QUANTIFYING RIVER FORM VARIATIONS IN THE MISSISSIPPI BASIN USING REMOTELY SENSED IMAGERY

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ABSTRACT

Zachary F. Miller: Quantifying River Form Variations in the Mississippi Basin Using Remotely Sensed Imagery
(Under the direction of Tamlin M. Pavelsky)

Geographic variations in river shape are often estimated using the framework of downstream hydraulic geometry (DHG), which links spatial changes in discharge and channel width, depth, and velocity through power-law models. Because these empirical relationships are derived from *in situ* data and may not describe all variability in channel form, we create a dataset of 1.2×10^6 river widths in the Mississippi Basin measured from remotely sensed imagery. We construct DHG for the Mississippi drainage by linking DEM-estimated discharge values to each width measurement. Well-developed DHG exists over the entire Mississippi basin, while individual sub-basins vary substantially from existing width-discharge scaling. Comparison of depth predictions from traditional depth-discharge relationships with one incorporating width into the DHG framework shows that including width improves depth estimates in basins with high width variability. Results suggest that channel geometry derived from remotely sensed imagery better characterizes variability in river form than the assumptions of DHG.

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LIST OF SYMBOLS AND ABBREVIATIONS

A .... Drainage area

a .... Width coefficient

b .... Width exponent

c .... Depth coefficient

d .... Channel depth

DEM .... Digital elevation model

DHG .... Downstream hydraulic geometry

f .... Depth exponent

k .... Velocity coefficient

m .... Velocity exponent

n .... Number of measurements

MAE .... Mean absolute error

NLCD .... National Land Cover Dataset

Q .... Channel discharge

v .... Channel velocity

w .... Channel width

ρ .... Spearman’s rank correlation coefficient

CHAPTER 1: QUANTIFYING RIVER FORM IN THE MISSISSIPPI BASIN USING REMOTELY SENSED IMAGERY

1. INTRODUCTION

Rivers systems connect the terrestrial and oceanic reservoirs of the hydrologic cycle and play a crucial role in landscape development and freshwater resources. Because spatial changes in river form are physical expressions of interaction between a river's flow and the surrounding environment, they are critical to a wide range of scientific and engineering fields. For example, channel geometry, which includes the key variables of width, depth, velocity, and slope, reflects local and regional uplift in bedrock and alluvial rivers and responds to changes in bedrock lithology [*Whipple,* 2004; *Montgomery,* 2004; *Harbor*, 1998; *Amos and Burbank,* 2007; *Montgomery and Gran,* 2001]. River width and depth play a vital role in CO_2 and nutrient exchange [*Butman and Raymond*, 2011; *Alexander et al*, 2000; *Wollheim, et al.*, 2006; *Peterson et al.*, 2001]. Aquatic habitat distribution is largely dependent on channel geometry, which both influences the spatial extent of habitats and acts as a barrier to terrestrial species migration [*Jowett*, 1998; *Newson and Newson*, 2000; *Ayres and Clutton-Brock,* 1992; *Hayes and Sewlal,* 2004]. Humans depend on accurate assessments of river form for understanding flooding hazards, transportation planning, and fisheries management [*Hobley, et al.*, 2012; *Apel, et al.*, 2009; *McCartney*, 1986; *Troitsky*, 1994; *Prevost et al.*, 2003]. Channel shape is also a principal parameter in hydrologic and hydrodynamic models [*Paiva, et al.*, 2013; *Neal et al*., 2012; *Yamazaki, et al.*, 2011]. Because of their wide-ranging importance to science and engineering, spatial patterns of channel shape have been studied for more than a century [*Humphreys and Abbott*, 1867; *Bellasis*, 1913].

The framework of downstream hydraulic geometry (DHG), developed by *Leopold and Maddock* [1953], relates spatial patterns of river form to variations in constant-frequency discharge throughout a basin. Three fundamental power-law equations relate width (*w*), depth (*d*), and velocity (*v*) to downstream changes in discharge (*Q*):

$$w = aQ^b \quad (1a)$$

$$d = cQ^f \quad (1b)$$

$$v = kQ^m \quad (1c)$$

where *b*, *f*, *m, a*, *c*, and *k* are empirically calculated exponents and coefficients. To facilitate comparison of channel shapes over a large geographic extent, the discharge used in DHG is spatially variable and considered to be of a magnitude equaled or exceeded the same percent of time at different locations. Due to the difficulty in obtaining spatially continuous measurements of channel geometry, these relationships are often used to estimate channel characteristics in studies of landscape evolution [*Tucker and Bras*, 1998], nutrient flux [*Butman and Raymond*, 2011; *Carleton and Mohamoud*, 2013], width distributions [*Andreadis, et al.,* 2013] and the movement of materials, energy, and organisms [*Sabo and Hagen*, 2012].

Traditional investigations of geographic variability in equilibrium channel form rely on *in situ* measurements of river geometry, which are usually available only at widely-spaced locations. This methodology faces two fundamental obstacles in characterizing spatial variations in width and depth. First, the time-intensive nature of *in situ* channel measurement limits the number of data points to a maximum of hundreds [*Moody and Troutman,* 2002] to thousands [*Lee and Julien,* 2006]. This restricts either the spatial extent of study areas to smaller basins [e.g. *Wolman,* 1955] or the density of measurements to wide spacing over larger areas [e.g. *Moody and Troutman,* 2002; *Leopold and Maddock*, 1953]. Second, *in situ* channel measurements are often acquired at permanent streamflow gauging sites where accuracy of discharge measurements is usually prioritized, potentially biasing site selection towards desired features such as stable, single-channel cross-sections that may not accurately represent the full range of channel characteristics [*Rantz*, 1982; *Ibbitt,* 1997]. These factors suggest that traditional investigations of river shape may not always encompass the full range of spatial variability in channel geometry.

Due to the importance of river form and the difficulty of obtaining wide-scale *in situ* channel measurements, remote sensing has increasingly been used to characterize river width, depth, and velocity [e.g. *Legleiter*, 2012; *Fonstad and Marcus*, 2005; *Pavelsky and Smith*, 2009; *Mersel, et al.*, 2013]. As the river parameter most readily observable from remotely sensed data, river width has been quantified using a variety of passive and active sensors since the early stages of the Landsat satellite program in the 1970s [*Rango and Salomonson*, 1974; *Watson*, 1991; *Smith et al.*, 1996, *Allen et al.,* 2013]. While remote sensing of channel width has generally covered single rivers or limited spatial extents, recognition of the potential for large-scale width measurement has recently led to regional and global studies [*Pavelsky, et al.*, in review*; Yamazaki, et al.,* in review*; Andreadis, et al.,* 2013].

The RivWidth software tool provides automated and spatially continuous channel width measurements from a variety of data sources at the native image resolution [*Pavelsky and Smith, 2008*]. In this study, we use RivWidth and the Landsat-based National Land Cover Dataset (NLCD) to quantify the spatial variability of river width at a constant-frequency discharge in the Mississippi River Basin and its major sub-basins (Figure 1). We then match width measurements with mean annual discharge values estimated from discharge-drainage area relationships to construct DHG relationships for the basin as a whole and for major sub-basins. Finally, we use our measured widths and estimated discharge values and *in situ* channel width, area, and discharge measurements from U.S. Geological Survey (USGS) streamflow gauging stations to estimate continuous mean channel depths using a multiple linear regression framework. With these high-resolution, spatially extensive datasets we both test the large-scale applicability of the power laws of downstream hydraulic geometry and create a dataset that replaces DHG-based estimates in many applications.

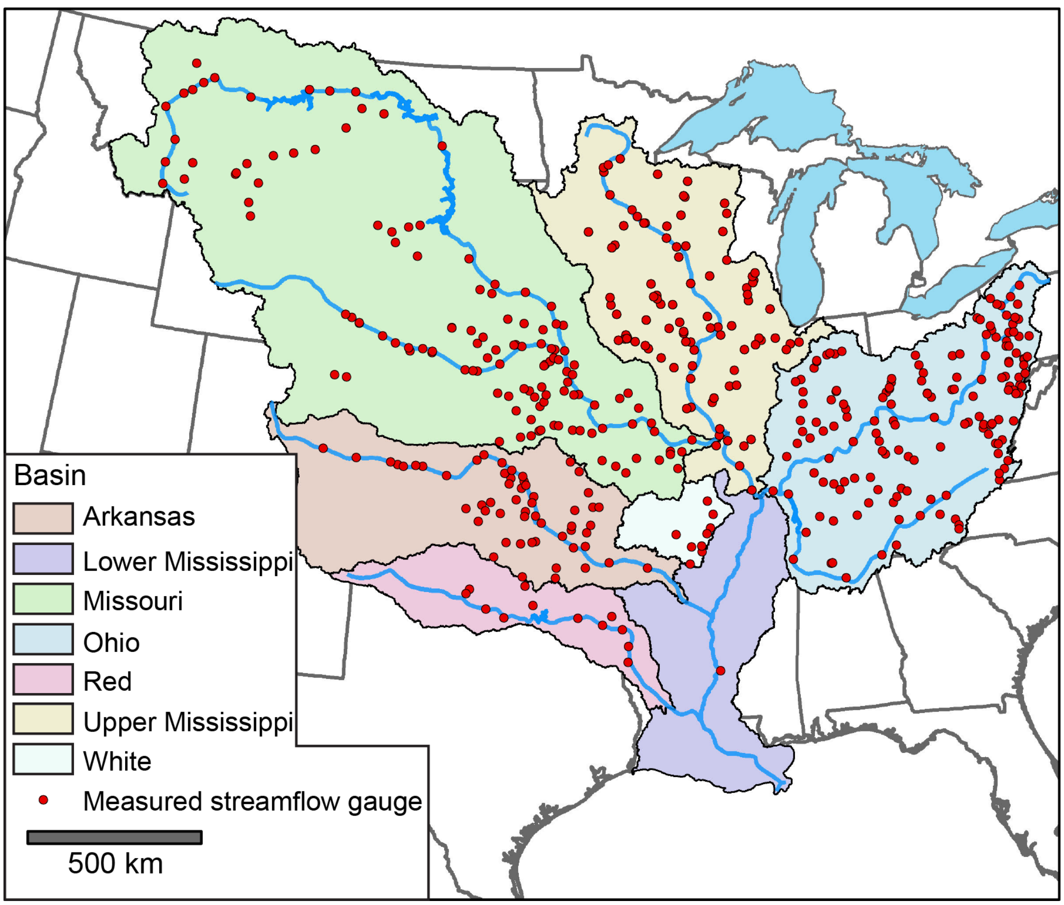

Figure 1: Major sub-basins of the Mississippi and USGS gauging stations used for width validation.

2. DOWNSTREAM HYDRAULIC GEOMETRY: A BRIEF REVIEW

The first studies of river form focused on quantifying equilibrium channel shapes in man-made canals that balanced discharge, width, and sediment load for engineering purposes [*Lacey*, 1930]. The modern framework of downstream hydraulic geometry was proposed by *Leopold and Maddock* [1953] to explain large-scale changes in channel form and applied to a range of natural rivers. Since then, the initial power-law relationships have been expanded to include sediment properties, slope, and shear stress [*Ferguson,* 1986*; Lee and Julien,* 2006]. In addition to hydrologic analyses of spatial changes in river from and flow, DHG is now commonly used in studies linking channel networks with formation of the landscapes they create [*Attal et al.,* 2008; *Tucker and Hancock*, 2010; *Allen et al.*, 2013].

Investigations of discharge and channel geometry show consistent relationships between width and increasing downstream flow. *Lacey* [1930] found width in stable canals to vary with the square root of discharge, while numerous subsequent analyses of natural channels obtained similar width exponents ($b \approx 0.5$, Equation 1a), as well as consistency in depth and velocity exponents ($f \approx 0.4$; $m \approx 0.1$, Equations 1b,c) [*Leopold and Maddock*, 1953; *Leopold and Miller,* 1956; *Stall and Fok*, 1968; *Moody and Troutman*, 2002; *Chaplin*, 2005]. Although these studies find similarity of DHG exponents across a wide range of river sizes and settings, coefficients *a*, *c*, and *k* vary for individual basins, regions, or spatial scales [*Leopold and Maddock*, 1953; *Moody and Troutman*, 2002]. While DHG relationships were initially empirical, observed consistency in exponents led to theoretical explanations based on minimum energy expenditure in conjunction with sediment transport and slope-area discharge methods like the Manning-Strickler formula [*Yang et al.*, 1981; *Ferguson*, 1986; *Molnar and Ramirez*, 2002; *Eaton and Church*; 2007; *Singh et al.*, 2003; *Singh*, 2003].

Other studies finding either substantial variation in DHG exponents or high variability in channel shape unrelated to discharge suggest that the framework sometimes fails to capture variations in river form. Exponents deviating substantially from previously assumed values are often related to variations in basin size, tectonic activity, bedrock lithology, channel vegetation, and levels of human influence [*Park*, 1977; *Klein*, 1981; *Montgomery and Gran*, 2001; *Montgomery*, 2004; *Piestch and Nanson,* 2011]. *Wohl* [2004] found evidence that "well-developed" DHG (defined as two of the three primary hydraulic variables having r^2 values greater than 0.5 in relation to discharge) exists where the stream power to sediment size ratio is high, implying that the erosive potential of a river relative to its bank strength governs its ability to adjust channel geometry to increasing flow. Finally, the framework of DHG does not provide for channel narrowing downstream, a characteristic observed in rivers crossing tectonic or lithologic discontinuities [*Harbor*, 1998; *Montgomery and Gran,* 2001; *Allen, et al., 2013*]. These deviations from DHG highlight its limitations in describing large-scale variations in river form.

Development of DHG relationships in a basin requires measurements of channel variables at constant-frequency discharge [*Leopold and Maddock*, 1953]. While bankfull discharge is often used in DHG studies because it approximates the dominant channel-forming flow [e.g. *Wolman*, 1955; *Leopold and Miller*, 1956; *Chaplin*, 2005*; Pietsch and Nanson*, 2011], other constant-frequency discharges such as mean annual discharge have also been used successfully [*Leopold and Maddock*, 1953; *Griffiths*, 1980; *Molnar and Ramirez*, 2002]. While mean annual flows are usually lower than channel-forming discharges, comparison of DHG exponents from a range of flow frequencies shows only minor variation [*Knighton*, 1974; *Griffiths*, 1980; *Ibbitt*, 1997].

3. DATA AND METHODS

3.1. Calculating river widths

The RivWidth software tool, described in detail by *Pavelsky and Smith* [2008], is an algorithm implemented in the IDL programming language that calculates a continuous sequence of river centerline pixels and channel width perpendicular to flow at each pixel. To extract river width data, the RivWidth software tool requires a binary image of inundation extent. Both the minimum river size measured and accuracy of RivWidth are highly dependent on the resolution of the imagery used. Previous studies have used inputs from MODIS, Landsat, and SPOT-5 satellite images [*Pavelsky and Smith*, 2008; *Smith and Pavelsky,* 2008; *Allen et al.*, 2013]. In this study, we use the open water classification from the U.S. Geological Survey's National Land Cover Dataset (NLCD). The NLCD is a continuous land cover classification based on tasseled cap transformations of Landsat 5 and 7 satellite imagery for three growing seasons [*Homer et al.*, 2004]. While ideal data for this study would include images from known periods of mean annual or bankfull discharge, we hypothesize that the NLCD water classification depicts rivers in an approximately mean discharge state because it represents an integration of river extent from early, peak, and late growing seasons. We test this hypothesis as described in sections 3.4 and 4.2. Although the extreme northernmost portion of the Mississippi Basin extends slightly outside the coverage of the NLCD into Canada, this area is not included in our analysis because the techniques used to classify open water would be inconsistent with the rest of the basin.

To prepare the NLCD water class for input into RivWidth, the open water classification was masked using the ENVI software suite (Figure 2a, 2b) and subset into major hydrologic regions as defined in the USGS's hydrologic unit code system [*Seaber et al.*, 1987]. These regions were then projected into the appropriate WGS 1984 UTM zone (Missouri/Arkansas-

Red—14N; Upper and Lower Mississippi—15N; Ohio—17N) and further divided into hydrologic accounting units (~3 x 10^4 km^2). To create as complete and continuous a dataset as possible, bridges and other small gaps were manually filled.

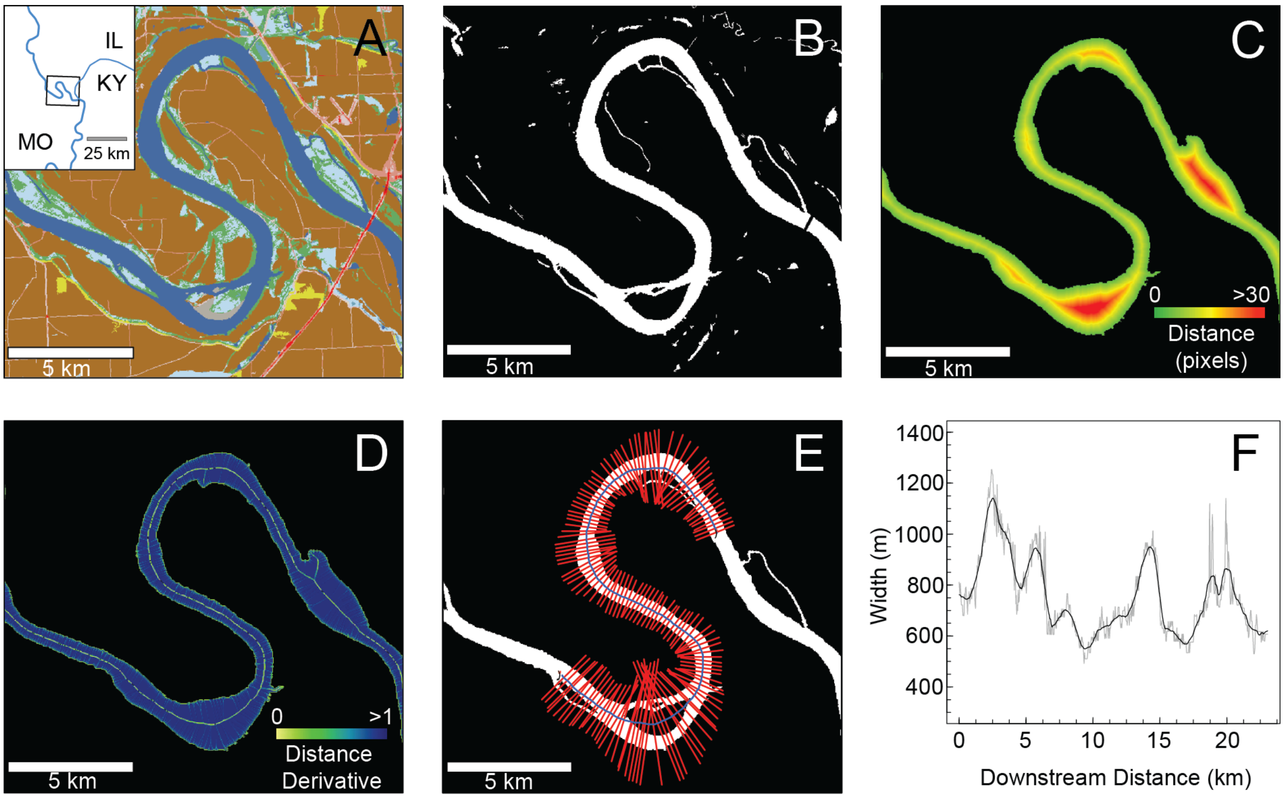

Figure 2: Inputs, intermediate steps, and products for calculation of river width in this study: A) National Land Cover Dataset; B) binary water mask of the open water classification; C) distance image based on a filled channel mask; D) derivative of distance image used to calculate the centerline; E) flow width measurements along orthogonal line segments to each centerline pixel; F) plot of raw (grey) and smoothed (black) continuous widths.

For each accounting unit, RivWidth then automatically executes five steps. It 1) creates a channel mask by removing water bodies not connected to the river channel; 2) fills in islands in the channel to create a mask of spatial river extent; 3) determines the distance from each river pixel to the nearest non-river pixel and calculates the derivative of the resulting distance image (Figure 2c, 2d); 4) determines the river centerline based on the derivative map, in which centerline pixels have values close to zero and all other river pixels have values of approximately one; and 5) calculates the flow width along a line segment orthogonal to the direction of flow at each centerline pixel (Figure 2e). For this study, start points and endpoints of 320 individual river segments were manually selected to exclude in-channel lakes and reservoirs. The final RivWidth output is a text file containing widths, the associated UTM coordinates, and the number of river channels in the cross-section. Further descriptions, updates and downloads are available from *Pavelsky and Smith* [2008] and at http://www.unc.edu/~pavelsky/.

3.2. Estimating river discharge

In addition to channel width, construction of DHG relationships requires knowledge of downstream changes in constant-frequency discharge. Because spatially continuous river discharge is not currently measurable, we use drainage area (A) as a proxy for flow. A linear relationship between discharge and contributing area is commonly assumed in studies of stream power, incision, and downstream hydraulic geometry in smaller basins [*Pazzaglia et al.*, 1998; *Montgomery and Gran*, 2001]. Drainage area was calculated for 318 channel segments by extracting river centerlines using USGS HydroSHEDS 3 arc-second (~90 m) digital elevation models and the hydrology tools in ArcGIS. Once DEM channels were delineated, we sampled flow accumulation rasters to determine drainage area at each pixel and re-projected the resulting pixel locations into the appropriate UTM zone for the respective basin. At small spatial scales the assumption of discharge-drainage area linearity often holds true, but for larger rivers this relationship may become nonlinear if the basin includes variations in topography, climate, or land use [*Stall and Fok*, 1968; *Galster et al.*, 2006; *Tague and Grant*, 2004]. We develop discharge-drainage area relationships using values of Q and A for all USGS stations of any drainage area with ≥10 years of approved mean annual discharge. Because discharge-drainage area scaling deviates from linearity over large spatial extents in some basins (Figure 3), we calculated least-squares linear regressions for each hydrologic accounting unit in the Ohio, Upper Mississippi, and much of the Missouri and Lower Mississippi basins. In 7 of the 34 accounting units in the Missouri, 12 of 22 in the Lower Mississippi, and all of the Arkansas basin (excluding the White River), lack of gauging stations, substantial precipitation variability, or large-scale water withdrawals precluded gauge-based discharge estimation.

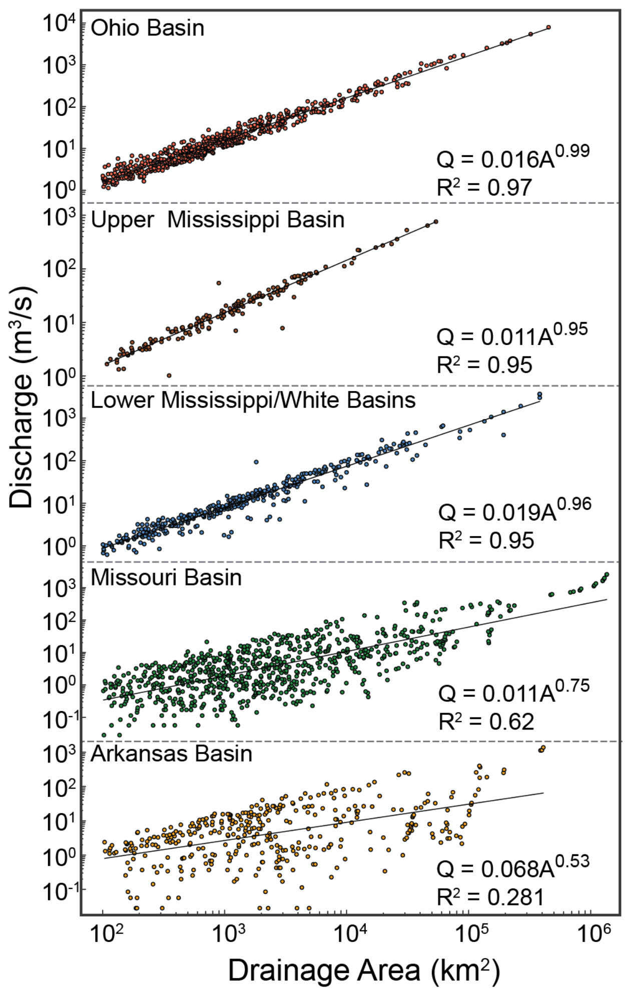

Figure 3: Discharge-drainage area relationships for sub-basins of the Mississippi; exponents close to one indicate a nearly linear fit in the Ohio, Upper and Lower Mississippi sub-basins, but there is substantial deviation from unity in the Missouri and Arkansas sub-basins.

3.3. Construction of downstream hydraulic geometry

Since RivWidth centerlines are based on higher resolution data than Hydrosheds streamlines, the two datasets are not always spatially coincident. Construction of width-drainage area relationships therefore required linking each RivWidth measurement to the nearest DEM pixel. Using the methodology developed by *Allen et al.* [2013], we assigned the nearest drainage area value to each RivWidth pixel (Figure 4). Although the two datasets match closely in comparatively steep channels in the mountainous areas towards the eastern and western boundaries of the basin, discrepancies of more than a kilometer are common in flatter terrain and for wider rivers. Once the two datasets were merged, we estimated discharge corresponding to width measurements using the discharge-drainage area relationships described in section 3.2.

To assess the applicability of Equation 1a in describing width-discharge relationships, we perform a least-squares linear regression of log-transformed width and discharge. Because the Mississippi basin contains broad ranges of topography, climate, and human influence, we investigate these relationships for all available RivWidth measurements and discharge estimates throughout the basin and individually for the Ohio, Upper Mississippi, and Missouri drainages.

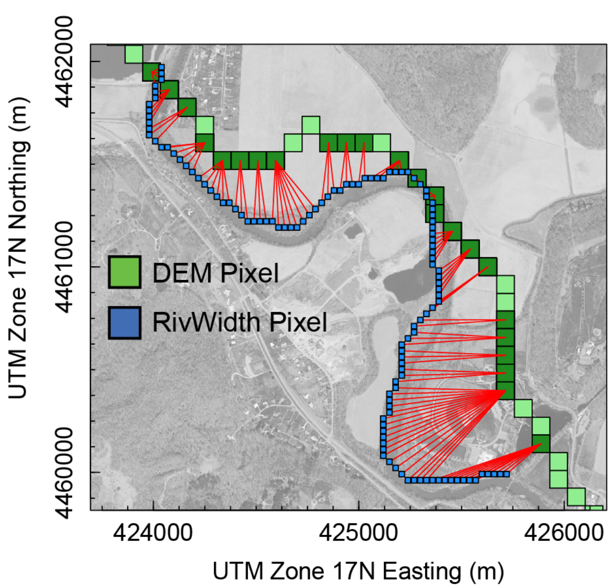

Figure 4: Linking RivWidth and DEM measurements; RivWidth measurements for the Walhonding River near Coshcocton, PA, matched to the nearest downstream DEM-derived channel pixels with drainage area values.

3.4. Width validation

To assess the accuracy of RivWidth measurements and the appropriateness of the NLCD for describing channel form at mean flows, we compared *in situ* USGS channel data corresponding to long-term mean annual discharges to validate width measurements. For many stations throughout the Mississippi Basin, the USGS measured width, depth, and velocities taken to develop discharge rating curves are available online [waterdata.usgs.gov/NWIS; *Juracek and Fitzpatrick*, 2009]. Although unpublished, these data have been used in investigations of channel geometry [*Bowen and Juracek*, 2011; *Stover and Montgomery*, 2001]. The number of measurements at each gauge location varies from fewer than ten to thousands across a range of flows. For each gauge, we estimated the width, depth, and velocity corresponding to mean annual discharge by calculating the mean value of all channel measurements acquired within +/- 10% of long-term mean annual discharge. Measurements that are clearly erroneous, listed as "poor" by the USGS, taken more than 60 m (two pixels upstream or downstream from the gauge location), or measured using a crane along a bridge not perpendicular to the river (therefore not representing true channel width) were removed. We then projected these gauge locations into UTM coordinates and calculated total error in our width measurements by comparing *in situ* gauge width from the 456 stations meeting our criteria against the mean of the five closest RivWidth measurements.

3.5. Depth estimation

We evaluated three methods of calculating spatial depth distributions, each using channel measurements from 358 USGS gauging stations in regions of the Missouri, Upper Mississippi, and Ohio Basins where both RivWidth measurements and DEM-based discharge estimates were available. First, we performed a multiple linear regression of log-transformed *in situ* depth against log-transformed *in situ* width and discharge measurements. We then used our measured widths and estimated discharge values to calculate depth at each pixel. In previous studies [e.g. *Alexander et al*, 2000] depth variations in large river basins have instead been estimated using traditional DHG relationships, and we develop such a relationship for the Mississippi to evaluate whether including river width as a variable improves depth estimates over previously used depth-discharge methods. We also estimate depth using the global depth-discharge equation developed by *Moody and Troutman* [2002]. Finally, we assess the effectiveness of including the influence of width in depth estimation by calculating the mean percentage error of all three depth estimates relative to USGS-measured depth values at the widest 151 gauging locations. Due to increasing uncertainty in RivWidth measurements and discharge estimations for smaller rivers, we limited this depth validation to rivers wider than 100 m.

4. Results

4.1. Measurement and distribution of river widths

Using the National Land Cover Dataset, we measured 1.194×10^6 individual channel widths representing 4.2×10^4 km of rivers in the Mississippi basin (Figure 5). Widths ranged from the minimum pixel size of 30 m to 7400 m in the inundated areas of the Upper Mississippi. This corresponds to an overall measured drainage density of ~0.013 km/km^2. Measurement count, length and density for each of the five sub-regions of the Mississippi are shown in Table 1. Overall distribution of river widths greater than 100 m and less than 1500 m (Figure 6) closely follows a negative power-law distribution:

$$n = 2.1\ x\ 10^9 W^{-1.9} \qquad (2)$$

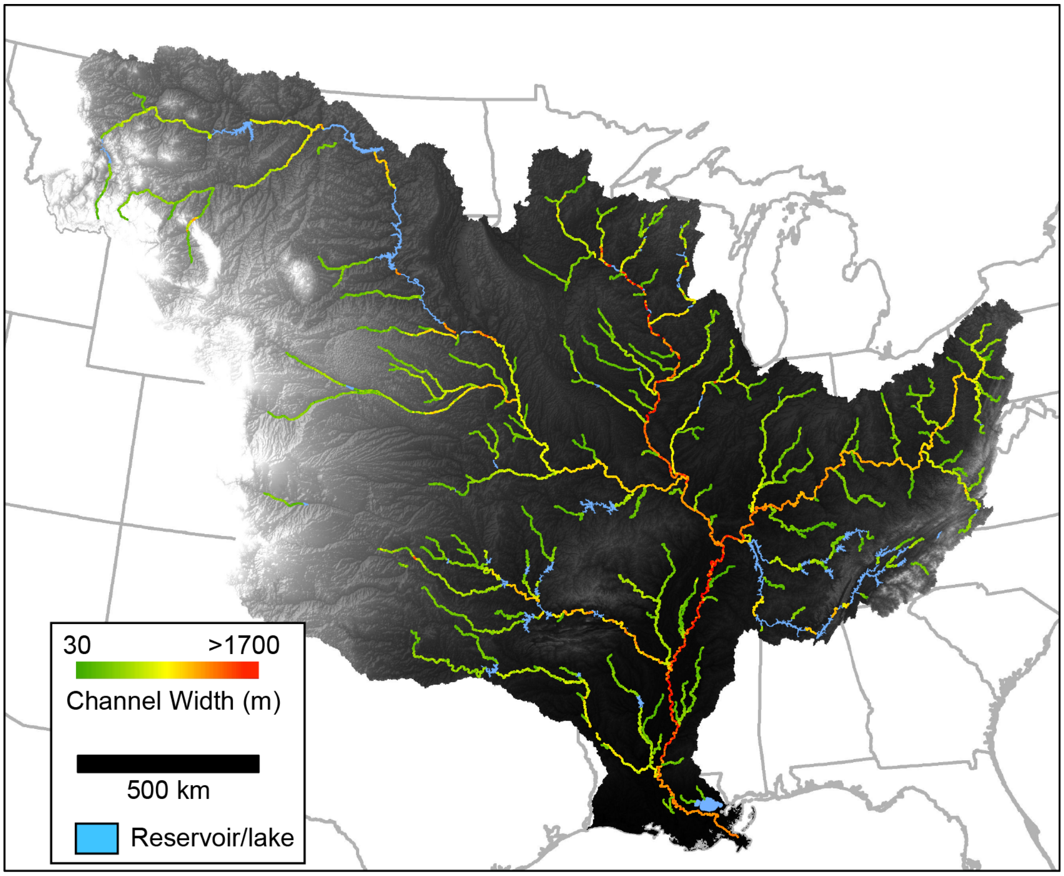

Figure 5: Mississippi River width map (shown with USGS HydroSHEDS DEM) of ~1.2 x 10^6 observations at 30 m resolution based on the NLCD open water classification.

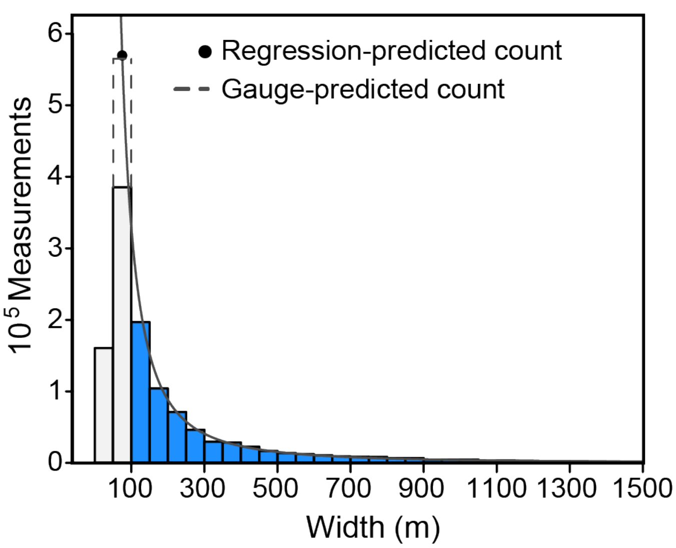

Figure 6: Width distributions for all rivers >100 m (blue bars) and many rivers < 100 m (grey bars); black circle represents measurements predicted by the 100-1500 m distribution regression (n=570,000, black line); dashed gray lines show estimated number of 50-100m rivers from the frequency distribution of USGS river gauges (n=565,000).

Table 1: Measurement coverage and density

Hydrologic Region	n	Length (km)	Density (km/km2)
Ohio-Tennessee	304685	10761	0.020
Upper Mississippi	223259	7872	0.016
Lower Mississippi	4819	4819	0.019
Arkansas-Red	218604	7699	0.012
Missouri	311029	10944	0.0081
Total	*1194000*	*42095*	*0.013*

To evaluate the completeness of this dataset and assess its accuracy, we downloaded historical channel measurements from 2,466 USGS streamflow gauges taken at long-term mean annual discharge. Of these, widths are greater than 30 m (the minimum width theoretically measurable) at 854 locations. Figure 7 shows the percentage of gauges measured in 10 m increments. Almost all (> 99%) gauge locations wider than 90 m are measured, while the most substantial decrease occurs as width falls below 60 m (two NLCD pixels). The failure to measure two 100 m gauges resulted from classification differences in the NLCD (e.g. woody wetlands rather than open water). At widths between 60 and 100 m, unmeasured stations are more common because not all channels in this size range are adequately visible in the NLCD for RivWidth to calculate an accurate river centerline. The rapid reduction in the percentage of gauges measured at less than 60 m is likely related to difficulties in classifying mixed land-water pixels, which will often represent the entire river as width decreases below twice the pixel resolution.

Because USGS gauge station data indicate that RivWidth measured ~68% of gauges 50-100 m, the actual number of channels this size in the basin is likely higher than the number we measured with RivWidth (Figure 7). Accounting for this discrepancy, the expected number of measurements for rivers 50 m-100 m wide is nearly identical to that predicted by equation (2)

(Figure 6). This suggests that although equation (2) is based on width measurements greater than 100 m, it may also describe the frequency distribution of widths narrower than 100 m.

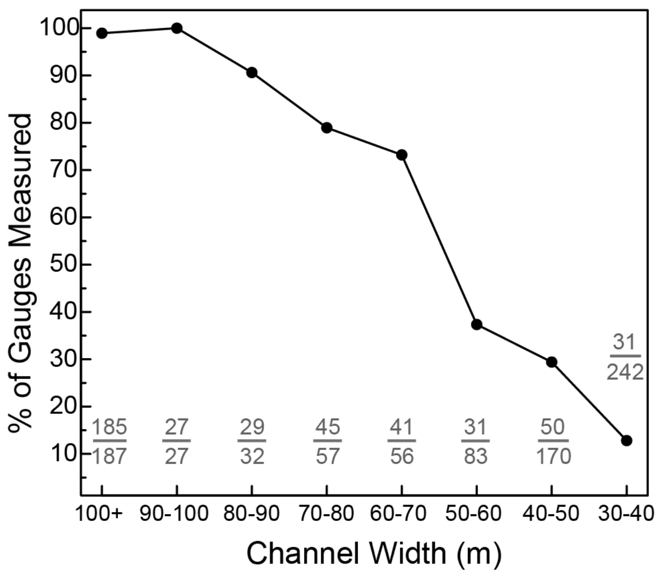

Figure 7: Percentage of USGS gauging stations measured in this study, binned by *in situ* channel width; grey fractions indicate number measured out of total gauges per 10-m width range.

4.2. Width measurement accuracy

Compared to widths at mean annual discharge from 456 gauging stations in the Ohio/Tennessee, Upper Mississippi, Missouri, and Arkansas regions, mean absolute width error (MAE) is 38 m (Figure 8). Because of high variability in USGS measurements and difficulty in distinguishing channels from inundated floodplains in the Lower Mississippi, gauging stations not on the main stem are excluded. Total mean and median errors of 20 m and 11 m indicate a slight positive bias in RivWidth measurements, although outliers with positive errors of more than 600 m skew these numbers substantially. This error can be partitioned into three groups: water mask misclassification, RivWidth error, and inaccuracies in USGS measurements. At gauging stations on the Mississippi River at Winona, MN and MacGregor, IA (Figure 9), RivWidth over-measured width by 1005 m and 848 m, respectively, because the NLCD classifies much of the adjacent floodplain as open water. At station 07157950 (Cimarron River near Buffalo, OK; Q = 3.2 m^3/s) USGS measurements of channel width at mean discharge of 26 m contrast with a RivWidth measurement of 651 m. Without these gauges, MAE is reduced to 33 m. While stations with $Q > 20$ m^3/s (n=379) show a relatively small positive bias of only 15 m, stations where $Q < 20$ m^3/s (n=77) have a positive bias of 41 m. This pattern is expected given that such small rivers approach the narrowest width discernable in 30 m input imagery. Classification of mixed pixels along banks also imparts a theoretical uncertainty of ½ the pixel resolution for each bank crossing (i.e. a minimum of 30 m for single-channel rivers at 30 m resolution; *Pavelsky and Smith*, 2008).

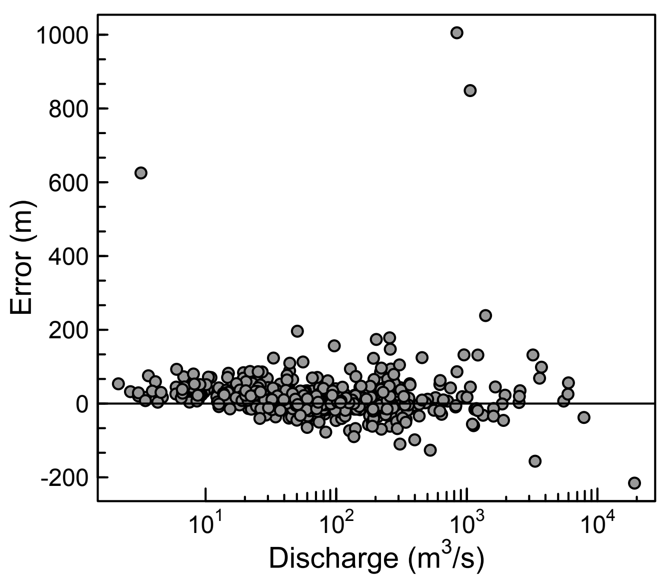

Figure 8: Width measurement error based on *in situ* channel measurements from 456 USGS streamflow gauging stations.

Inaccuracies associated with the measurement mechanics of RivWidth are limited to orthogonal angle errors. Uncertainty results from the predefined spacing of endpoints used to define orthogonals to each centerline pixel. In highly sinuous channels where centerlines change direction rapidly, over-measurement can occur when orthogonals are not truly perpendicular to the channel. Basin-wide error analysis of widths calculated with multiple endpoint spacings showed that inaccuracies are minimized when 11-pixel centerline segments are used, as we do here. Finally, although not quantifiable, error associated with US Geological Survey measurements is minimized through standardized data collection methods [*Buchanan and Somers*, 1969; *Rantz*, 1982] and the careful selection of stations as described in section 3.4.

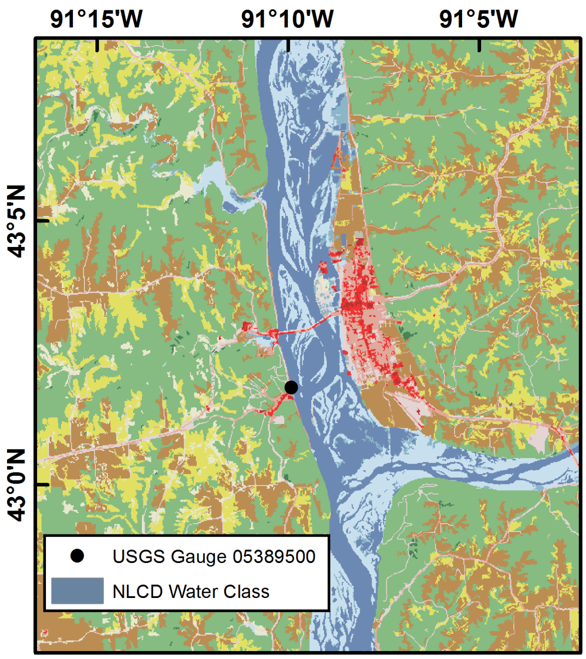

Figure 9: NLCD image of the Upper Mississippi River near MacGregor, IA; inundated floodplains are extensively connected to channels, leading to high width error.

4.3. Estimation of discharge

Using the methods described in section 3.2, we estimated discharge for rivers totaling 2.8 x 10^4 km in length and covering 2.2 x 10^6 km^2 of the Mississippi Basin. To assess discharge accuracy, we compared mean discharges from 346 gauging stations in the measured drainage area to the mean of the nearest 5 discharge estimations. Figure 10 shows the nearly 1:1 relationships between estimated discharge and gauge-measured discharge for individual sub-basins and for the entire Mississippi. Because ordinary least-squares linear regressions are greatly influenced by high-discharge outliers, we use the Theil-Sen median estimator [*Sen*, 1968] to derive robust linear regressions for each sub-basin (Table 2). We use the non-parametric Spearman's ρ to characterize goodness-of-fit, as discharges are not normally distributed. Regression slopes close to one and strong correlation between predicted and measured values indicate that estimates of discharge are likely accurate.

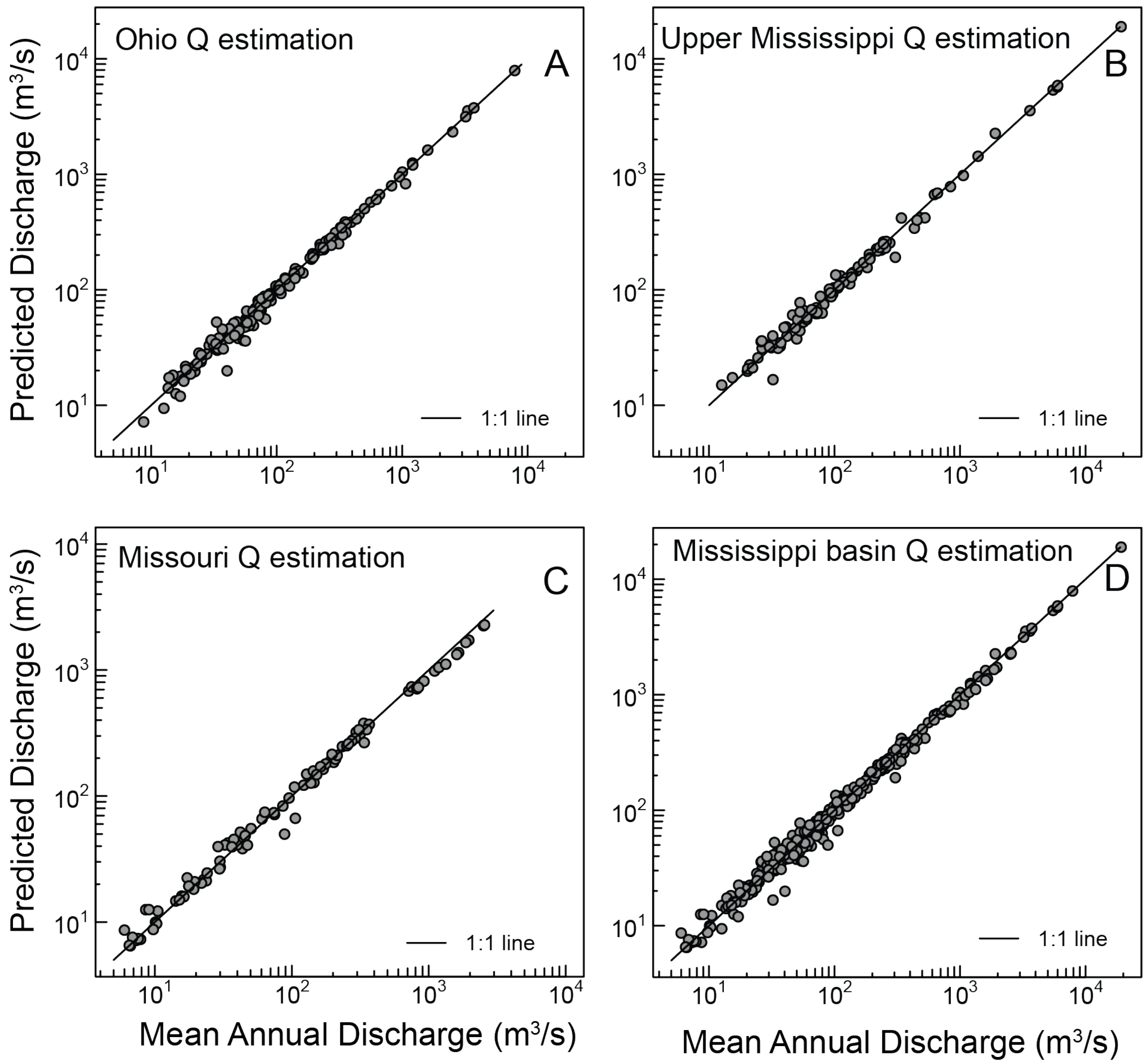

Figure 10: Estimated and USGS measured mean discharges for 346 gauging stations in the Mississippi basin.

Table 2: Estimated discharge-measured discharge regressions

	Ohio	**Upper Mississippi/ Lower main stem**	**Missouri**	***Total***
Regression	y=1.00x-0.59	y=0.98x+1.8	y=0.95x+2.0	y=0.98x+0.8
Spearman's ρ	0.99	0.99	0.99	0.99

4.4. Mississippi Basin downstream hydraulic geometry

Using spatially continuous discharge estimates, we construct width-discharge relationships for the Mississippi Basin and, separately, three of its major sub-basins (Figure 11a-d). Linear least-squares regression of log-transformed width and discharge for the 857,808 width measurements in the basin shows that their relationship can be described by the power-law equation:

$$w = 16.0Q^{0.43} \quad (r^2 = 0.62) \tag{3}$$

However, these values include 38654 discharge measurements less than 10 m^3/s, which represents a low discharge for a river greater than 30m wide. 89% (34573) of these low-discharge measurements are found in the Missouri sub-basin, where braided streams with high width-depth ratios are common. Of 38 USGS gauging station with mean discharge <10 m^3/s, width is overestimated in all with an mean bias of 52 m (Figure 8). It is then likely that basin-wide widths for discharges below 10 m^3/s are erroneously high. If we remove these anomalous measurements, the width DHG equation is:

$$w = 13.4Q^{0.46} \ (r^2 = 0.64) \tag{4}$$

These values of coefficient *a* and exponent *b* fall close to the range of values calculated for world rivers by Moody and Troutman (2002). However, individual sub-basins show substantial variation from these values, with exponents ranging from 0.3 in the Missouri to 0.63 for the Upper Mississippi (Figure 11). With the exception of the Missouri, variations in discharge account for > 50% of width variability (r^2 = 0.67 and 0.73 for the Upper Mississippi and Ohio), indicating that in those sub-basins changes in discharge are the primary control on downstream variations in width.

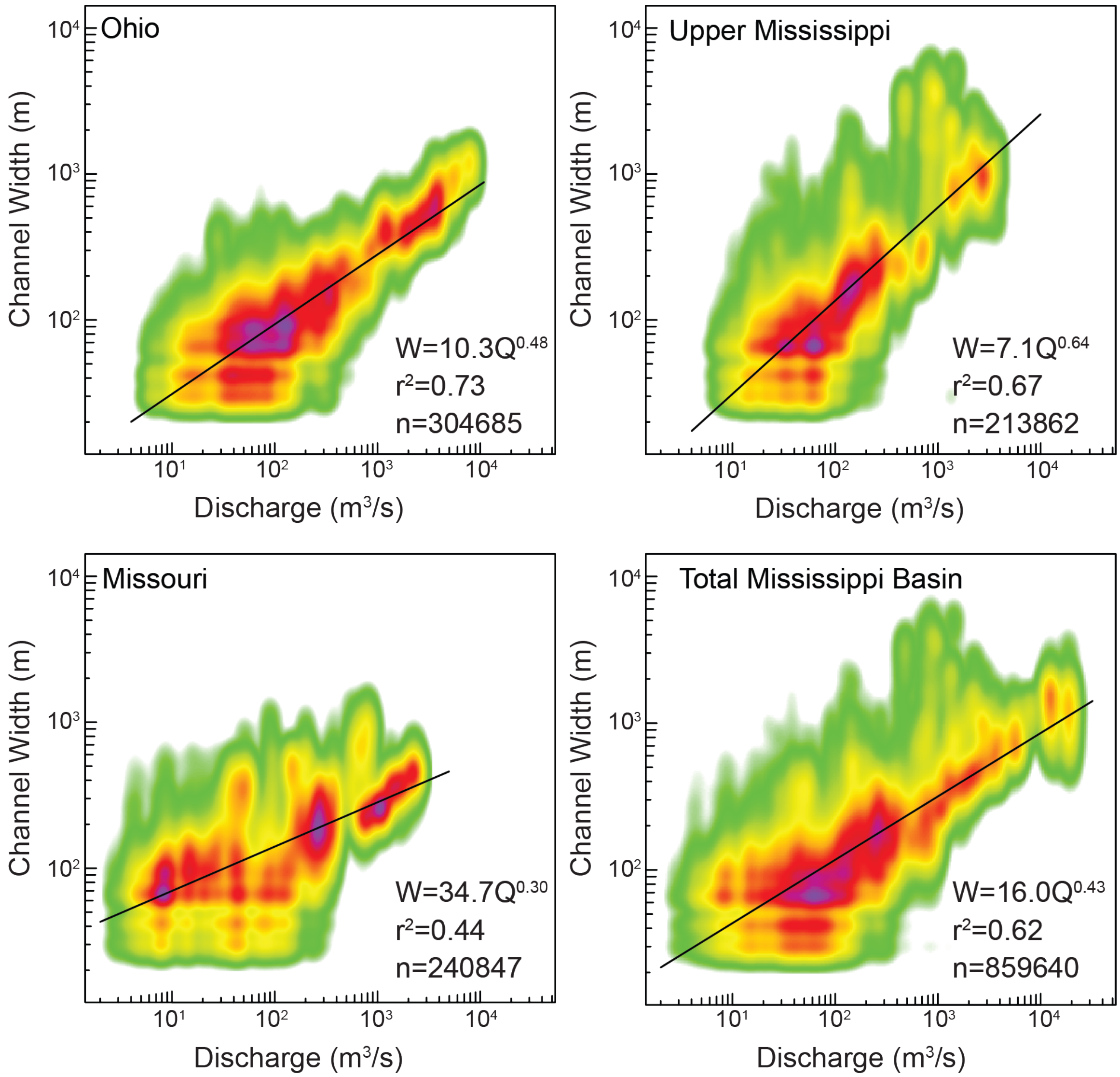

Figure 11: Density plots of width versus discharge for the Ohio, Upper Mississippi, Missouri, and entire Mississippi basin. Linear fits represent downstream hydraulic geometry relationships analogous to Equation 1a.

4.5. Estimating depth

Using channel measurements from all gauges located on streams measured by RivWidth with corresponding discharge estimates, we compared methods of estimating depth with and without width data. The first method is a simple least-squares linear regression of log-transformed depth and discharge from the gauge station dataset, which results in a power-law expression in the framework of downstream hydraulic geometry:

$$d = 0.18Q^{0.47} \quad (5)$$

The second method is a multiple linear regression of log-transformed depth against log-transformed discharge and width, which yielded the equation

$$\ln(d) = 0.44 - 0.82\ln(w) + 0.83\ln(Q) \quad (6)$$

Figure 12 shows depths calculated from equation 6 for the Ohio, Upper Mississippi, Missouri, and main stem of the Lower Mississippi using our estimated discharge and measured widths.

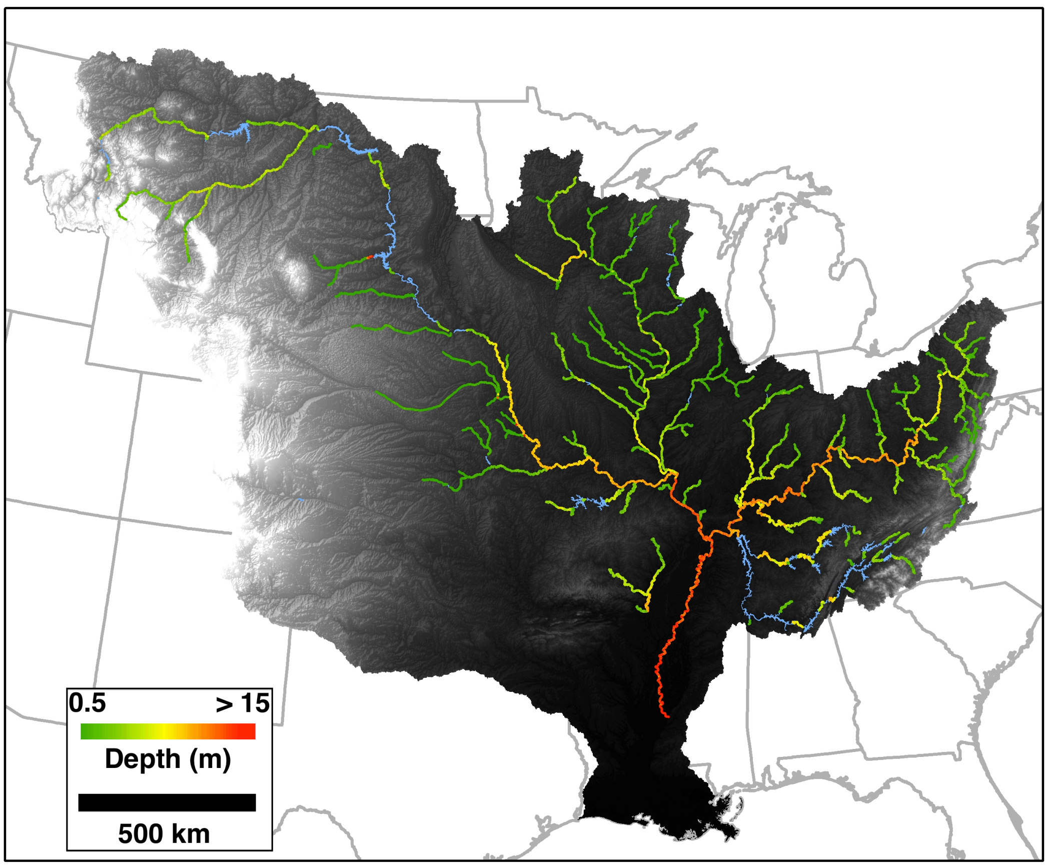

Figure 12: 8 x 10^5 mean depths in the Mississippi basin estimated using multiple regression of *d* against *Q* and *w*; lakes shown in blue.

Basin-wide mean depth error is 40% for the two DHG estimations, and 31% for the multiple regression method (Table 3). Figures 13a-b compare the percentage error of equation (6) to that of the two simple downstream hydraulic geometry relationships (Equation 5 and

Moody and Troutman [2002]). Although mean relative error is nearly identical in the Ohio and Upper Mississippi sub-basins, the two discharge-based methods both substantially overestimate depth for seven gauging stations along the Platte River in the Missouri sub-basin, leading to relative errors of 50%. The disparity between approaches in the Missouri accounts for the higher error of the discharge-based equations in the basin as a whole.

Table 3: Mean absolute depth errors (%)

Sub-basin	Equation 5	Equation 6	Moody-Troutman
Ohio	29%	29%	31%
Upper Mississippi	38%	36%	36%
Missouri	58%	30%	58%
Total	*41%*	*31%*	*41%*

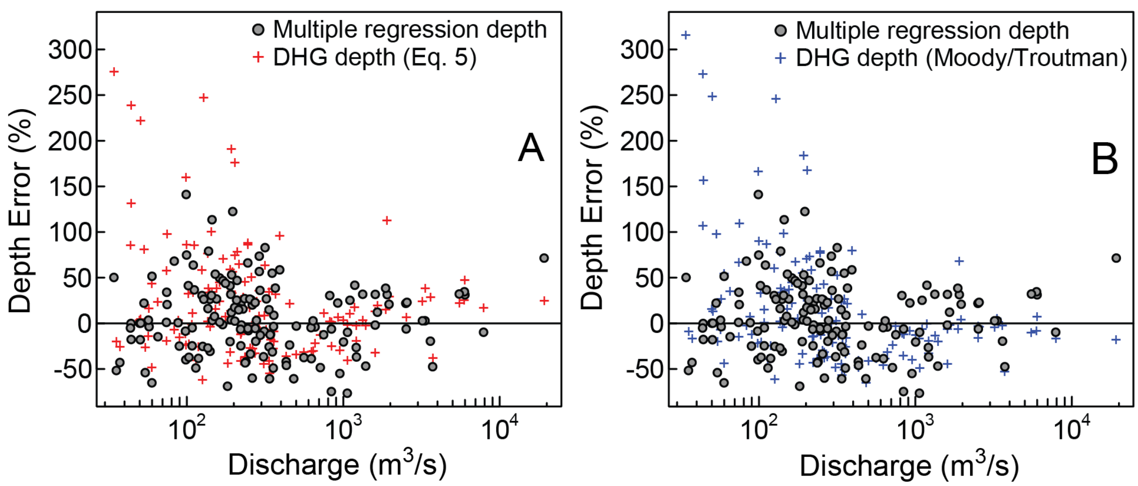

Figure 13: Relative depth error for multiple regression method (circles) and A) DHG estimate (this study); B) DHG estimate (Moody and Troutman, 2002).

5. Discussion and Conclusions

In this study, we present one of the first high-resolution, spatially continuous width datasets covering a continental-scale river basin. The utility of remote-sensing based measurement of channel geometry is increasingly recognized for both characterization of width-discharge relationships and applications for hydrologic modeling [*Pavelsky, et al.*, in review; *Yamazaki, et al.*, in review]. Construction of a width frequency distribution using 1.2 x 10^6 measurements (Equation 2) shows that Mississippi widths follow a power-law distribution comparable to that found by *Pavelsky et al.* [in review] for the 8.5 x 10^5 km^2 Yukon basin (n=1.778x10^9 $W^{(-1.831)}$). Similarities between these two basins—which represent highly contrasting geology, ecology, climate, and flow regimes—suggest that width distributions in other basins may follow similar patterns.

Basin-wide width-discharge relationships are characteristic of the downstream hydraulic geometry framework proposed by *Leopold and Maddock* [1953]. However, in the global analysis of *Moody and Troutman* [2002], changes in discharge account for >94% of width variation compared to 62% for the Mississippi basin in this study. While error inherent in the RivWidth dataset undoubtedly accounts for some of the higher width variability observed here, it seems unlikely that channel width corresponds as precisely to discharge as is shown in previous work. One explanation for this discrepancy is the widely-spaced and non-random site selection for *in situ* channel measurements. To facilitate accurate discharge measurements, USGS gauging station selection criteria suggest using straight channel segments located away from tributary junctions, with only one channel and easy access (*Rantz*, 1982). It is not unreasonable to assume that similar site selection bias exists for most *in situ* channel and discharge measurement locations. In particular, the measurement bias towards single-channel rivers in previous DHG studies using gauge data may explain the higher width variability observed in this dataset. Finally, previous investigations of DHG have used datasets incorporating a much wider range of discharges [e.g. *Moody and Troutman*, 2002] than the rivers used in this study, which may result in higher r^2 values for those width-discharge relationships.

Individual sub-basins demonstrate different levels of adherence to traditional downstream hydraulic geometry. Missouri sub-basin channel widths increase with discharge at a much lower rate (b=0.3) than has been found in previous studies (e.g. *Leopold and Maddock*, 1953; *Moody and Troutman*, 2002) with a much lower proportion of width variation explained by discharge increases (r^2=0.44). Conversely, the Ohio sub-basin closely matches previous findings (b=0.48; r^2=0.72). Several factors could explain this discrepancy. Multi-channel rivers are much more common in the Missouri sub-basin than in the Ohio; despite similar total measured lengths (Table 1) the Missouri contains nearly 2.5 times as many multi-channel measurements as the Ohio. While multiple channel crossings increase inherent RivWidth measurement error as explained in section 4.2, braided streams are also likely to show increased width variability in response to changes in climate and flow regime [*Schumm*, 2005]. The Missouri sub-basin also has some of the highest levels of human influence and control in North America, factors that can affect variability in channel form. In particular, dam construction has varied but pronounced effects on channel morphology [*Gregory*, 2006; *Williams and Wolman*, 2004]. *Williams* [1978] documented highly variable channel narrowing of the Platte River as it crosses the Great Plains due to upstream flow regulation. We believe human factors across the central section of the Missouri drainage lead to the high width variability and lower than expected increase in width with discharge observed in Missouri sub-basin.

Human influence also likely plays a role in the high b-value (0.64) observed in the Upper Mississippi sub-basin. In larger rivers—particularly along the main stem of the Mississippi—lock and dam control structures artificially widen the channel or connect it to secondary channels in its floodplain. Because of difficulties in differentiating the main stem of the Mississippi from ancillary channels and inundated floodplains that connect to the main channels in the NLCD, these features are included in the width-discharge dataset (Figure 9). While the high *b*-value may not represent the natural width changes, we believe it accurately describes present-day inundation extent along the Upper Mississippi more effectively than would a lower width exponent.

In sub-basins with well-developed width-discharge relationships, traditional depth-discharge DHG predicts depth well without inclusion of additional information on river width. In the Ohio and Upper Mississippi sub-basins, depth estimates based on the two *d-Q* relationships show similar accuracy to that of the multiple regression estimation that incorporates width (Equation 6). In the Missouri sub-basin, however, both traditional DHG methods substantially underestimate depth for wide, shallow rivers compared to the multiple regression analysis. Although basin-wide absolute error is not significantly reduced, consistent overestimation of depth for these rivers suggest that in applications where depths are based on downstream hydraulic geometry [e.g. *Alexander*, 2000], factoring width into depth estimations substantially reduces uncertainty in drainages like the Missouri that exhibit high width variability.

Potential errors from multiple sources must be addressed when studying channel form using remote sensing data. The largest sources of uncertainty in our Mississippi dataset are inherent to the input imagery. Because higher pixel resolution decreases classification error, increases total channel length, and decreases the size of smallest rivers measured, selecting appropriate input data is critical. Figure 7 indicates that all rivers greater than three times the pixel resolution and substantial numbers of smaller rivers are measured. While our results suggest that the NLCD represents an approximation of river extent close to mean discharge, there are clear instances where channels are wider than expected due to connectivity with the surrounding floodplain, misclassification of channel boundary pixels, or potential use of images taken during times of higher than mean flows. To reduce the error associated with the input water mask, future investigations should use a consistent and effective classification scheme on images taken during periods of the desired flow state. Finally, RivWidth must be configured properly, as the segment length used to calculate the orthogonal direction can create non-perpendicular cross-sections when poorly chosen (section 4.2).

Provided these sources of error are addressed, RivWidth offers the capability to measure river width at a high resolution over large basins with small and predictable error. Despite the importance of river form and flow, *in situ* river monitoring capabilities have declined over the last several decades [*Vorosmarty et al.*, 2001], highlighting the importance of remote sensing techniques that can produce high-resolution, spatially continuous observations of river channels over large areas [*Alsdorf et al.*, 2007]. Although significant challenges remain in combining remotely sensed channel observations into direct measurements of discharge, non-real time estimations of river flow relying on width measurement have been made [*LeFavour and Alsdorf*, 2004; *Smith and Pavelsky*, 2008]. As the most easily observable of the three primary dimensions of river discharge, understanding variations in width is a critical first step in characterizing discharge from remotely sensed data.

In addition to its importance in the direct measurement of discharge, remote sensing of river width contributes to the accuracy of hydrologic and hydraulic modeling. While width parameters are often characterized through empirically derived discharge relationships [e.g. *Yamazaki, et al.,* 2011, *Andreadis et al*., 2013], the utility of widths from satellite imagery in improving hydraulic modeling of river and floodplain dynamics is increasingly recognized [*Neal et al.*, 2012; *Schumann, et al.*, 2009]. Given growing interest in river modeling at continental and global scales and the importance of rivers in natural and human systems, this paper and its companion study [*Yamazaki, et al.,* in review] both contribute to the National Aeronautics and Space Administration's goal of measuring the spatial and temporal variability in Earth's surface water resources [*Fu, et al.*, 2012]. While *Yamazaki et al.* [in review] focuses on producing global-scale width measurements applicable to large-scale hydrodynamic modeling, this study creates a high-resolution channel geometry dataset including rivers as narrow as 30 m. These two products, combined with ongoing work to produce Landsat-derived width datasets globally, will allow for more accurate characterization of spatial variability in channel form than is currently afforded by empirically-derived estimation methods

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