the channel bounded on *both* sides by something other than floodplain (e.g., high terrace or valley wall). Therefore, it was not necessary to exclude any transects based on not being able to identify a representative bankfull elevation for at least one bank. The data for all three rivers provide the basis for identification of bankfull stage along the entire length of the reaches.

In Step 6, bank elevations are plotted versus distance both separately and as bankfull stage to visualize the pattern of spatial variability in these elevations. To evaluate and quantify spatial variability in bank elevations and bankfull stage, the elevation data are first detrended using ordinary least squares regression. The root mean square error (RMSE) of the residuals about the trend line corresponding to the regression relation provides a quantitative statistical metric of mean variability in bank elevations.

3.2. Hydrodynamic Modeling

To compare patterns of inundation with spatial variability in bankfull stage, flows corresponding to different discharges within each river reach were simulated using the U.S. Army Corps of Engineers Hydrologic Engineering Center's River Analysis System (HEC-RAS) Version 5.03 (Brunner, 2016). In discharge simulations, HEC-RAS solves the 2-D diffusive wave equations and calculates hydraulic parameters including depth, velocity, and water-surface elevation as model outputs. The model uses user-input information on channel and floodplain morphology (in this case the lidar-derived DTMs) to generate a computational mesh. For the USR, the mesh contained 185,000 cells with an average area of 25 m^2. The downstream boundary condition was set as a normal depth with a friction slope of 0.001, and the upstream boundary condition was set as a user-specified flow hydrograph. Channel bed elevations were approximated by lowering the water surface at the time of lidar acquisition uniformly by an amount equal to the difference between the lidar water-surface elevation and the zero-discharge stage at the Monticello gaging station. Steady-state conditions were simulated by maintaining constant discharge at the upstream boundary after a run-up time of

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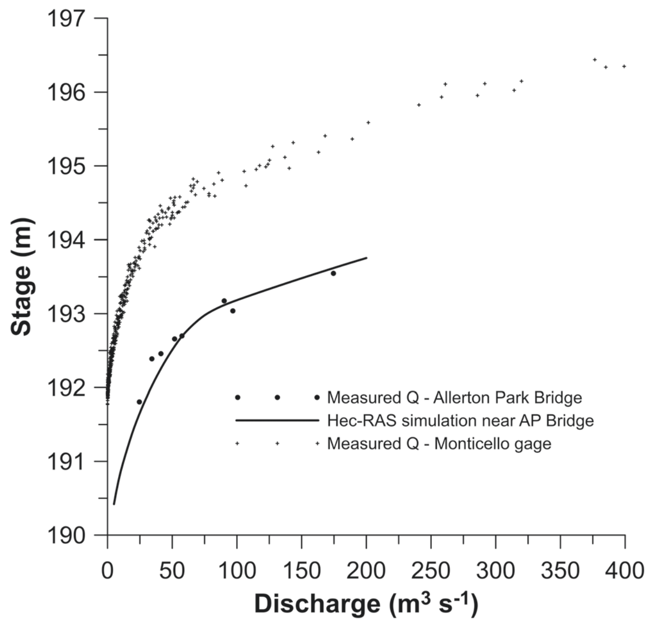

Figure 5. Rating-curve data for the Sangamon River at Monticello compared to simulated rating curve for the Sangamon River about 20 m downstream of the Allerton Park bridge and measurements of stage and discharge at this bridge.

120 hr. Twenty week-long flow events were simulated at discharges between 5 and 200 m^3/s. Roughness coefficients were defined for two regions, channel and floodplain, with Manning's *n* values of 0.045 and 0.12, respectively. These values were selected by comparing for particular discharges simulated water-surface elevations with measured water-surface elevations. Similar simulations were performed using HEC-RAS for the EFWR and MR to map patterns of channel and floodplain inundation over wide ranges of flows and water-surface elevations. Details of model calibrations and simulations can be found in Czuba et al. (2019) for the EFWR and in Castillo (2020) for the MR.

The general shape of the simulated HEC-RAS stage-discharge curves for the USR is consistent with the shape of the rating curve for the U.S. Geological Survey gaging station on the Sangamon River at Monticello, about 6 km upstream (Figure 5). Also, the simulated curve for a location about 15 to 20 m downstream of the Allerton Park bridge at the upstream end of the study reach closely matches stage-discharge measurements obtained at this bridge as part of the present study (Figure 5). Slight discrepancies between the simulations and measurements at intermediate stages reflect the influence of the bridge, which locally confines the flow at the location of measurements, on stage. The comparisons for the USR confirm that the simulated curves are good approximations of actual rating curves. The same is true for the EFWR and the MR where the simulated curves have been shown to represent closely rating curves for nearby U.S. Geological Survey stream gages (Castillo, 2020; Czuba et al., 2019).

4. Results

4.1. Identification of Bank Elevations and Bankfull Stage

The methodology readily identifies bank elevations and bankfull stage of all three river systems based on the morphological criteria of abrupt breaks in slope on width-area plots and minimums on width-depth ratio plots. Where the elevations of the channel banks are relatively equal and the floodplain is relatively flat, typical of straight reaches of the rivers, the bankfull stage, which corresponds to the elevation of the lowest bank, is closely approximated by the elevations of both banks (Figure 6a). Where the elevations of banks are not the same, common in meandering reaches, the bankfull stage clearly differs from the elevation of the highest bank (Figure 6b). This condition becomes extreme in the case of major breaks in the bankline associated with entrances or exits from secondary channels or sloughs on the floodplain (Figure 7a). Similarly, when one side of the channel abuts against a high valley wall or terrace, the bankfull stage corresponds to the elevation of the opposite bank bordered by the floodplain (Figure 7b).

4.2. Spatial Variability in Bankfull Stage

Plots of bankfull stage versus distance downstream for the USR, the EFWR, and the MR for sets of transects at wide spacing (3 × channel width) and narrow spacing (1/6 × channel width) illustrate the pattern of spatial variability in bankfull stage along these rivers (Figures 8 and 9). For both the narrowly and widely spaced transects, the RMSE of residuals about the trend lines for the three rivers ranges from 0.41 to 0.76 m, values an order of magnitude greater than the vertical resolution of the lidar data. Differences in slope of the trend lines (Table 2) are a consequence of the reach for the narrowly spaced transects being a short subsection of the reach for the widely spaced transects. Local variability in bankfull stage is persistent along the rivers and appears to fluctuate randomly but is greatest at sloughs that branch from the main channel, which result in exceptionally low bank elevations (Figure 8). In general, RMSEs for each river are not affected greatly by the size of the transect spacing. The ratios of RMSEs for widely spaced to narrowly spaced transects are 0.88 m for the USR, 0.82 m for the ERWR, and 1.34 m for the MR. The total range in bankfull stage, determined from the widely spaced transects, varies from 2.46 m on the USR to 3.90 m on the MR (Table 2).

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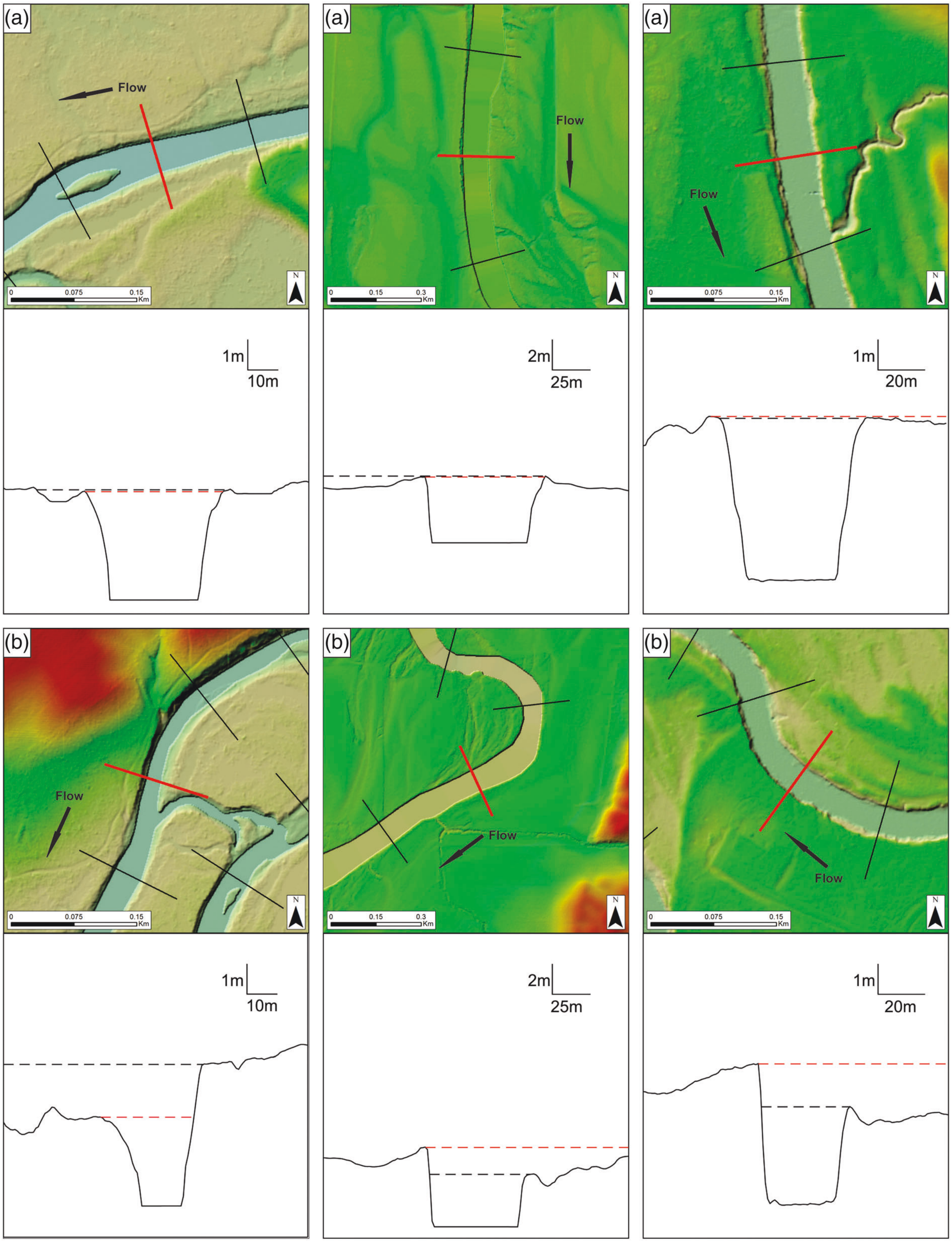

Figure 6. Bank elevation identification (left to right) for the Upper Sangamon, White, and Mission Rivers. Transects are oriented looking downstream. (a) Transects in which bank elevations are approximately equal; (b) transects in which bank elevations differ substantially. Red dashed line is left bank elevation, and right dashed line is right bank elevation. Plotted transects are shown in red on LiDAR image.

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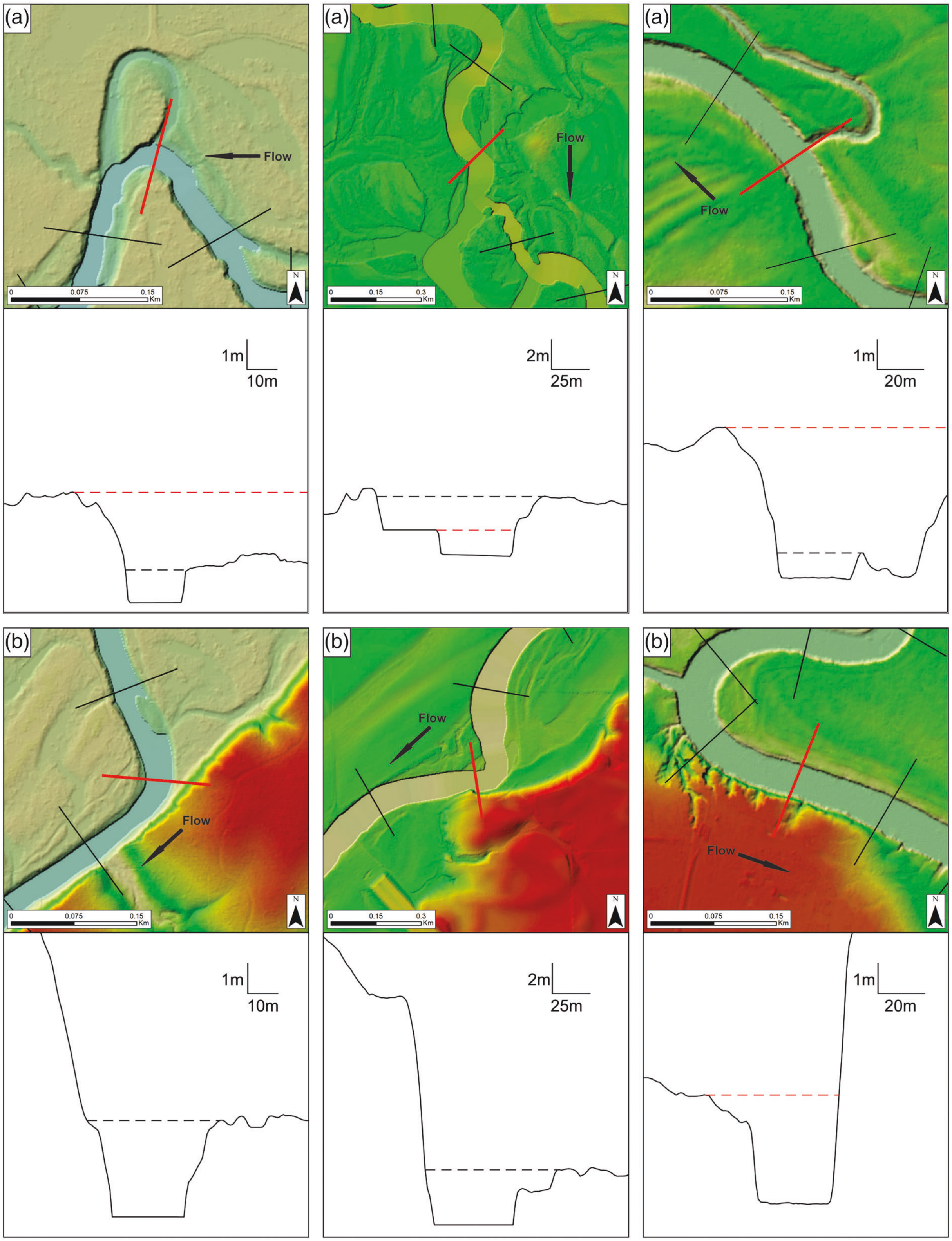

Figure 7. Bank elevation identification (left to right) for the Upper Sangamon, White, and Mission Rivers. Transects are oriented looking downstream. (a) Transects in one bank elevation is low because the channel intersects a floodplain slough. (b) Transects in which the channel abuts a valley wall so that identification of a bank elevation is impractical. Red dashed line is left bank elevation, and black dashed line is right bank elevation. Plotted transects are shown in red on LiDAR images.

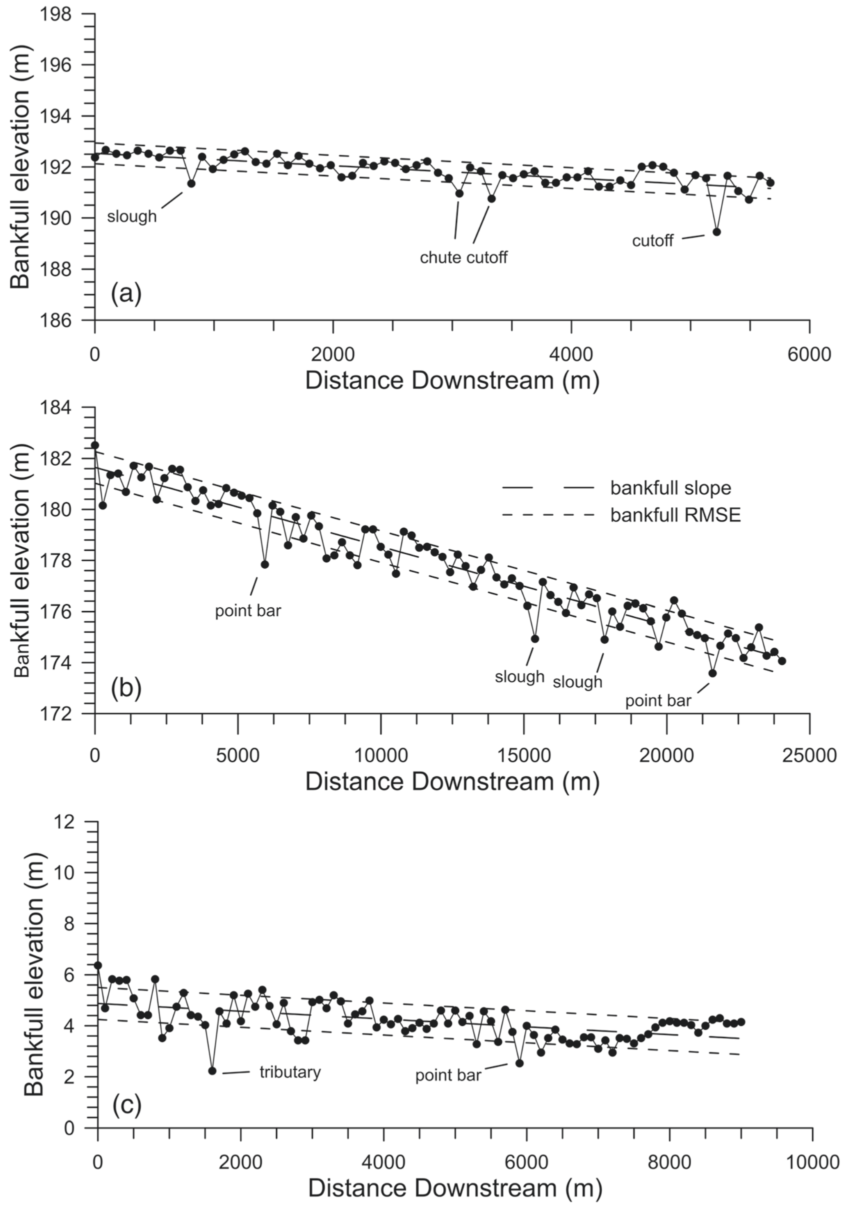

Figure 8. Spatial variation in bankfull stage—widely spaced transects. (a) Upper Sangamon River, (b) White River, and (c) Mission River.

To evaluate the relative variability of the bankfull stage in relation to the channel depth, the RMSE and the range of bankfull stage are divided by the estimated average bankfull depth over the length of the reach containing the widely spaced transects. Average bankfull depths were estimated by lowering the flattened surface corresponding to the water-surface elevation at the time of lidar measurement by a fixed amount. The amount of lowering was ascertained from the stage corresponding to zero flow at U.S. Geological Survey gaging stations along each river—a procedure that provides a conservative estimate of bed elevation (see the supporting information of Czuba et al., 2019). For both the narrowly and widely spaced transects, RMSEs for the USR and the MR are 10% to 15% of the bankfull depth, whereas the RMSE for the EFWR is 15% to 20% of this depth (Table 2). The total range of bankfull stages is 70% to 90% of the estimated bankfull depth (Table 2). The lowest bankfull stages are at elevations slightly below one half of the average channel depth, assuming that the elevation reference for the average depth is the average bankfull stage. These

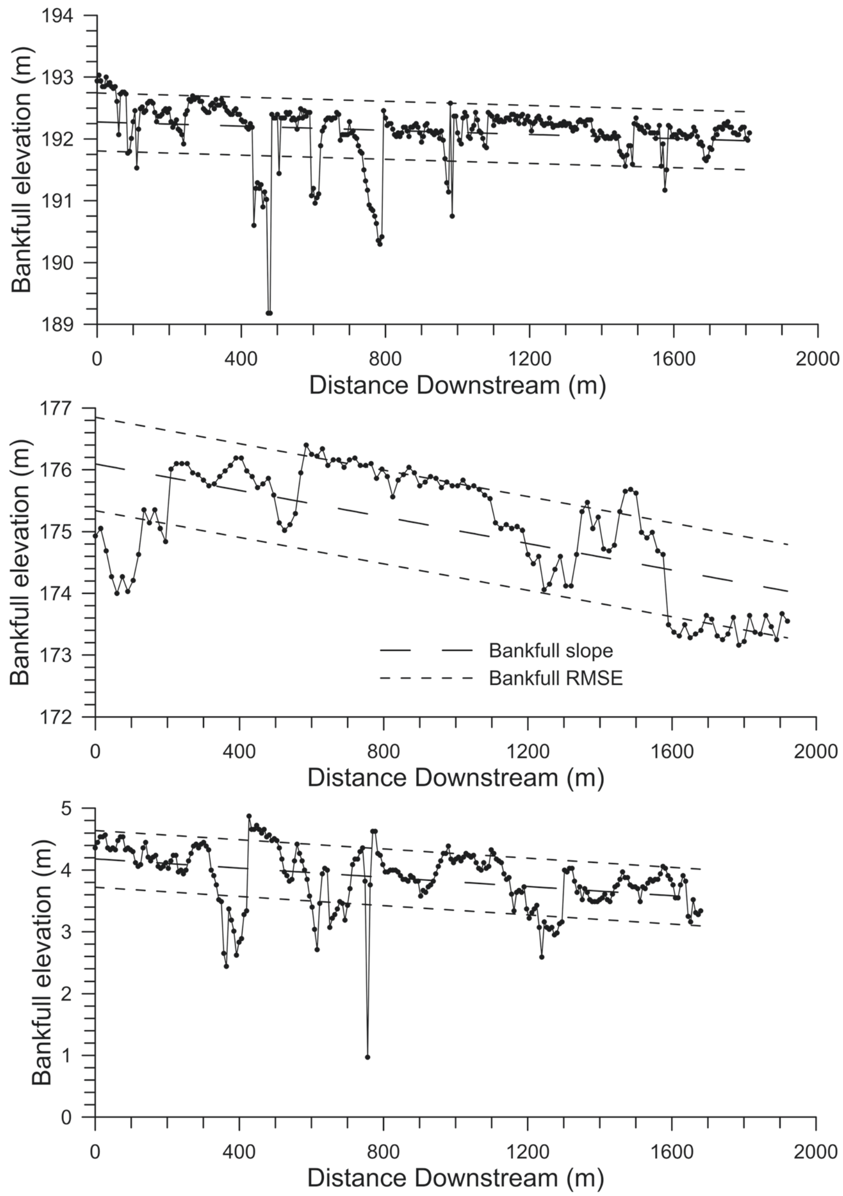

Figure 9. Spatial variation in bankfull stage—narrowly spaced transects. (a) Upper Sangamon River, (b) White River, and (c) Mission River.

lowest bankfull stages, normally associated with sloughs intersecting the main channel, are essentially gaps in the banks where water enters sloughs or floodplain depressions at low water levels.

4.3. Spatial Variation in Channel Bank Elevations

Trend lines fitted to elevation data for each channel bank define slopes in average bank elevations over the entire lengths of the study reaches (Figure 10). Gaps in the bank-elevation data occur where one side of the river valley bounds a valley wall or high terrace. In such cases, identification of a bank elevation for a channel carved into floodplain alluvium is not possible.

Generally, the slopes of the average bank elevations are similar for each bank for each river (Figure 10; Table 3), and the averages of the two slopes for the three rivers are consistent with the corresponding slopes of bankfull stage (Tables 2 and 3). Only the MR exhibits slopes of opposing banks that differ by more than 3%. Along this river, the slope of the average elevation of the right bank is 16% greater than the slope of

Table 2
Bankfull Stage Statistics for the Three Study Sites

	Slope of average bankfull stage (m/m)	RMSE of bankfull stage (m)	Range of bankfull stage (m)	Estimated average bankfull depth (m)	RMSE/depth	Range/depth
Upper Sangamon						
Wide spacing (90 m)	0.000243	0.41	2.49	3.45	0.12	0.72
Narrow spacing (5 m)	0.000169	0.47			0.14	
East Fork White						
Wide spacing (270 m)	0.000311	0.62	3.04	3.88	0.16	0.78
Narrow spacing (15 m)	0.00107	0.76			0.20	
Mission						
Wide spacing (100 m)	0.000153	0.63	3.90	4.34	0.15	0.90
Narrow spacing (7 m)	0.000373	0.46			0.11	

the average elevation of the left bank. Although this result indicates that, on average, the right bank becomes progressively lower than the left bank in the downstream direction, this tendency is largely overwhelmed by high variability in bank elevations along the MR.

RMSE values for each bank for the widely spaced transects are similar to those for bankfull stage, ranging from 0.48 to 0.87 m (Tables 2 and 3). Whereas the values of RMSE for the two banks along the USR and the EFWR differ by only a few centimeters, the difference in RMSE between the two banks for the MR exceeds 20 cm. The high degree of variability in the elevations of the left bank (RMSE = 0.87 m) counteracts to some extent the tendency of this bank to have a lower average slope than the right bank. Both the highest and lowest bank elevations along the reach occur on the left bank (Figure 10). For all three rivers, local lows in bank elevation reflect sloughs and chute channels that connect to the main channel as well as point-bar platforms that merge with low areas of the adjacent floodplain. The values of RMSE for the narrowly spaced transects are similar to those for the widely spaced transects. Four of the six banks have RMSEs within a few centimeters of one another, clustering near values slightly greater than 0.5 m (Table 3). The other two banks exhibit the most extreme values of RMSE for either bankfull stage or bank elevations. The right bank of the USR has relatively uniform elevations (RMSE = 0.25 m), whereas the left bank of the EFWR has a high degree of variability in bank elevations (RMSE = 0.97 m). Thus, local spatial variability in bank elevations can be both greater and less than the variability at coarser levels of spatial resolution.

Detrending of bank elevations for the narrowly spaced transects illustrates the relation between channel bank elevations and channel planform (Figure 11). The plotted data reveal that elevations of the bank on one side of the channel tend to be higher than the elevations of the bank on the opposite side of the channel over discrete sections of the river. Organizing the transects within these discrete sections into groups based on the locations of the sections highlights the alternating pattern between the sides of the river corresponding to high versus low average bank elevation (Figure 11). The breaks between the channel sections defining the groups coincide closely with locations where the pattern of curvature along the rivers reverses, resulting in switching in the sides of the meandering rivers corresponding to the outer and inner banks. Thus, differences in elevations between right and left banks on the same transect are associated with meander bends (Figure 11). Outer banks of bends are uniformly higher than inner banks of bends, and the locus of switching occurs close to inflection points between bends. Differences in average bank elevations are most pronounced for the MR and EFWR and least pronounced for the USR (Table 4).

4.4. Hydrodynamic Modeling Results

Results of flow modeling using HEC-RAS 2D show that at all study sites inundation of parts of the floodplain occurs over a wide range of flows (Figure 12). Low areas connected to the main channel, such as secondary channels and sloughs, are the first areas to be occupied by water outside the main channel. Increases in stage

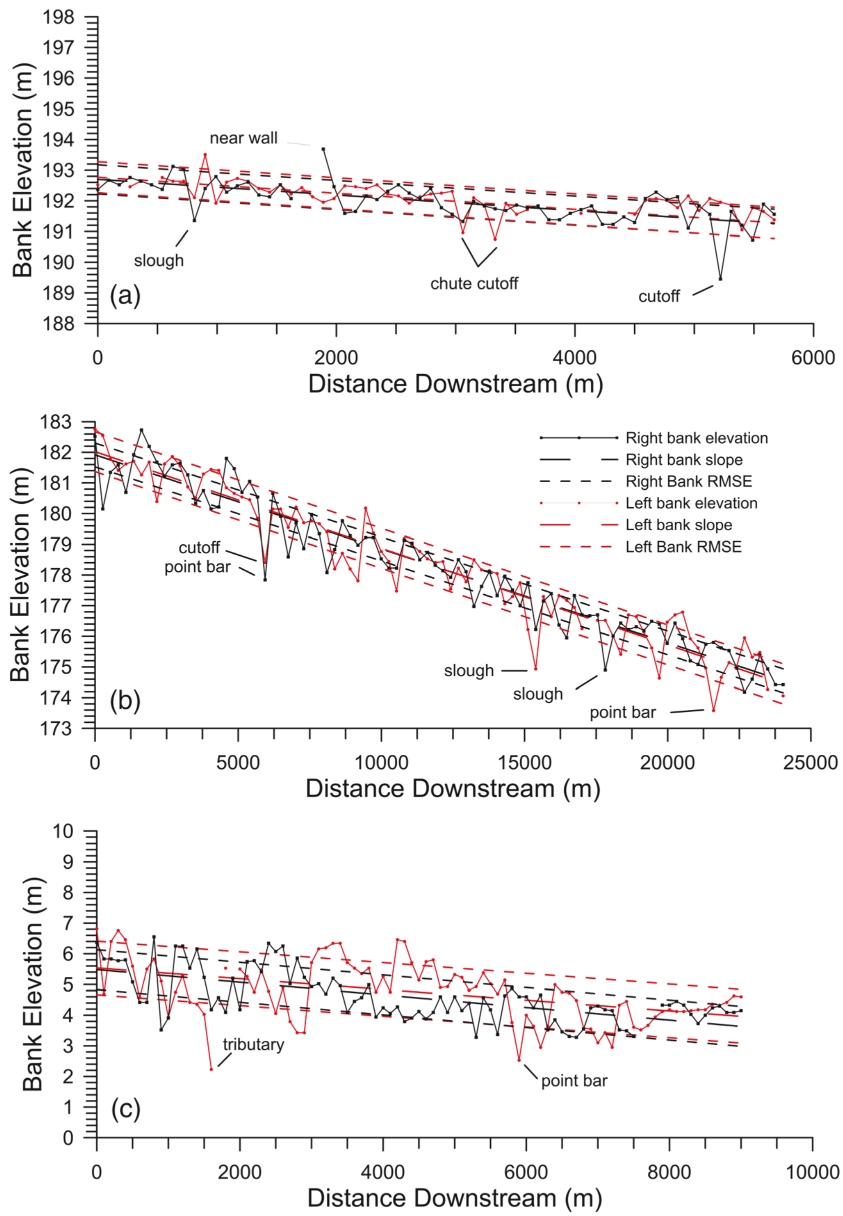

Figure 10. Spatial variation in bank elevations for widely spaced transects along (a) Upper Sangamon River, (b) White River, and (c) Mission River.

lead to local escape of water onto areas of the floodplain associated with low areas of the channel banks. Eventually, much of the floodplain becomes inundated as the water elevation exceeds the elevation of the banks along large sections of the main channel. The changing spatial patterns of floodplain inundation with increasing stage are consistent with local variability in bankfull stage documented at each site.

Most of the rating curves generated from the HEC-RAS simulations for locations along all three rivers display a curved segment between a steep rate of increase in stage with increasing discharge and a low rate of increase in stage with discharge (Figure 13). Typically, the segment of high curvature in a rating curve is assumed to reflect the transition between subbankfull flow within the channel and above-bankfull flow that extends onto the floodplain. Under this assumption, the zone of curvature should approximate the bankfull stage. To evaluate this assumption, the elevation range associated with the RMSE of bankfull stage is plotted on each rating curve. Because variation in bankfull stage provides opportunities for water within

Table 3
Bank Elevation Statistics for Widely Spaced and Narrowly Spaced Transects for the Three Study Sites

	Widely spaced transects		Narrowly spaced transects
	Slope (m/m)	RMSE (m)	RMSE (m)
Upper Sangamon			
Right Bank	0.000255	0.48	0.25
Left Bank	0.000262	0.51	0.52
Average	0.000259	0.49	0.38
East Fork White			
Right Bank	0.000307	0.62	0.51
Left Bank	0.000315	0.65	0.97
Average	0.000311	0.64	0.74
Mission			
Right Bank	0.000205	0.65	0.56
Left Bank	0.000175	0.87	0.57
Average	0.000190	0.76	0.57

the channel to flow onto the floodplain, once water rises to the level of variability, as defined by the range of elevations associated with the RMSE, water should progressively be moving onto the adjacent floodplain. The results show that the elevation range where curvature is greatest on the simulated rating curves overlaps with the range of mean variability in bankfull stage (Figures 13a–13j). This overlap is pronounced for composite rating curves for the reaches produced by averaging stages standardized to the mean stage at each location within a reach (Figures 13k–13m). These composite curves probably capture best the effect of reach-scale variability in bankfull stage on reach-scale stage-discharge relations. At all three sites, the range of high curvature on the composite curves is shifted upward slightly in relation to the range in mean variability of bankfull stage, indicating that the stage-discharge relation continues to be affected somewhat by exceptional high areas of the banks and by irregularities in floodplain topography as flow stage rises above the range of mean variability in bankfull stage. At the stage corresponding to the upper end of the range in mean variability, flow exceeds the heights of about 90% of the local bankfull stages along the three reaches. The overlap between the range of mean variability in bankfull stage and the zone of strong curvature on rating curves confirms that the structure of these curves, and thus the relation between floodplain inundation and increases in water stage, are strongly influenced by spatial variability in bankfull stage.

5. Discussion

5.1. High-Resolution Mapping of Bank Elevations and Bankfull Stage

Application of the new methodology developed in this work to three meandering rivers illustrates its usefulness for extracting bankfull elevations and bank elevations from lidar-derived DTMs at any user-defined spacing along a river channel. Although it aims to maximize objectivity in identifying the tops of channel banks and limit reliance on individual judgment, some subjectivity cannot be avoided given that criteria for identifying tops of banks must be defined by the user. However, if absolute objectivity is unattainable, consistency is achievable by adhering to the defined selection criteria at each transect. At all transects along the three study reaches, the three morphological-based methods used in this study, when considered in conjunction with the other selection criteria, located the tops of banks at the same elevation. Thus, for lowland alluvial meandering rivers, the methods are mutually confirmatory.

Bankfull elevations in this study were defined solely on the basis of morphological criteria because of the method's reliance on lidar DTM data. By contrast, traditional field-based methods have emphasized the use of multiple criteria to identify bankfull stage, including morphological, vegetation, and sedimentological characteristics (Williams, 1978). Although not as comprehensive as field-based identifications, the method developed here is more objective than the subjective expert judgment on which most field methods rely. Moreover, the reliance on morphological characteristics is most relevant for exploring hydrological connectivity because the morphology of the channel-floodplain interface governs the way in which water in the channel spreads onto the floodplain.

Consistent application of the method provides the basis for high-resolution mapping of longitudinal variability in bankfull stage and bank elevations on each side of a river and for exploring the geomorphic factors that produce this variability. These factors include sloughs, secondary channels, and point bars. Information generated through the methodology can be used to quantify the spatial characteristics of bankfull stage and its associated geomorphic properties along lowland meandering rivers, including the slopes and spatial variability of bankfull stage and bank elevations at different spatial intervals. Widely spaced transects over long reaches are best for determining general variability of bank elevations at the scale of general downstream trends in bankfull stage and bank elevations, whereas narrowly spaced transects over short reaches clearly define differences in elevations of channel banks in relation to river meandering.

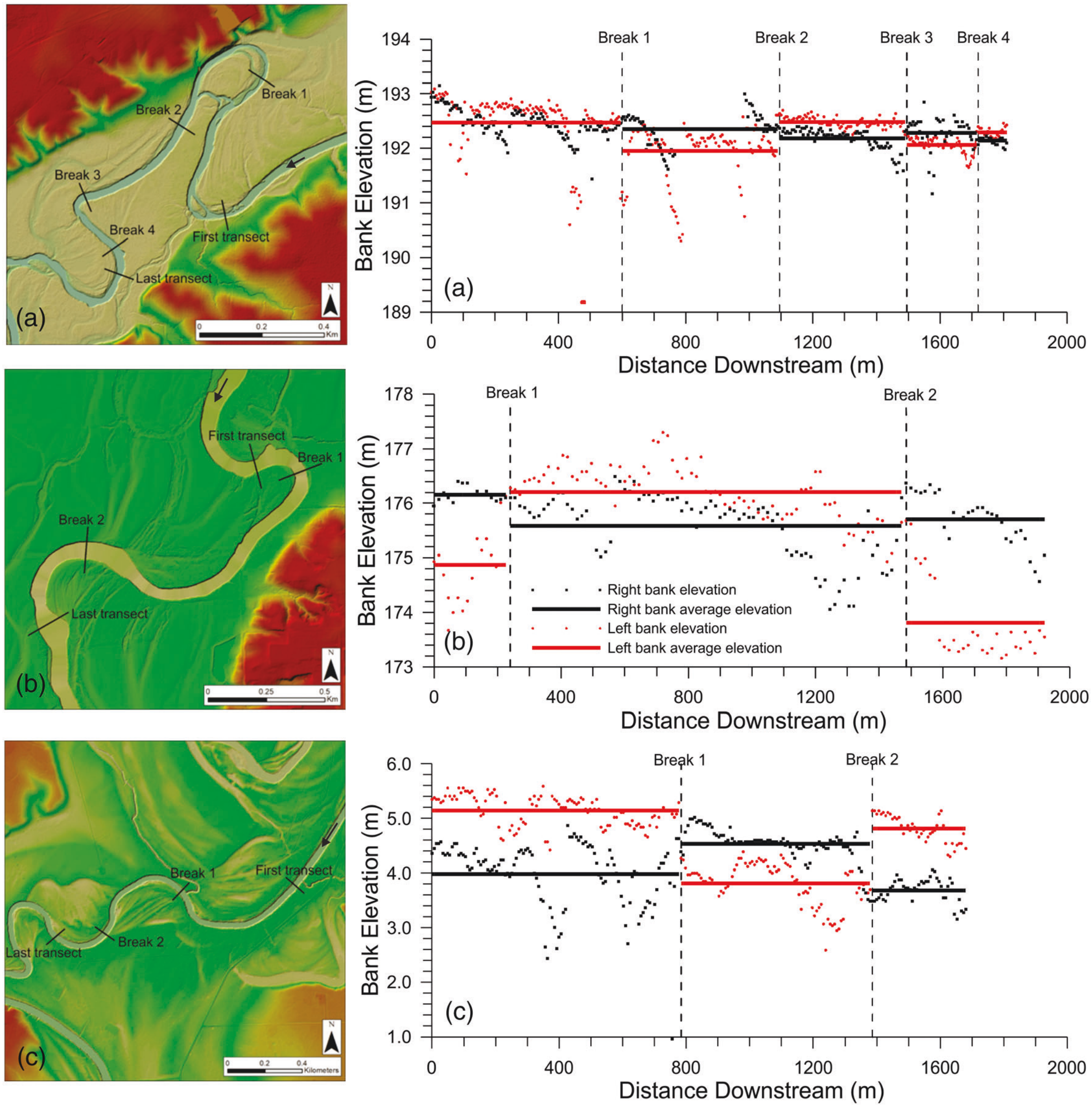

Figure 11. Detrended variation in bank elevations for narrowly spaced transects along (a) Upper Sangamon River, (b) White River, and (c) Mission River. Corresponding lidar images on the left show extent of subreaches corresponding to narrowly spaced transects and the location of breaks shown on the plots on the right.

5.2. Spatial Variability in Bankfull Stage and Bank Elevations

The results of this study demonstrate that variability in bankfull stage and bank elevations is an inherent characteristic of the rivers and does not represent deviations from an ideal norm of uniform bank elevations. This variability is considerable both over short reaches of a channel and over extended reaches. Apparently, lowland meandering rivers, the archetype of alluvial rivers that, through processes of erosion and deposition, shape their own channels, produce banks that are typified by topographic variability. Only a few past studies have explored this important geomorphic characteristic of rivers (Hudson et al., 2013; Johnston et al., 2019; Passalacqua et al., 2012). The high-resolution variability in bank elevations documented in this study is consistent with previous research showing that spatial variability of flow depth and width at high spatial resolutions is greater than that predicted by downstream hydraulic geometry relations (Fonstad & Marcus, 2010).

Not only does this work show that bankfull stage and bank elevations exhibit considerable spatial variability at different spatial sampling intervals but it also suggests that the magnitude of this variability is relatively

Table 4
Mean Bank Elevations for Narrowly Spaced Transects Divided Into Groups Based on Position Around Meander Bends

	Group 1	Group 2	Group 3	Group 4	Group 5
Upper Sangamon (5 m)					
Right Bank	192.46	192.35	192.18	192.29	192.15
Left Bank	192.47	191.95	192.48	192.07	192.30
Difference	0.02	0.40	0.30	0.22	0.15
East Fork White (15 m)					
Right Bank	176.16	175.58	175.70		
Left Bank	174.87	176.20	173.80		
Difference	1.29	0.62	1.90		
Mission (7 m)					
Right Bank	4.00	4.54	3.68	—	—
Left Bank	5.14	3.81	4.81	—	—
Difference	1.14	0.73	1.13	—	—

consistent in relation to average channel depth. The mean variability in bankfull stage for all sites is about 10% to 20% of the estimated average bankfull depth. The EFWR, which has the greatest mean variability of the three rivers, also displays the greatest amount of flow in floodplain secondary channels at stages less than the average bankfull elevation defined by the longitudinal gradient in bankfull stage (Figure 12). The limited range of mean variability for the three rivers suggests the possibility of a feedback effect limiting the relative amount of variability in bankfull stages along these rivers, despite differences in river size. The total range in bank elevations is nearly equal to the estimated average depth of the main channel, resulting in flow leaking from this channel into floodplain channels at stages well below the average bankfull elevation —a finding confirmed by the HEC-RAS modeling. The total range is governed by sloughs, secondary channels, and tributaries that branch from or join the main channel.

The mean variability in bankfull stage for the three rivers examined in this study represents a range of discharges that vary by a factor of 2 to 3 (Figure 13), indicating that bankfull discharge is a rather imprecise metric, even in lowland meandering rivers with a well-defined main channel and readily identifiable banks. Further work is needed to determine the extent to which the findings here can be extrapolated to lowland meandering rivers generally and to determine if variability in bankfull conditions is common in other types of alluvial rivers, especially those that respond morphodynamically to individual hydrological events. If generalizable, the results of this study have important implications for river management in the sense that attempts to restore or naturalize lowland meandering rivers by producing channel banks of uniform height along and on opposite sides of a river are not consistent with the natural configuration of these rivers.

Results of this work add support to previous empirical and theoretical studies on differences in bank elevations produced by the dynamics of river meandering. Construction of a floodplain on the inner bank of a bend lower than the floodplain on the outer bank is a known consequence of lateral migration (Wolman & Leopold, 1957). Temporal lag between the vertical accretion of the opposite banks results in difference in bank elevations. As meandering channels migrate into a relatively high floodplain along the outer bank and build relatively low banks along the inner bank, a net transfer of floodplain material to the channel occurs through a process referred to as floodplain shaving (Lauer & Parker, 2008a, 2008b). The method employed in this study documents the difference between the inner and outer bank elevations around bends and shows that bank-elevation variability is associated in part with the floodplain shaving process. It should also be possible to use the method to identify the lateral extent of shaving by extending transects laterally away from the inner bank. Such information would also be useful for estimating thicknesses of overbank deposition relative to lateral accretion.

Variability of bankfull stage is not associated with the floodplain-shaving effect because only the lowest of the two banks is used to identify this stage; around meander bends, the elevation of inner banks consistently corresponds to bankfull stage. Instead, variability in bankfull stage is strongly influenced by geomorphic features that intersect the main channel, such as floodplain sloughs and secondary channels produced through cutoffs (Zinger et al., 2011) and headcutting (David et al., 2018), as well as by inherent local variability in bank elevations.

The interaction between erosional and depositional processes at the channel-floodplain interface and variability in the elevations of channel banks requires further investigation. The results here suggest that these processes vary locally, producing spatial variability in bank elevations. Likely, this variability results both from erosional processes associated with flow exiting and re-entering the main channel as well as with depositional processes associated with decreases in transport competence and capacity at the transition from deep, fast flow within the channel to shallow, slow flow on the floodplain. Factors enhancing local complexity in deposition and erosion at the top of banks include variable sediment trapping by bank vegetation and gaps created by tree falls.

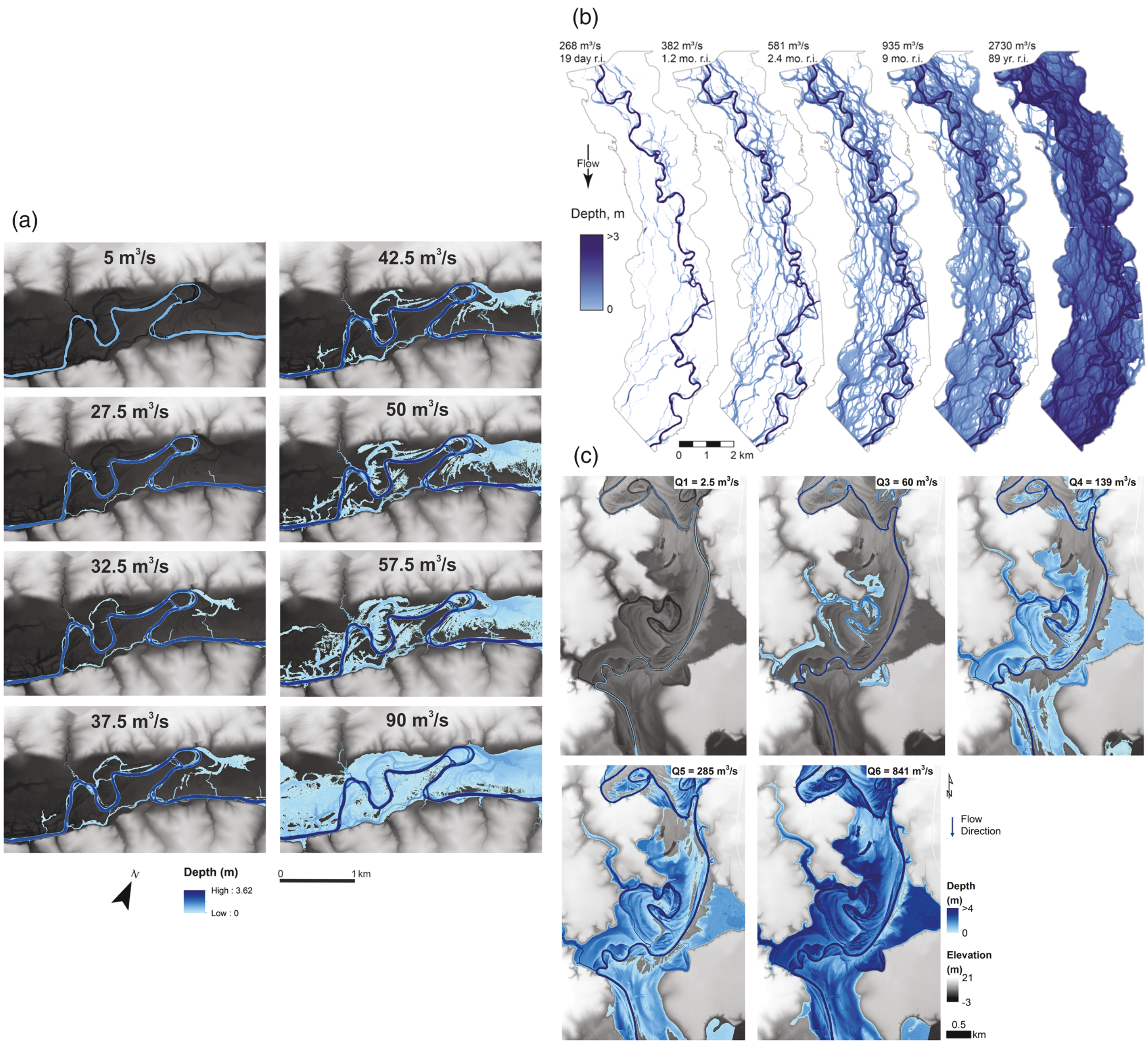

Figure 12. Simulations of flow for different discharges using HEC-RAS2D for (a) Upper Sangamon River, (b) White River (from Czuba et al., 2019; r.i. is recurrence interval), and (c) Mission River (from Castillo, 2020).

5.3. Bank Elevation Variability and Stream Restoration

The variability of bankfull stage has implications for efforts to restore streams. Bankfull stage and discharge are essential parameters in stream restoration and river engineering. Restoration designs are generally based on bankfull conditions (Johnson & Heil, 1996; Rosgen, 1994). The idea that practitioners should work with natural processes to produce outcomes consistent with natural fluvial forms is a basic philosophy underpinning much of stream restoration (Wohl et al., 2015). Restoration designs generally assume that bankfull conditions are constant along a reach, that is, that the elevation of both channel banks or of the bankfull stage decreases uniformly along a reach. The results of this work suggest that such uniformity is not characteristic of natural channels. The extent to which spatial variation in bank elevations reflects spatial variations in channel width, depth, and slope—factors that govern conveyance capacity—is a topic in need of further investigation.

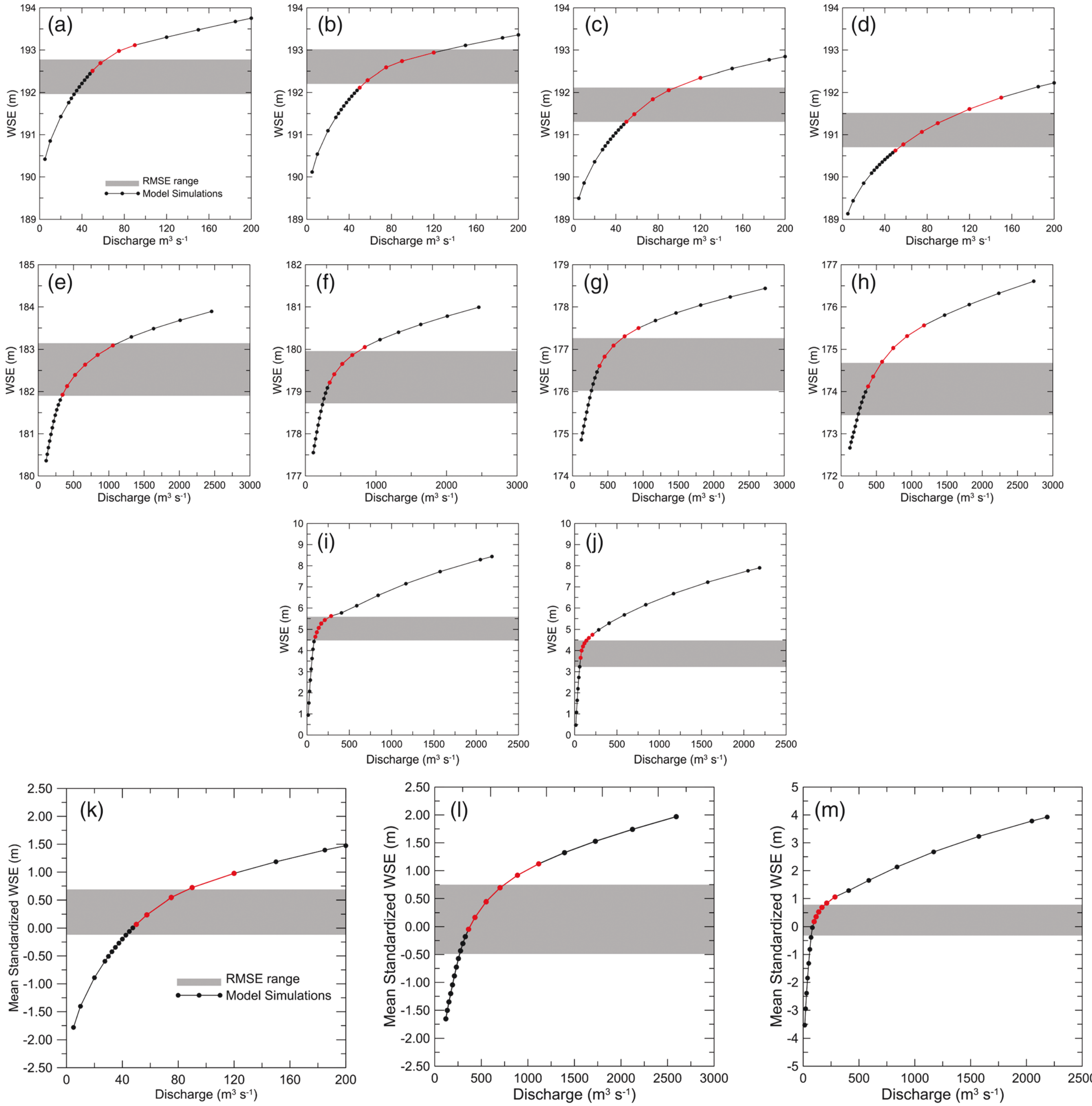

Figure 13. Simulated rating curves for individual locations along the study reaches of the Upper Sangamon River (a–d), the White River (e–h), and the Mission River (i and j). Also shown are composite rating curves based on mean standardized water-surface elevations (WSE) determined by subtracting values of stage from the mean stage for each rating curve and then averaging the standardized values corresponding to a particular discharge for all rating curves in a reach: (k) Upper Sangamon River, (l) White River, and (m) Mission River. Shaded areas represent the elevation range of the RMSE in bankfull stage. Red dots and lines correspond to the segment of high curvature on the simulated rating curves.

5.4. Variability in Bankfull Stage and Floodplain Inundation

The results of this work also demonstrate that variability in bankfull stage has implications for variability in flooding and patterns of inundation. The 2-D hydrodynamic simulations show that floodplain inundation occurs over a range of discharges and associated stages, rather than at an exact bankfull

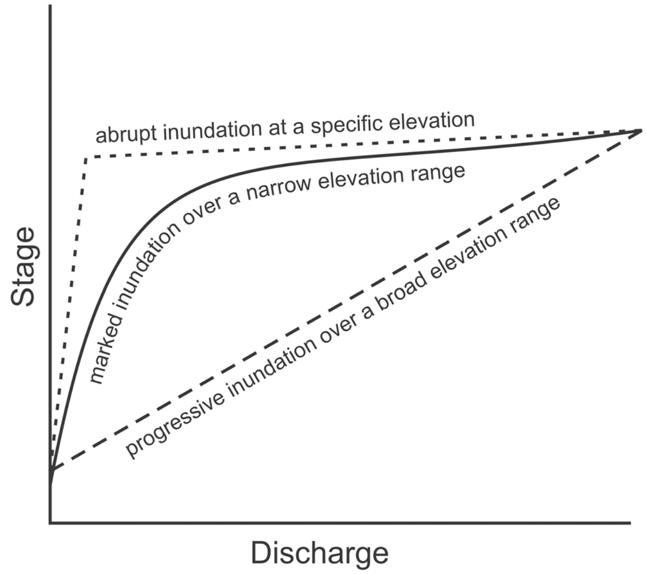

Figure 14. Conceptualization of differences in the shape of a rating curve based on inundation of the floodplain in relation to spatial variability in bankfull stage along a river reach.

discharge and accompanying water-surface elevation. The presence of water in low areas connected to the main channel before large sections of the banks are overtopped indicates that channel-floodplain connectivity is directly influenced by the spatial variability of bankfull stage. Activation of hydrological and geomorphological processes on the floodplain does not require widespread overtopping of the channel banks but occurs when flow exits the main channel into specific pathways below the average bankfull stage. Some of these pathways are connected to floodplain depressions that trap water, preventing it from returning to the main channel. The complexity of channel-floodplain connectivity is therefore greater than suggested by the traditional two-dimensional conceptual model of a spatially uniform bankfull channel bounded by an alluvial floodplain (Figure 1). This complexity has implications for biogeochemical processes on the floodplain, such as mineral weathering and nutrient processing (Bouchez et al., 2012), given that low areas of the floodplain connected to the channel will be inundated more frequently than predicted by an average bankfull stage.

The degree of variability in bankfull stage also influences stage-discharge relations as flow transitions from solely in-channel to inundating the floodplain. If a reach exhibited no variability in bankfull stage, a stage-discharge rating curve would display a sharp break in slope as all banks are overtopped at the same discharge (Figure 14). With an extremely high RMSE of bankfull elevations, a rating curve would approximate a straight line as flow would escape from the channel onto the floodplain almost continuously as stage increases (Figure 14). Intermediate levels of variability, such as those documented in this study, lead to a transitional increase in curvature of the stage-discharge relation as flow escapes from the channel onto the floodplain over a fairly narrow range of elevations.

6. Conclusion

This study has developed a methodology for extracting information on bankfull stage and channel bank elevations from high-resolution DTMs at user-specified intervals along the river. It has used the methodology to examine spatial variability in bankfull stage and bank elevations at different spatial scales for three different lowland meandering rivers. The results demonstrate that local variability in bankfull stage and bank elevations is an inherent characteristic of all three rivers. The mean variability of bankfull stage about the longitudinal profile of this stage is about 10–20% of the average bankfull channel depth. Although systematic variability in bank elevations in meandering rivers is related to planform characteristics, with outer banks having higher bank elevations than inner banks, this systematic variability does not account for variability in bankfull stage, which is defined on the basis of the lowest bank elevation at any particular transect across the channel. Variability in bankfull stage is related mainly to secondary channels, sloughs, and tributaries that branch from or enter the main channel as well as to low point bar surfaces along inner banks of bends. Because of variability in bankfull stage, water escapes from the main channel at local lows in the banks. Hydrodynamic simulations verify that low areas of the floodplain connected to the main channel are flooded before the elevation of the water surface rises to the average level of the lowest channel bank. The importance of spatial variability in bankfull stage in governing the connection between the channel and floodplain also is confirmed by the close correspondence between the mean variability in bankfull stage and the elevation range corresponding to segments of high curvature on rating curves.

Further work is required to assess the capability of the lidar-based methodology for identifying bankfull stage and bank elevations of rivers. A first step in this regard is to compare identifications of bankfull stage based on field surveys of channel transects with corresponding identifications based on lidar DTM data for the same transects. This type of analysis is needed to evaluate consistency between field- and lidar-based methods. If results of this study can be extrapolated to lowland meandering rivers generally, the findings have important implications for river-management efforts that seek to restore natural configurations of channel banks. Additional research also is needed to confirm the general validity of the relationship between mean variability in bankfull stage and average bankfull depth. In particular, the nature of this relationship should be evaluated for large lowland meandering rivers and for alluvial rivers of other planform types. At present, the factors producing local variability in bankfull stage and bank elevations are not clearly understood. Detailed investigations are needed to identify how the variability of flooding is related to specific factors influencing the variability of bank elevations. Two-dimensional hydrodynamic modeling of floodplain fluvial processes, including erosion and deposition, supplemented by field studies of these processes can provide the basis for such investigations.

Data Availability Statement

Data for this paper are available online (at https://doi.org/10.13012/B2IDB-6100626_V1).

Acknowledgments

Work on this project by E. M. L. and B. L. R. was supported by the NSF Grant EAR-1331906 for the Critical Zone Observatory for Intensively Managed Landscapes (IML-CZO), a multi-institutional collaborative effort. D. A. E. was supported by NSF Grant 1911321. J. A. C. was partially supported by Virginia Agricultural Experiment Station and USDA Hatch program (1017457). We thank Michael Church, Kenuske Naito, and an anonymous reviewer for insightful comments that improved the final manuscript.

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