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DEVELOPMENT OF REGIONAL CURVES FOR HYDROLOGIC LANDSCAPE REGIONS (HLR) IN THE CONTIGUOUS UNITED STATES[1]

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ABSTRACT: Regional curves relate drainage area to the bankfull channel characteristics discharge, cross-sectional area, width, and mean depth. These curves are used for a variety of purposes, including aiding in the field identification of bankfull elevation and in the natural channel design process. When developing regional curves, the degree to which landform, geology, climate, and vegetation influence stream systems within a single physiographic province may not be fully considered. This study examined the use of the U.S. Geological Survey's Hydrologic Landscape Regions (HLR), as well as data from 2,856 independent sites throughout the contiguous United States (U.S.), to develop a set of regional curves (bankfull discharge, cross-sectional area, width, and mean depth) for (1) the contiguous U.S., (2) each of the 20 HLRs, (3) each of the eight physiographic divisions, (4) 22 of the 25 physiographic provinces, and (5) individual HLRs within the physiographic provinces. These regional curves were then compared to each other, as well as those from the literature. Regional curves developed for individual HLRs, physiographic divisions, and physiographic provinces tended to outperform the contiguous U.S. indicating increased stratification was beneficial. Further stratifying physiographic provinces by HLR markedly improved regional curve reliability. Use of HLR as a basis of regional curve development, rather than physiographic region alone, may allow for the development of more robust regional curves.

(KEY TERMS: geomorphology; hydraulic geometry; hydraulic landscape unit; regional curve; restoration; rivers/streams; watershed management.)

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INTRODUCTION

Streams and their riparian or streamside buffers provide essential ecosystem services related to water quantity and quality such as water, sediment, nutrient and organic matter conveyance, nutrient cycling, filtration, temperature modification, and habitat provision for aquatic and terrestrial organisms (Vannote *et al.*, 1980; Meyer and Wallace, 2001; Gomi *et al.*, 2002; Alexander *et al.*, 2007; Meyer *et al.*, 2007). Larger order streams as well as smaller headwater channels (*e.g.*, 1st–3rd order) provide these ecosystem services (Vannote *et al.*, 1980; Nadeau and Rains, 2007). When streams and their watersheds are impacted by anthropogenic disturbances (*e.g.*, agriculture, urbanization, and mining), the ability of these waterways to provide ecosystem services is reduced if not lost (Knopf *et al.*, 1988; Pond *et al.*, 2008; Fritz *et al.*, 2010; USEPA, 2011). The USEPA (2015) estimated that of the nearly 1.8 million

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kilometers of assessed rivers and streams in the United States (U.S.), over 55% were classified as threatened or impaired with regard to their designated uses.

In an effort to help reduce the net loss of streams and their ecosystem services as a result of anthropogenic impacts, federal and state agencies fund stream restoration projects (Bernhardt *et al.*, 2005; Hough and Robertson, 2009). These stream restoration projects serve as a means of compensatory mitigation to help offset unavoidable impacts to waters of the U.S. (33 CFR Part 332). Stream restoration involves the reestablishment of a stream's structure and function (*e.g.*, hydrologic, geomorphic, and ecologic) as closely as possible to predisturbance conditions (NRC, 1992; Shields *et al.*, 2003; Bennett *et al.*, 2013). This approach typically involves the reconstruction of the stream's dimensions, pattern, and profile as guided by reference conditions (Rosgen, 1996; Hey, 2006; Beechie *et al.*, 2010; Brockman *et al.*, 2012). Bernhardt *et al.* (2005) estimated that over 37,000 stream restoration projects were undertaken between 1990 and 2003, most at a small scale (<1 km stream length), and at a cost of more than $1 billion per year. During this period, Bernhardt *et al.* (2005) noted that the profession of stream restoration experienced exponential growth, and with the requirement for compensatory mitigation, this rate of growth is expected to continue (Cunningham, 2002).

Developing a stream restoration design, such as through natural channel design techniques, is an iterative process that often begins by identifying the appropriate bankfull discharge and bankfull channel dimensions such as cross-sectional area, width, and mean depth in the riffles, predominately in perennial streams, with the aid of regional curves (Doll *et al.*, 2003; Hey, 2006; USDA-NRCS, 2007). Regional curves relate these bankfull channel characteristics (*i.e.*, dependent variable) to drainage area (*i.e.*, independent variable) and can provide designers with (1) tools to help identify bankfull elevation in the field such as when bankfull indicators are absent or infrequent (Castro and Jackson, 2001; Metcalf *et al.*, 2009; Brockman *et al.*, 2012) and (2) a basis for stream assessment and design (Hey, 2006; USDA-NRCS, 2007). Similar to hydraulic geometry curves (Leopold and Maddock, 1953), regional curves (Dunne and Leopold, 1978) are of the form:

$$Q_{\mathrm{bkf}} = aA_w{}^b \tag{1}$$

$$A_{\mathrm{bkf}} = cA_w{}^d \tag{2}$$

$$W_{\mathrm{bkf}} = gA_w{}^h \tag{3}$$

$$D_{\mathrm{bkf}} = jA_w{}^k \tag{4}$$

The variable A_w represents drainage area (km^2), Q_{bkf} is bankfull discharge (m^3/s), A_{bkf} is bankfull cross-sectional area (m^2), W_{bkf} is bankfull width (m), D_{bkf} is bankfull mean depth (m), and the coefficients a, c, g, and j as well as the exponents b, d, h, and k are empirically derived values used to fit the data (Dunne and Leopold, 1978).

Regional curves are typically developed for a single physiographic province meaning an area with similar landform (Fenneman, 1917) such as Piedmont of North Carolina (Harman *et al.*, 1999), Valley and Ridge of Maryland, Virginia, and West Virginia (Keaton *et al.*, 2005), Florida Coastal Plain (Metcalf *et al.*, 2009), or Inner and Outer Bluegrass Regions of Kentucky (Brockman *et al.*, 2012). Bieger *et al.* (2015) compiled data from over 50 studies representing 1,566 sites to develop regional curves for each of the eight physiographic divisions as well as 22 of the 24 physiographic provinces in the U.S. The degree to which geology (*e.g.*, karst *vs.* nonkarst), climate (*e.g.*, rainfall patterns), and vegetation (*e.g.*, forest *vs.* grassland) influence stream systems within a single physiographic province may not be considered when developing regional curves. While studying bankfull discharge recurrence intervals in the Pacific Northwest, Castro and Jackson (2001) found that the regional factors climate and ecoregion influenced the frequency of bankfull discharge, indicating such factors should be considered when developing regional curves. Johnson and Fecko (2008) compared regional curves from six physiographic provinces (Appalachian Plateau, Blue Ridge, Coastal Plain, New England, Piedmont, and Valley and Ridge) located in the eastern U.S. on the basis of bankfull width. The authors found that the bankfull width regional curves from the Appalachian Plateau, New England, and Valley and Ridge physiographic provinces were similar while those from the Blue Ridge, Coastal Plain, and Piedmont differed. Using data from the U.S. Environmental Protection Agency's National Wadable Stream Assessment, Faustini *et al.* (2009) developed downstream hydraulic geometry relationships for 18 hydrologically defined physiographic regions (Seaber *et al.*, 1987) as well as nine aggregate ecoregions (Omernik, 1987) in the conterminous U.S. Similar to regional curves, hydraulic geometry curves relate the bankfull dimensions cross-sectional area, width, and depth to bankfull discharge rather than to drainage area. However, to use hydraulic geometry curves, knowledge of bankfull discharge is required. For ungaged streams, bankfull discharge is often estimated, using Manning's equation (Chow, 1959; Doll *et al.*, 2002), a process that can produce significant error (Sefick *et al.*, 2015). Faustini *et al.* (2009) found that hydraulic geometry equations developed for these large regions offered a good first approximation of channel width, more so in the eastern U.S. than in the western portion. If multiple changes in topography, geology, and climate were present within a larger geographic region, the authors recommended subdividing the region into smaller units over which to develop separate hydraulic geometry curves. This recommendation, to subdivide the landscape based on topographic, geologic, and climate characteristics, has merit in regional curve development (Troch *et al.*, 2015; Blöschl, 2016). Landscape features, such as slope and geologic material, influence a stream's morphology (Rosgen, 1994; Montgomery and Gran, 2001; Allan, 2004; Wohl and David, 2008).

Hydrologic Landscape Units (HLUs) are one method of further dividing large geographic regions into smaller more homogenous ones on the basis of the movement of water as driven by landform (surface water), geology (groundwater), and climate (atmospheric water) (Winter, 2001). Using geographic information system (GIS) tools and multivariate statistical analyses (principal component and cluster analysis), Wolock *et al.* (2004) separated the U.S. into 20 Hydrologic Landscape Regions (HLRs) on the basis of similar hydrologic characteristics as related to land-surface form, geology, and climate for watersheds approximately 212 km^2 in size (Table 1). Land-surface form characteristics included topographic relief, minimum elevation, total flat land (<1% slope), flat land in the lowland portions of the watershed, and flat land in the upland portions of the watershed. Geologic characteristics included soil permeability, which was estimated based on percentage of sand in the soil, and bedrock permeability based on general lithologic groups. Climatic characteristics included mean annual precipitation, mean annual evapotranspiration, mean annual temperature, and mean annual precipitation minus mean annual evapotranspiration. HLRs more similar in number exhibit more similar land-surface form, geologic, and climatic characteristics. For example, HLR 1 is very similar to HLR 2 but is very dissimilar to HLR 20. Important to note is that a single HLR may be found in the northern, southern, eastern, and/or western portions of the U.S., as seen with HLR 16. HLR 16, as described by Wolock *et al.* (2004), is characterized as "humid mountains with permeable soils and impermeable bedrock" and is found along the western section of the Appalachian Mountains (*e.g.*, Georgia, Kentucky, Pennsylvania, Tennessee, Virginia, and West Virginia), portions of New England (*e.g.*, Maine, New Hampshire, New York, and Vermont), portions of the northwest coast (*e.g.*, California and Oregon), and even portions of Arkansas. Furthermore, multiple HLRs may occur within a small area as seen in Figure 1.

Separation of the landscape based on HLUs has proven useful in predicting shallow groundwater flow and modeling the effects of climate change on streamflow. Santhi *et al.* (2008) found the descriptive variables relief, percent sand, and effective rainfall, which offer a means of differentiating between HLUs, are useful in predicting mean shallow groundwater

TABLE 1. Hydrologic Landscape Region (HLR) Descriptions and Hydrologic Responses as Presented in Wolock *et al.* (2004).

HLR	Description	Surface Flow Response	Groundwater Flow Response
1	Subhumid plains with permeable soils and bedrock		X
2	Humid plains with permeable soils and bedrock		X
3	Subhumid plains with impermeable soils and permeable bedrock	X	
4	Humid plains with permeable soils and bedrock		X
5	Arid plains with permeable soils and bedrock		X
6	Subhumid plains with impermeable soils and bedrock	X	
7	Humid plains with permeable soils and impermeable bedrock		X
8	Semiarid plains with impermeable soils and bedrock	X	
9	Humid plateaus with impermeable soils and permeable bedrock	X	
10	Arid plateaus with impermeable soils and permeable bedrock	X	
11	Humid plateaus with impermeable soils and bedrock	X	
12	Semiarid plateaus with permeable soils and impermeable bedrock		X
13	Semiarid plateaus with impermeable soils and bedrock	X	
14	Arid playas with permeable soils and bedrock		X
15	Semiarid mountains with impermeable soils and permeable bedrock	X	
16	Humid mountains with permeable soils and impermeable bedrock		X
17	Semiarid mountains with impermeable soils and bedrock	X	
18	Semiarid mountains with permeable soils and impermeable bedrock		X
19	Very humid mountains with permeable soils and impermeable bedrock		X
20	Humid mountains with permeable soils and impermeable bedrock		X

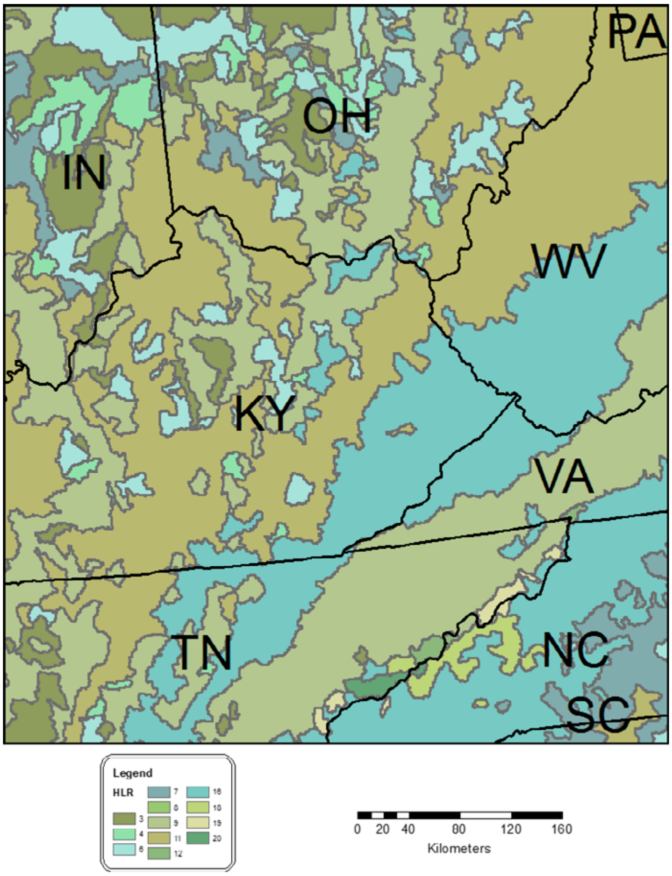

FIGURE 1. Multiple Hydrologic Landscape Regions (HLRs) May Occur within a Relatively Small Area Commonly Thought to Represent a Single Physiographic Region; These HLRs May Be Quite Different. IN, Indiana; OH, Ohio; KY, Kentucky; NC, North Carolina; PA, Pennsylvania; SC, South Caroline; TN, Tennessee; VA, Virginia; WV, West Virginia.

flow. Leibowitz *et al.* (2014) used the hydrologic landscape classification, developed for Oregon by Wigington *et al.* (2012), to evaluate climate change scenarios on three case study basins in Oregon. The authors concluded that a main advantage of using HLUs is the application of their model to ungaged basins of similar classification.

The objectives of this study were to (1) develop a set of regional curves for the contiguous U.S., each physiographic division, each physiographic province, each HLR, and individual HLRs within each physiographic province, and to (2) compare these developed regional curves and evaluate their accuracy in predicting bankfull channel dimensions. All regional curves were developed and compared within the framework of the contiguous U.S. Previously published regional curves tend to focus on individual physiographic regions (*e.g.*, Valley and Ridge) largely using landform as a basis for site selection when in fact a single physiographic region may contain multiple distinct and dissimilar HLRs. Based on work by Faustini *et al.* (2009) and Bieger *et al.* (2015), it is hypothesized that regional curves developed over more homogenous landscapes and climates will enable better predictions of bankfull channel dimensions (*i.e.*, regional curves for each HLR within each physiographic province will yield more reliable predictions than regional curves developed for the contiguous U.S.). HLR-based regional curves (*i.e.*, individual regional curves for each HLR) could serve as a basis for stream assessment and restoration design procedures in areas lacking acceptable stream sites from which to develop regional curves, such as in the case of an area that has experienced a large number of land disturbance activities.

METHODOLOGY

Dataset Description

Drainage area along with the bankfull parameters discharge, cross-sectional area, width, and mean depth for 3,466 sites were collected from 65 published studies. The majority of the sites (90%) were obtained from peer-reviewed journal articles or government documents. The remaining 10% of the sites were from nonrefereed conference proceedings or reports developed by consulting agencies. Sites were excluded from the dataset if latitude and longitude information were not provided or could not be determined based on a referenced U.S. Geological Survey (USGS) gaging station that was located in close proximity to the site. A total of 610 sites (18%) were excluded from the dataset leaving 2,856 for analysis (Table 2). The analysis was limited to single-threaded streams and streams with little or no urban land use within the watershed. The site selection criteria described in each source were examined prior to inclusion of data from the respective sources in this study. Sites which were identified as impacted were not used in the study.

Using ArcMap 10.1, the regional curve dataset was separated based on HLR, physiographic division, and physiographic region (Fenneman and Johnson, 1946; USGS, 1998; Wolock *et al.*, 2004) (Tables 2-3; Figure 2). The contiguous U.S. contains 20 HLRs. Each HLR is comprised of a number of small watersheds (approximately 212 km^2) deemed hydrologically similar (USGS, 1998). The HLR shapefile was obtained from http://water.usgs.gov/GIS/metadata/usgswrd/XML/hlrus.xml. Fenneman and Johnson (1946) divided the contiguous U.S. into eight physiographic divisions (Appalachian Highlands, Atlantic Plain, Interior Highlands, Interior Plains, Intermontane Plateau, Laurentian Upland, Pacific Mountain System, and

TABLE 2. Summary of Studies Used to Compile the Dataset as Separated by HLR.

HLR	No. of Sites	Studies
1	44	Eash (1993), McCandless (2003b), Metcalf *et al.* (2009), Rachol and Boley-Morse (2009), Sweet and Geratz (2003), USEPA (2006)
2	83	Bent and Waite (2013), Castro and Jackson (2001), Doll *et al.* (2003)[1], Emmert (2004)[1], Krstolic and Chaplin (2007), McCandless (2003b), Metcalf *et al.* (2009), Mistak and Stille (2008), Parola *et al.* (2007)[1], Parrett *et al.* (1983), Rachol and Boley-Morse (2009), Robinson (2013), Sweet and Geratz (2003), USEPA (2006), Williams (1978), Yochum (2003)
3	82	Brockman *et al.* (2012), Castro and Jackson (2001), Chaplin (2005), Doll *et al.* (2003)[1], Dutnell (2000)[1], Eash (1993), Emmert (2004)[1], Keaton *et al.* (2005), Lawrence (2003)[1], Mulvihill *et al.* (2007), Parola *et al.* (2007)[1], Robinson (2013), Sherwood and Huitger (2005), Sweet and Geratz (2003), USEPA (2006)
4	115	Bent and Waite (2013), Chaplin (2005), Cinotto (2003), Doll *et al.* (2003)[1], Dutnell (2000)[1], Eash (1993), Krstolic and Chaplin (2007), Lotspeich (2009), McCandless (2003b), McCandless and Everett (2002), Metcalf *et al.* (2009), Mulvihill *et al.* (2005, 2006), Mulvihill and Baldigo (2007), Mulvihill *et al.* (2009), Padmanabhan and Johnson (2010), Rachol and Boley-Morse (2009), Robinson (2013), Sherwood and Huitger (2005), Sweet and Geratz (2003), USEPA (2006), White (2001), Williams (1978)
5	40	Castro and Jackson (2001), Dutnell (2000)[1], Emmert (2004)[1], Padmanabhan and Johnson (2010), Parrett *et al.* (1983), USEPA (2006), Williams (1978), Yochum (2003)
6	138	Brockman *et al.* (2012), Doll *et al.* (2002), Dutnell (2000)[1], Eash (1993), Emmert (2004)[1], Harman *et al.* (1999)[1], Jaquith and Kline (2006), Lotspeich (2009), Mater *et al.* (2009)[1], Mulvihill *et al.* (2006, 2009), Padmanabhan and Johnson (2010), Parola *et al.* (2005)[1], Parola *et al.* (2007)[1], Parrett *et al.* (1983), Rachol and Boley-Morse (2009), Robinson (2013), Sherwood and Huitger (2005), Tetra Tech (2004)[1], USEPA (2006)
7	141	Bent and Waite (2013), Chaplin (2005), Cinotto (2003), Doheny and Fisher (2007), Doll *et al.* (2002), Dudley (2004), Dutnell (2000)[1], Eash (1993), Harman *et al.* (1999)[1], Haucke and Clancy (2011), Lotspeich (2009), McCandless and Everett (2002), Mistak and Stille (2008), Mulvihill and Baldigo (2007), Pruitt (2001)[1], Rachol and Boley-Morse (2009), Robinson (2013), Tetra Tech (2004)[1], USEPA (2006)
8	102	Castro and Jackson (2001), Dutnell (2000)[1], Eash (1993), Haucke and Clancy (2011), Omang *et al.* (1983), Padmanabhan and Johnson (2010), Parrett *et al.* (1983), Tetra Tech (2004)[1], USEPA (2006), Williams (1978)
9	279	Babbit (2005)[1], Bent and Waite (2013), Brockman *et al.* (2012), Castro and Jackson (2001), Chang *et al.* (2004)[1], Chaplin (2005), Dutnell (2000)[1], Eash (1993), Harman *et al.* (2000)[1], Jaquith and Kline (2006), Keaton *et al.* (2005), Lawrence (2003)[1], McCandless (2003a), McPherson (2011)[1], Messinger (2009), Mulvihill *et al.* (2006, 2007), Parola *et al.* (2005)[1], Parola *et al.* (2007)[1], Parrett *et al.* (1983), Robinson (2013), Sherwood and Huitger (2005), USEPA (2006), Vesely *et al.* (2008)[1], Williams (1978)
10	34	Castro and Jackson (2001), Dutnell (2000)[1], Lawlor (2004), Parrett *et al.* (1983), USEPA (2006)
11	182	Brockman *et al.* (2012), Chang *et al.* (2004)[1], Chaplin (2005), Cinotto (2003), Doll *et al.* (2002), Dudley (2004), Eash (1993), Harman *et al.* (1999)[1], Haucke and Clancy (2011), Lotspeich (2009), Mater *et al.* (2009)[1], McCandless and Everett (2002), Messinger (2009), Mulvihill *et al.* (2005), Parola *et al.* (2005)[1], Parola *et al.* (2007)[1], Pugh *et al.* (2008), Robinson (2013), Sherwood and Huitger (2005), USEPA (2006), Vesely *et al.* (2008)[1], White (2001), Williams (1978)
12	133	Andrews (1984), Castro and Jackson (2001), Emmett (1975), Foster (2012), Howell (2009)[1], King *et al.* (2004), Lawlor (2004), Lotspeich (2009), Mulvihill *et al.* (2007), Omang *et al.* (1983), Parrett *et al.* (1983), USEPA (2006), Williams (1978), Yochum (2003)
13	176	Andrews (1984), Castro and Jackson (2001), Emmett (1975), Haucke and Clancy (2011), McCandless and Everett (2002), Mulvihill *et al.* (2007), Omang *et al.* (1983), Parrett *et al.* (1983), USEPA (2006), Williams (1978)
14	73	Foster (2012), Lawlor (2004), Parrett *et al.* (1983), USEPA (2006), Williams (1978)
15	101	Castro and Jackson (2001), Emmett (1975), King *et al.* (2004), Lawlor (2004), Parrett *et al.* (1983), USEPA (2006), Williams (1978)
16	379	Babbit (2005)[1], Bent and Waite (2013), Castro and Jackson (2001), Chaplin (2005), Cinotto (2003), Dudley (2004), Dutnell (2000)[1], Harman *et al.* (2000)[1], Haucke and Clancy (2011), Jaquith and Kline (2006), Keaton *et al.* (2005), Lawrence (2003)[1], McCandless (2003a), McCandless and Everett (2002), Messinger (2009), Mulvihill *et al.* (2005, 2006), Mulvihill and Baldigo (2007), Mulvihill *et al.* (2007, 2009), Parola *et al.* (2005)[1], Robinson (2013), Sherwood and Huitger (2005), USEPA (2006), Vesely *et al.* (2008)[1], Westergard *et al.* (2004), White (2001), Williams (1978)
17	217	Castro and Jackson (2001), Dutnell (2000)[1], Elliott and Cartier (1986), Emmett (1975), Foster (2012), Lawlor (2004), Omang *et al.* (1983), Parrett *et al.* (1983), USEPA (2006), Williams (1978), Yochum (2003)
18	385	Andrews (1984), Castro and Jackson (2001), Emmett (1975), Foster (2012), Harman *et al.* (2000)[1], Howell (2009)[1], King *et al.* (2004), Lawlor (2004), Mulvihill *et al.* (2007), Omang *et al.* (1983), Parrett *et al.* (1983), USEPA (2006), Williams (1978), Yochum (2003)
19	76	Castro and Jackson (2001), Lawrence (2003)[1], USEPA (2006), Williams (1978)
20	76	Andrews (1984), Castro and Jackson (2001), Lawlor (2004), Parrett *et al.* (1983), USEPA (2006), Williams (1978), Yochum (2003)

Notes: HLR, Hydrologic landscape region.
[1]Indicates data obtained from a nonrefereed source.

TABLE 3. Number of Sites (n = 2,856) with Available Data Based on HLR, Physiographic Division, and Physiographic Region.

HLR Dataset

HLR	No. of Sites	%
1	44	1.5
2	83	2.9
3	82	2.9
4	115	4.0
5	40	1.4
6	138	4.8
7	141	4.9
8	102	3.6
9	279	9.8
10	34	1.2
11	182	6.4
12	133	4.7
13	176	6.2
14	73	2.6
15	101	3.5
16	379	13.3
17	217	7.6
18	385	13.5
19	76	2.7
20	76	2.7

Physiographic Division Dataset

Physiographic Division	No. of Sites	%
AHI	696	24.4
APL	150	5.3
IHI	37	1.3
IMP	279	9.8
IPL	823	28.8
LUP	22	0.8
PMS	361	12.6
RMS	488	17.1

Physiographic Province Dataset

Physiographic Province	No. of Sites	%
Adirondack	12	0.4
Appalachian Plateaus	260	9.1
Basin and Range	92	3.2
Blue Ridge	32	1.1
Cascade-Sierra Mountains	140	4.9
Central Lowland	445	15.6
Coastal Plain	150	5.3
Colorado Plateaus	75	2.6
Columbia Plateau	112	3.9
Great Plains	287	10.0
Interior Low Plateaus	91	3.2
Lower Californian	9	0.3
Middle Rocky Mountains	72	2.5
New England	119	4.2
Northern Rocky Mountains	311	10.9
Ouachita	17	0.6
Ozark Plateaus	20	0.7
Pacific Border	212	7.4
Piedmont	149	5.2
Southern Rocky Mountains	77	2.7
St. Lawrence Valley	8	0.3
Superior Upland	22	0.8
Valley and Ridge	116	4.1
Wyoming Basin	28	1.0

(continued)

TABLE 3. (continued)

Note: HLR, Hydrologic landscape region; AHI, Appalachian Highlands; APL, Atlantic Plain; IHI, Interior Highlands; IMP, Intermontane Plateau; IPL, Interior Plains; LUP, Laurentian Upland; PMS, Pacific Mountain System; and RMS, Rocky Mountain System.

Rocky Mountain System) and 24 physiographic provinces (25 if including the Continental Shelf). The physiographic division and province shapefile was obtained from http://water.usgs.gov/GIS/metadata/usgswrd/XML/physio.xml.

Statistical Analysis

A linear regression model in SigmaPlot version 13 (Systat Software, Inc., San Jose, California) was developed for each dependent variable (bankfull discharge, cross-sectional area, width, and mean depth) for each HLR, physiographic province, physiographic division, and each HLR within each physiographic province, provided sufficient data were available (*i.e.*, minimum of eight data points). Drainage area was the explanatory variable in all cases. All data were log transformed to normalize the data. The following general linear model was used:

$$Y = \delta X + \varepsilon \tag{5}$$

The variable Y represents the log transformed bankfull variable (*e.g.*, bankfull discharge, cross-sectional area, width, or mean depth); X is the log transformed drainage area; δ is the modeled slope; and ε is the modeled intercept (*e.g.*, $a = 10^{\varepsilon}$ and $b = \delta$ in Equation 1). Coefficients of determination (R^2) were used to classify the fit of the HLR, physiographic division, and physiographic province regression equations (bankfull discharge, cross-sectional area, width, and mean depth) as good ($R^2 \geq 0.6$), moderate ($0.5 \leq R^2 < 0.6$), or poor ($R^2 < 0.5$) (Faustini *et al.*, 2009). Standard errors of regression (SE_r) were used to evaluate the precision of the linear regression models with smaller values of SE_r indicating less variability or dispersion in predicted bankfull parameters (McHugh, 2008). The regional curves were also evaluated by examining the relationships between the coefficients and the exponents of the bankfull discharge,

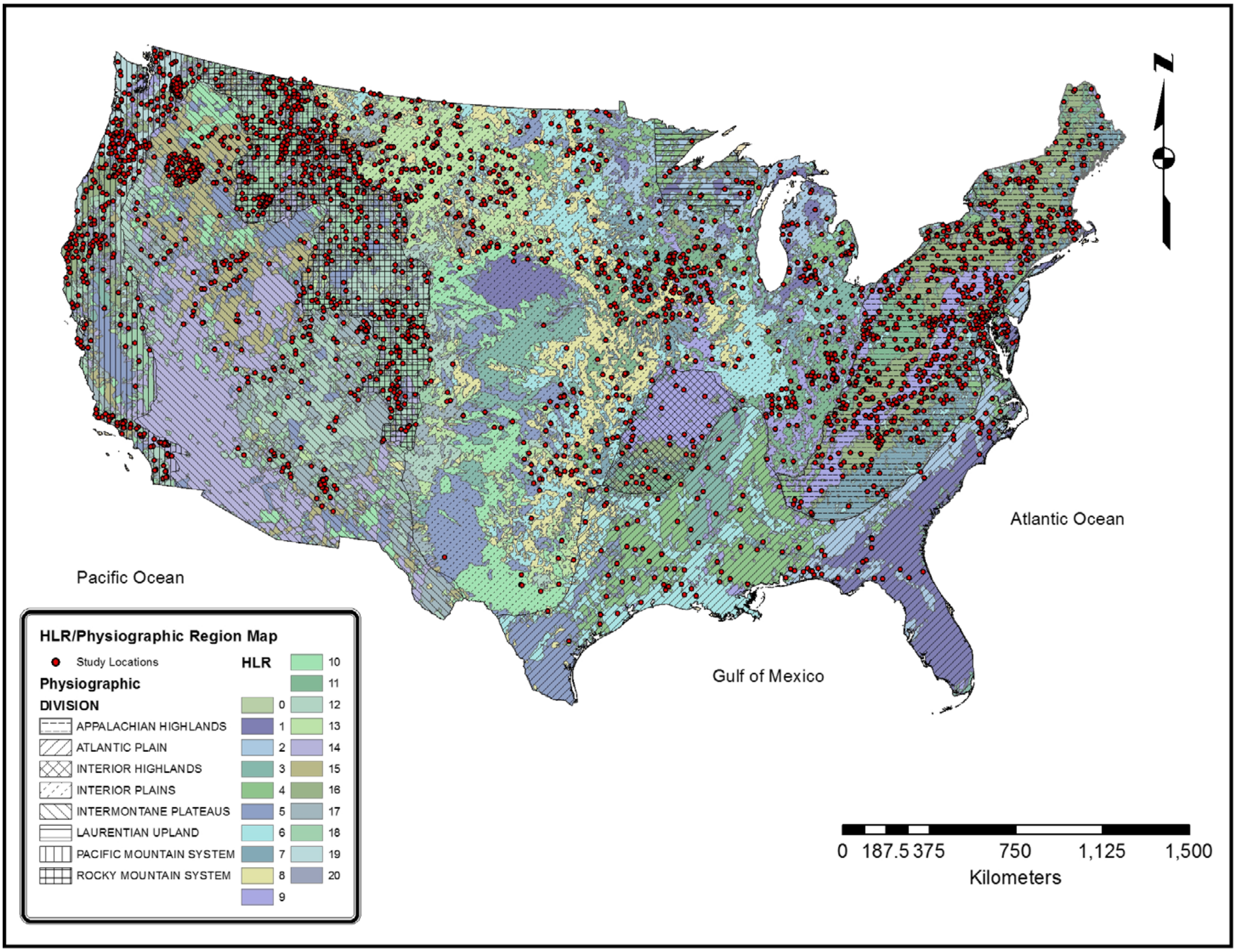

FIGURE 2. Contiguous U.S. by Hydrologic Landscape Region (HLR) (n = 20), Physiographic Division (n = 8), and Site Locations (n = 2,856).

cross-sectional area, width, and mean depth. As A_{bkf} is the product of W_{bkf} and D_{bkf}, the sum of the exponents h and k, from Equations (3) and (4), respectively, should equal the exponent d from Equation (2). Likewise, the product of the coefficients g and j, from Equations (3) and (4), respectively, should equal the coefficient c from Equation (2).

Comparison to Bieger et al. (2015)

Bieger *et al.* (2015) used data from 1,566 sites throughout the contiguous U.S. to develop regional regression equations for the bankfull parameters cross-sectional area, width and mean depth. The authors developed regional regression equations for the contiguous U.S. as well as each physiographic division and province. This study included all of the data used by Bieger *et al.* (2015) as well as data from an additional 1,290 sites. This study also developed regional regression equations for the parameter bankfull discharge. Where possible, comparisons between the regional regression equations developed by Bieger *et al.* (2015) and those developed in this study were made by examining exponent, coefficient, R^2 and $\mathrm{SE_r}$ values.

RESULTS AND DISCUSSION

Site Characteristics

Drainage area along with the bankfull parameters discharge, cross-sectional area, width, and mean depth were collected and analyzed for 2,856 sites throughout the contiguous U.S. Drainage areas ranged from 0.2 km^2 to 59,961 km^2 (median = 71.2 km^2);

bankfull discharge ranged from 0.01 to 2,832.0 m^3/s (median = 19.5 m^3/s); bankfull cross-sectional areas ranged from 0.1 m^2 to 1,889.4 m^2 (median = 7.0 m^2); bankfull widths ranged from 0.6 m to 228.6 m (median = 10.5 m); and bankfull mean depths ranged from 0.03 m to 8.3 m (median = 0.7 m) (Table 4). The majority of sites had drainage areas <1,000 km^2 (92%), bankfull discharges <50 m^3/s (85%), bankfull cross-sectional areas <25 m^2 (88%), bankfull widths <15 m (74%), and bankfull mean depths <0.9 m (71%). As seen in Figure 3, all parameters were positively skewed and hence nonnormally distributed, most notably so with bankfull cross-sectional area (skewness = 14.2, kurtosis = 359.8) followed by drainage area (skew = 11.0, kurtosis = 174.6), bankfull discharge (skewness = 8.6, kurtosis = 95.1), bankfull width (skew = 3.6, kurtosis = 21.1), and bankfull mean depth (skew = 2.5; kurtosis = 11.2). The histogram patterns shown in Figure 3 demonstrate that drainage area and bankfull cross-sectional area, drainage area and bankfull discharge, and drainage area and bankfull width are expected to exhibit stronger relationships (*i.e.*, coefficients of determinations) as compared to drainage area and bankfull mean depth, a pattern that was also present in the results presented in the examined studies (Table 2).

For the HLRs, the largest drainage area and bankfull parameter ranges occurred in HLRs 7 and 8 while the smallest occurred in HLRs 1, 2, and 20 (Table 4). As seen in Table 3, the largest number of sites were located in HLRs 18 (13.5%), 16 (13.3%), and 9 (9.8%) while the fewest number of sites were located in HLR 10 (1.2%), 1 (1.5%), 14 (2.6%), 19 (2.7%), and 20 (2.7%). Similar to Bieger *et al.* (2015), the largest ranges for drainage area and bankfull parameters occurred in the Interior Plains physiographic division and the smallest occurred in the Laurentian Upland (Table 5). These findings are reflective of the number of sites within each physiographic division with the Interior Plains containing 823 sites (28.8%) and the Laurentian Upland representing only 22 sites (0.8%) (Table 3). As seen in Tables 3 and 6, the Central Lowland physiographic province had the largest ranges for drainage area and the bankfull parameters as well as the largest number of sites (n = 445, 15.6%). The Lower Californian and St. Lawrence Valley physiographic provinces had the smallest drainage area and bankfull parameter ranges and fewest number of sites at 8 (0.3%) and 9 (0.3%), respectively.

Bankfull Regional Curves

Tables 7-9 contain coefficients (intercepts), exponents (slopes), standard errors of regression (SE_r), coefficients of determination (R^2), and fit classifications for the regional curves developed for the contiguous U.S. and each HLR, physiographic division, and physiographic province. The online supporting information contains figures of each HLR (S1-S20) showing the relationships between drainage area and the bankfull dimensions discharge, cross-sectional area, width, and mean depth. The online Supporting Information also contains regression equations for each HLR within each physiographic province, provided sufficient data were available (*i.e.*, minimum of eight data points) (Table S1).

Contiguous U.S. For the contiguous U.S., bankfull discharge (R^2 = 0.53), bankfull cross-sectional area (R^2 = 0.56), and bankfull width (R^2 = 0.58) exhibited moderate fits while bankfull mean depth (R^2 = 0.39) had a poor fit (Table 7) (Figure 4). Faustini *et al.* (2009) found a poor fit (R^2 = 0.42) for bankfull width *vs.* drainage area for the contiguous U.S. The authors only used data from the USEPA Wadeable Streams Assessment (USEPA, 2006) and did not examine the bankfull parameters discharge, cross-sectional area, or mean depth. Including data from additional studies throughout the U.S. produced an improved bankfull width model as compared to the one provided by Faustini *et al.* (2009). Using data from 1,566 sites across the contiguous U.S., Bieger *et al.* (2015) developed regional curves for the bankfull parameters cross-sectional area (R^2 = 0.58, SE_r = 0.42), width (R^2 = 0.66, SE_r = 0.24), and mean depth (R^2 = 0.43, SE_r = 0.23). Using nearly 60% fewer sites, the curves produced by Bieger *et al.* (2015) had higher R^2 and similar SE_r, to the ones produced in this study.

In examining the sum of the coefficients and the products of exponents from Equations (3) and (4), the results indicated the relationship $h + k = d$ and $g{\cdot}j = c$ occurred for all of the HLRs except HLR 4. For HLR 4, the sum of the coefficients h and k was 0.72 while the value for the coefficient d was 0.28, a difference of 88%. The product of the exponents g and j was 0.18 while the value for the exponent c was 5.32, which was a difference of 187%.

Regionalization by HLR. Bankfull Discharge. For bankfull discharge, 14 of the HLRs had a good fit, four a moderate fit, and two a poor fit (Table 7). Bankfull discharge was the parameter for which the least amount of data was available with only 1,055 sites or 37% including this measurement. The mean value for the exponent of the bankfull discharge regression equation (b in $Q_{\mathrm{bkf}} = aA_w{}^b$) was 0.70. HLRs 4, 6, and 11 had the lowest exponent values at 0.47, 0.48, and −0.36, respectively. The negative value for HLR 10 is due in part to the limited

TABLE 4. Bankfull Summary Data for Each HLR.

	Drainage Area (km^2)			Bankfull Discharge (m^3/s)			Bankfull Cross-sectional Area (m^2)			Bankfull Width (m)			Bankfull Mean Depth (m)		
HLR	Minimum	Maximum	Median	Minimum	Maximum	Median	Minimum	Maximum	Median	Minimum	Maximum	Median	Minimum	Maximum	Median
U.S.	0.2	59,962	71.2	0.01	2,832.0	19.5	0.1	1,889.4	7.0	0.6	228.6	10.5	0.03	8.3	0.7
1	0.5	4,302	113.3	0.2	37.1	5.5	0.6	186.2	7.3	3.1	71.0	10.6	0.2	2.6	0.6
2	0.6	4,380	92.6	0.8	75.1	8.4	0.3	82.0	8.6	1.2	43.9	11.5	0.2	2.4	0.7
3	0.9	16,861	106.2	1.4	1,122.5	15.4	0.4	908.6	13.5	2.5	182.9	15.9	0.1	5.0	1.0
4	0.5	22,279	71.6	0.6	288.9	13.2	0.6	515.0	21.1	0.6	159.4	21.1	0.1	3.2	0.8
5	10.4	27,938	911.4	0.7	455.1	34.6	0.8	261.4	14.0	1.8	152.5	18.6	0.2	2.1	0.8
6	0.3	12,704	69.7	0.3	295.7	22.0	0.3	208.7	8.3	2.0	72.9	10.9	0.1	3.3	0.9
7	0.6	59,961	72.5	0.01	1,182.4	24.6	0.1	429.9	11.6	0.7	214.7	13.3	0.1	3.8	1.0
8	1.8	54,747	182.3	2.0	391.4	19.7	0.5	216.5	11.9	1.8	168.4	11.0	0.2	3.6	0.9
9	0.3	11,145	77.7	0.4	2,832	30.3	0.4	1,889.4	14.5	1.7	228.6	16.6	0.1	8.3	0.9
10	5.4	9,935	249.9	4.5	131.9	39.7	0.4	267.3	7.2	1.0	95.4	9.8	0.3	3.0	0.7
11	0.6	8,912	57.4	0.3	1,880.0	11.4	0.3	262.5	11.4	1.8	76.2	13.2	0.2	4.2	0.8
12	0.4	34,912	91.4	0.4	431.8	60.0	0.1	277.8	4.2	1.0	99.1	8.6	0.1	3.5	0.6
13	6.0	20,331	455.5	4.9	175.6	51.5	0.1	143.1	7.2	0.8	77.7	9.5	0.1	4.1	0.8
14	2.1	15,952	37.0	0.3	109.3	6.8	0.2	71.1	2.7	1.3	57.0	6.1	0.1	2.3	0.6
15	0.6	19,632	38.9	1.7	316.1	47.5	0.1	153.9	2.8	0.9	86.9	5.7	0.1	2.5	0.5
16	0.2	10,202	49.0	0.2	2.031	31.4	0.1	438.3	7.5	1.2	142.2	13.5	0.1	4.0	0.6
17	0.8	13,183	68.7	0.03	420.0	6.3	0.1	161.0	3.0	1.0	79.3	5.8	0.03	4.2	0.5
18	0.4	9,197	58.8	0.2	651.3	9.6	0.3	245.4	4.2	1.1	94.5	8.1	0.1	2.7	0.5
19	0.6	3,577	40.6	5.2	736.3	85.2	0.9	432.0	8.3	2.9	106.7	12.4	0.2	5.1	0.7
20	0.2	1,492	22.3	0.8	92.6	7.5	0.5	49.4	3.5	1.5	34.1	6.7	0.1	1.8	0.6

Note: HLR, Hydrologic landscape region.

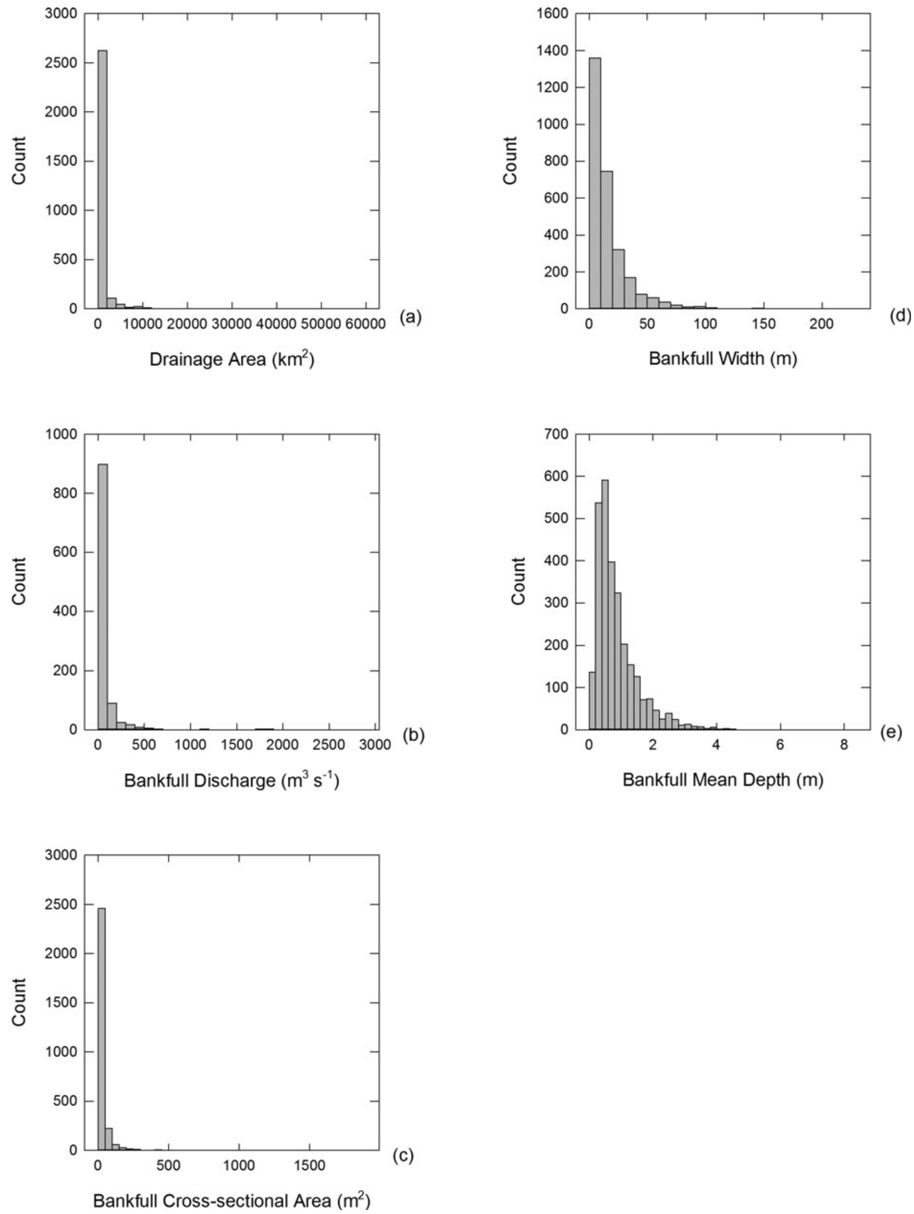

FIGURE 3. Distribution of Site Characteristics for the Contiguous U.S. for (a) Drainage Area, (b) Bankfull Discharge, (c) Bankfull Cross-sectional Area, (d) Bankfull Width, and (e) Bankfull Mean Depth.

available discharge data; only larger drainage areas (*e.g.*, 1,000 to 10,000 km^2 range) were represented. Brockman *et al.* (2012) reported that for the southeastern U.S., exponents of regional curves for bankfull discharge typically ranged between 0.63 and 0.94. Data were available for HLRs 1, 2, 3, 4, 6, 7, 9, 11, and 16, all of which have portions located in the southeastern U.S. With the exception of HLRs 2, 4, and 6, the bankfull discharge exponents for these regional curves were within the typical values of 0.63 and 0.94 reported by Brockman *et al.* (2012). For HLRs 2, 4, and 6, exponents were lower (0.51, 0.47, and 0.48), indicating larger amounts of water are stored, for some period, in the drainage basin (Leopold *et al.*, 1964; Chaplin, 2005; Brockman *et al.*, 2012). Both HLRs 2 and 4 represent humid areas with permeable soils and bedrock, the primary hydrologic flowpath is shallow groundwater, percentage of flat land is high, and the overall topographic relief (difference between maximum and minimum elevations) is low (Wolock *et al.*, 2004). HLR 6 is subhumid with impermeable soils and bedrock with overland flow as the dominant hydrologic flowpaths, but like HLRs 2 and 4, it contains a high percentage of flat land and has a small topographic relief.

TABLE 5. Bankfull Summary Data for Each Physiographic Division.

Physiographic Division	Drainage Area (km^2)			Bankfull Discharge (m^3/s)			Bankfull Cross-sectional Area (m^2)			Bankfull Width (m)			Bankfull Mean Depth (m)		
	Minimum	Maximum	Median	Minimum	Maximum	Median	Minimum	Maximum	Median	Minimum	Maximum	Median	Minimum	Maximum	Median
U.S.	0.2	59,962	71.2	0.01	2,832.0	19.5	0.1	1,889.4	7.0	0.6	228.6	10.5	0.03	8.3	0.7
AHI	0.2	2,435	51.7	0.01	1,803.8	25.9	0.1	205.2	9.6	0.7	142.2	13.7	0.1	3.2	0.7
APL	0.3	2,815	28.3	0.2	75.1	6.3	0.4	108.0	8.7	0.6	45.8	7.2	0.1	3.1	0.6
IHI	2.6	2,484	60.6	48.3	308.1	103.0	0.9	195.9	18.3	2.2	65.9	19.3	0.4	3.0	0.9
IMP	0.6	34,912	46.8	0.03	333.3	12.1	0.1	267.3	2.8	0.9	89.1	5.7	0.03	3.2	0.5
IPL	0.6	59,961	189.5	0.3	2,832	16.8	0.1	1,889.4	11.6	0.6	228.6	12.1	0.1	8.3	0.9
LUP	3.6	948	70.4	1.4	45.3	22.4	0.6	69.4	9.2	2.4	40.9	14.1	0.1	1.7	0.6
PMS	0.2	20,927	32.7	4.8	1,122.5	95.0	0.3	908.6	3.6	1.1	182.9	7.8	0.1	5.1	0.5
RMS	0.4	18,803	81.3	0.2	651.3	9.6	0.1	245.4	5.0	1.0	99.1	8.5	0.1	3.7	0.6

Note: AHI, Appalachian Highlands; APL, Atlantic Plain; IHI, Interior Highlands; IMP, Intermontane Plateau; IPL, Interior Plains; LUP, Laurentian Upland; PMS, Pacific Mountain System; RMS, Rocky Mountain System.

Data were available for the western portion of the U.S. (west of the Mississippi River) for HLRs 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, and 20. Exponents of the bankfull discharge regression equations were largely within the range (0.40-0.97) of reported values for the western U.S. (Elliott and Cartier, 1986; Dutnell, 2000; Castro and Jackson, 2001; Moody *et al.*, 2003; Emmert, 2004; Lawlor, 2004). HLR 10 had a much lower value at −0.36 while HLRs 13 and 17 had values >1 (1.08 and 1.20, respectively) making these bankfull discharge regression equations questionable (Dunne and Leopold, 1978). From a water balance perspective, an exponent <0 indicates the watershed is storing more water than it receives while an exponent >1 indicates the watershed is discharging more water than it receives from precipitation events (Dunne and Leopold, 1978).

Bankfull Cross-sectional Area. For bankfull cross-sectional area, 16 of the HLRs exhibited a good fit, one a moderate fit, and three a poor fit (Table 7). The mean value for the exponent of the bankfull cross-sectional area regression equation (d in $A_{\mathrm{bkf}} = cA_w{}^d$) was 0.56 but was as low as 0.28 for HLR 4 and as high as 0.72 for HLR 9. Brockman *et al.* (2012) reported that for the southeastern U.S., exponents of regional curves for bankfull cross-sectional area typically ranged between 0.62 and 0.81. With the exception of HLRs 4 and 6, the bankfull cross-sectional area exponents for these regional curves (HLRs 1, 2, 3, 6, 7, 9, 11, and 16) were between 0.56 and 0.72. A poor relationship between drainage area and bankfull cross-sectional area occurred within HLR 4 while a moderate relationship was found for HLR 14.

HLR 4, which is the only nonsemiarid or nonarid HLR to a show poor fit for bankfull cross-sectional area and width, is spread amongst several states but is predominately split between three areas: (1) Alabama, Louisiana, Mississippi, and Texas in the southern portion of the U.S.; (2) Michigan, Minnesota, and Wisconsin in the northern portion of the U.S.; and (3) Maryland, North Carolina, and Virginia in the eastern portion of the U.S. Sites within HLR 4 were split between land cover types dominated by forest, wetlands, or agriculture (USEPA, 2006). The type of riparian vegetation present, which would likely differ notably between the land cover types, is expected to influence channel geometry. Hession *et al.* (2003) noted that riparian vegetation strongly influenced channel shape with grassed riparian buffers resulting in more narrow channels than forested ones. The influence of riparian vegetation on channel geometry is also expected to vary with watershed size (Anderson *et al.*, 2004). Larger watersheds produce wider channels (Schumm, 1977) meaning less of the wetted perimeter is influenced by riparian vegetation. Additionally, USEPA (2006) indicated that 70 and 51% of

TABLE 6. Bankfull Summary Data for Each Physiographic Province.

Physiographic Province	Drainage Area (km^2)			Bankfull Discharge (m^3/s)			Bankfull Cross-sectional Area (m^2)			Bankfull Width (m)			Bankfull Mean Depth (m)		
	Minimum	Maximum	Median	Minimum	Maximum	Median	Minimum	Maximum	Median	Minimum	Maximum	Median	Minimum	Maximum	Median
U.S.	0.2	59,962	71.2	0.01	2,832.0	19.5	0.1	1,889.4	7.0	0.6	228.6	10.5	0.03	8.3	0.7
Adirondack	0.6	910	16.0	0.8	182.4	78.2	1.6	205.2	4.5	4.3	69.8	16.2	0.2	2.9	0.5
Appalachian Plateaus	0.4	1,391	37.6	0.2	1,803.8	22.7	0.1	178.3	8.0	1.2	142.2	12.7	0.1	2.8	0.6
Basin and Range	1.1	15,952	40.2	12.0	109.3	23.6	0.1	267.3	2.9	0.9	89.1	6.3	0.1	3.0	0.5
Blue Ridge	0.2	496.3	33.9	6.6	98.9	64.1	0.4	53.2	4.1	1.4	42.8	10.1	0.2	2.0	0.6
Cascade-Sierra Mountains	0.2	20,927	28.3	7.9	654.2	215.4	0.4	252.7	4.4	1.1	106.7	8.8	0.1	3.5	0.6
Central Lowland	0.6	59,961	189.5	0.7	2,030.9	19.5	0.3	515.0	15.4	0.6	214.7	14.6	0.1	5.2	1.0
Coastal Plain[1]	0.3	2,815.3	28.4	0.2	75.1	6.3	0.4	108.0	8.7	0.6	45.8	7.2	0.1	3.1	0.6
Colorado Plateaus	1.8	34,912	125.1	0.03	73.6	0.6	0.1	46.3	4.0	1.3	57.8	6.3	0.03	3.2	0.6
Columbia Plateau	0.6	19,632	31.2	4.4	333.3	68.2	0.1	161.0	2.2	1.1	86.9	5.2	0.1	2.4	0.5
Great Plains	0.6	20,331	340.9	4.5	131.9	22.3	0.1	143.1	7.8	0.8	95.4	9.4	0.1	4.2	0.8
Interior Low Plateaus	0.7	8,417	50.9	0.3	2,832	10.3	0.3	1,889.4	10.4	1.8	228.6	12.1	0.2	8.3	0.8
Lower Californian	7.9	145.1	34.7	ND	ND	ND	0.4	3.8	1.7	2.0	10.3	4.1	0.2	0.9	0.3
Middle Rocky Mountains	1.0	9,197	68.3	ND	ND	ND	0.2	167.2	5.6	1.1	91.4	9.0	0.2	1.8	0.6
New England	1.6	772	71.2	0.5	155.5	25.0	0.5	72.5	9.9	1.8	42.1	15.4	0.2	2.1	0.6
Northern Rocky Mountains	0.4	18,803	69.9	0.2	651.3	8.9	0.1	245.4	5.3	1.0	99.1	8.5	0.1	3.7	0.7
Ouachita	2.6	237	42.7	ND	ND	ND	0.9	46.3	10.4	2.2	45.9	18.7	0.4	1.3	0.7
Ozark Plateaus	7.2	2,484	149.3	48.3	308.1	103.0	1.8	195.9	22.9	4.9	65.9	23.5	0.4	3.0	1.1
Pacific Border	0.2	10,202	37.4	4.8	1,123	69.3	0.3	908.6	3.5	1.2	182.9	7.9	0.1	5.1	0.4
Piedmont	0.7	2,434.6	47.4	0.01	246.7	25.9	0.1	176.1	11.9	0.7	66.3	13.0	0.1	3.2	0.8
Southern Rocky Mountains	1.0	4,379.7	133.5	0.7	111.6	8.4	0.3	62.6	4.1	1.8	54.6	8.7	0.1	1.6	0.5
St. Lawrence Valley	7.7	200	103.2	15.6	52.4	20.8	1.4	26.7	16.3	4.3	28.0	19.2	0.3	1.5	0.8
Superior Upland[1]	3.6	948	70.4	1.4	45.3	22.4	0.6	69.4	9.2	2.4	40.9	14.1	0.1	1.7	0.6
Valley and Ridge	0.3	1,026	66.7	0.4	179.0	32.1	0.4	147.2	11.5	1.9	66.5	15.4	0.1	3.1	0.8
Wyoming Basin	7.6	8,832	295.9	13.2	255.0	90.2	0.5	155.0	9.0	1.8	83.8	15.1	0.3	1.9	0.7

Notes: ND, No data were available.
[1]Coastal Plain is same as Atlantic Plain and Superior Upland is same as Laurentian Upland.

TABLE 7. Comparison of HLR Regional Curves Where $Q_{bkf} = aA_w{}^b$, $A_{bkf} = cA_w{}^d$, $W_{bkf} = gA_w{}^h$, and $D_{bkf} = jA_w{}^k$.

	Bankfull Discharge (m^3/s)						Bankfull Cross-sectional Area (m^2)						Bankfull Width (m)						Bankfull Mean Depth (m)					
HLR	**No. of Sites**	***a***	***b***	***R*²**	**SE$_r$**	**Fit[1]**	**No. of Sites**	***c***	***d***	***R*²**	**SE$_r$**	**Fit[1]**	**No. of Sites**	***g***	***h***	***R*²**	**SE$_r$**	**Fit[1]**	**No. of Sites**	***j***	***k***	***R*²**	**SE$_r$**	**Fit[1]**
U.S.	1,055	0.86	0.63	0.53	0.51	**M**	2,805	0.75	0.53	0.56	0.44	**M**	2,832	2.44	0.34	0.58	0.27	**M**	2,806	0.27	0.21	0.39	0.25	P
1	35	0.16	0.73	0.82	0.23	**G**	44	0.44	0.63	0.77	0.29	**G**	44	2.30	0.34	0.74	0.17	**G**	44	0.19	0.29	0.58	0.21	**M**
2	55	0.77	0.51	0.67	0.28	**G**	81	0.70	0.56	0.73	0.29	**G**	83	2.27	0.38	0.79	0.16	**G**	81	0.31	0.19	0.35	0.21	P
3	29	0.78	0.65	0.79	0.32	**G**	82	0.90	0.57	0.73	0.37	**G**	82	3.15	0.33	0.73	0.22	**G**	82	0.29	0.24	0.55	0.23	**M**
4	49	1.40	0.47	0.47	0.45	P	115	5.32	0.28	0.27	0.46	P	115	1.18	0.44	0.57	0.38	**M**	115	0.15	0.28	0.32	0.40	P
5	23	0.09	0.80	0.74	0.38	**G**	40	0.27	0.59	0.65	0.38	**G**	40	1.54	0.38	0.52	0.31	**M**	40	0.16	0.22	0.39	0.24	P
6	45	1.69	0.48	0.58	0.44	**M**	133	1.12	0.46	0.62	0.62	**G**	138	3.68	0.25	0.61	0.20	**G**	133	0.30	0.21	0.47	0.23	P
7	76	0.75	0.71	0.56	0.53	**M**	135	0.67	0.67	0.75	0.34	**G**	135	2.49	0.39	0.81	0.16	**G**	135	0.26	0.28	0.52	0.24	**M**
8	25	0.84	0.66	0.85	0.56	**G**	101	1.17	0.42	0.40	0.45	P	102	2.21	0.32	0.58	0.24	**M**	101	0.53	0.10	0.10	0.27	P
9	159	0.74	0.76	0.85	0.26	**G**	279	0.62	0.72	0.81	0.29	**G**	279	2.66	0.41	0.84	0.15	**G**	279	0.23	0.30	0.62	0.20	**G**
10	11	494.00	-0.36	0.04	0.61	P	34	0.16	0.65	0.68	0.43	**G**	34	0.59	0.49	0.70	0.30	**G**	34	0.28	0.16	0.33	0.22	P
11	90	0.88	0.73	0.64	0.43	**G**	175	1.00	0.62	0.75	0.30	**G**	179	3.54	0.34	0.70	0.19	**G**	175	0.28	0.27	0.59	0.19	**M**
12	26	0.41	0.70	0.75	0.44	**G**	131	0.38	0.56	0.71	0.39	**G**	132	1.54	0.38	0.76	0.23	**G**	131	0.24	0.19	0.44	0.23	P
13	8	0.05	1.08	0.57	0.39	**M**	170	0.37	0.54	0.67	0.38	**G**	176	1.41	0.34	0.72	0.21	**G**	170	0.26	0.20	0.42	0.24	P
14	7	0.13	0.90	0.73	0.44	**G**	73	0.39	0.47	0.53	0.45	**M**	73	1.71	0.31	0.64	0.23	**G**	73	0.23	0.16	0.23	0.30	P
15	16	0.42	0.66	0.75	0.32	**G**	99	0.29	0.60	0.72	0.38	**G**	100	1.30	0.39	0.78	0.21	**G**	99	0.22	0.21	0.47	0.23	P
16	214	0.74	0.83	0.72	0.36	**G**	378	0.61	0.71	0.83	0.26	**G**	378	2.67	0.44	0.83	0.16	**G**	378	0.23	0.27	0.62	0.17	**G**
17	45	0.01	1.20	0.71	0.60	**G**	213	0.33	0.52	0.46	0.49	P	217	1.45	0.34	0.53	0.28	**M**	213	0.22	0.18	0.22	0.29	P
18	109	0.16	0.87	0.78	0.37	**G**	370	0.42	0.60	0.65	0.36	**G**	373	1.72	0.39	0.70	0.21	**G**	371	0.24	0.21	0.39	0.22	P
19	22	0.34	0.89	0.55	0.43	**M**	76	1.18	0.59	0.77	0.32	**G**	76	3.51	0.38	0.86	0.15	**G**	76	0.34	0.21	0.45	0.23	P
20	11	0.35	0.71	0.72	0.36	**G**	76	1.05	0.45	0.62	0.31	**G**	76	2.68	0.33	0.74	0.18	**G**	76	0.39	0.12	0.22	0.20	P
Mean		25.24	0.70	0.66	0.41			0.87	0.56	0.66	0.38			2.18	0.37	0.71	0.22			0.27	0.21	0.41	0.24	

Notes: HLR, Hydrologic landscape region; SE$_r$, standard error of regression.
[1]Fit refers to the quality of the regression fit using criteria specified by Faustini *et al.* (2009). Good: $R^2 \geq 0.6$, Moderate: $0.5 \leq R^2 < 0.6$, and Poor: $R^2 < 0.5$. Regressions with Good or Moderate fits are in bold.

TABLE 8. Comparison of Physiographic Division Regional Curves Where $Q_{\mathrm{bkf}} = aA_w{}^b$, $A_{\mathrm{bkf}} = cA_w{}^d$, $W_{\mathrm{bkf}} = gA_w{}^h$, and $D_{\mathrm{bkf}} = jA_w{}^k$.

Physiographic Division	Bankfull Discharge (m^3/s) No. of Sites	*a*	*b*	R^2	SE_r	Fit[1]	Bankfull Cross-sectional Area (m^2) No. of Sites	*c*	*d*	R^2	SE_r	Fit[1]	Bankfull Width (m) No. of Sites	*g*	*h*	R^2	SE_r	Fit[1]	Bankfull Mean Depth (m) No. of Sites	*j*	*k*	R^2	SE_r	Fit[1]
U.S.	1,055	0.86	0.63	0.53	0.51	**M**	2,805	0.75	0.53	0.56	0.44	**M**	2,832	2.44	0.34	0.58	0.27	**M**	2,806	0.27	0.21	0.39	0.25	P
AHI	459	0.75	0.80	0.76	0.32	**G**	686	0.70	0.69	0.79	0.28	**G**	686	2.76	0.42	0.80	0.17	**G**	686	0.24	0.28	0.57	0.19	**M**
APL	73	0.37	0.64	0.72	0.30	**G**	150	1.84	0.43	0.38	0.45	P	150	2.03	0.33	0.45	0.30	P	150	0.21	0.27	0.31	0.33	P
IHI	5	3.33	0.51	0.58	0.22	**M**	37	1.99	0.50	0.61	0.31	**G**	37	4.52	0.34	0.65	0.19	**G**	37	0.44	0.16	0.31	0.18	P
IMP	44	0.00	1.20	0.82	0.51	**G**	279	0.41	0.48	0.53	0.47	**M**	279	1.60	0.32	0.61	0.27	**G**	279	0.26	0.15	0.25	0.27	P
IPL	234	1.34	0.49	0.46	0.54	P	802	0.78	0.51	0.56	0.44	**M**	823	2.36	0.32	0.58	0.27	**M**	802	0.31	0.20	0.35	0.26	P
LUP	9	0.03	1.05	0.81	0.22	**G**	22	1.14	0.46	0.41	0.41	P	22	1.96	0.42	0.77	0.17	**G**	22	0.21	0.22	0.30	0.26	P
PMS	66	0.94	0.71	0.51	0.44	**M**	361	0.56	0.61	0.64	0.42	**G**	361	2.24	0.39	0.74	0.22	**G**	361	0.25	0.22	0.36	0.27	P
RMS	165	0.19	0.79	0.78	0.34	**G**	468	0.38	0.60	0.67	0.37	**G**	474	1.50	0.40	0.71	0.22	**G**	469	0.25	0.20	0.43	0.21	P
Mean		0.87	0.77	0.68	0.36			0.98	0.54	0.57	0.39			2.37	0.37	0.66	0.23			0.27	0.21	0.36	0.25	

Notes: AHI, Appalachian Highlands; APL, Atlantic Plain; IHI, Interior Highlands; IMP, Intermontane Plateau; IPL, Interior Plains; LUP, Laurentian Upland; PMS, Pacific Mountain System; RMS, Rocky Mountain System; SE_r, standard error of regression.

[1]Fit refers to the quality of the regression fit using criteria specified by Faustini *et al.* (2009). Good: $R^2 \geq 0.6$, Moderate: $0.5 \leq R^2 < 0.6$, and Poor: $R^2 < 0.5$. Regressions with Good or Moderate fits are in bold.

the assessed streams in coastal plains and upper Midwest ecoregions, respectively, had moderate to highly disturbed riparian buffers as a result of anthropogenic activities. Variations in the level of riparian disturbance between sites within the HLRs encompassing these regions may have influenced bankfull characteristics.

In the western portion of the U.S. (west of the Mississippi River), exponents of bankfull cross-sectional area displayed ranges similar to those found in the eastern U.S. (Elliott and Cartier, 1986; Castro and Jackson, 2001; Lawrence, 2003; Emmert, 2004; Lawlor, 2004) though lower values such as 0.39 (Dutnell, 2000) and 0.54 (Moody *et al.*, 2003) were reported. All HLRs, with data present in the western portion of the U.S., had good fits ($R^2 \geq 0.6$) with the exception of HLR 14 which had a moderate fit ($0.5 \leq R^2 < 0.6$). HLR 14 is described by Wolock *et al.* (2004) as "arid playas," which are dynamic landforms. The locations of the sites within HLR 14, which predominately encompasses portions of California, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming, may exhibit greater levels of variability due to changes in snow pack conditions, vegetation, precipitation patterns, and bedload transport (Neal and Motts, 1967; Patten, 1998; Adams and Sada, 2014).

Bankfull Width. Fit categorization for bankfull width was similar to that of bankfull cross-sectional area with 16 of the HLRs exhibiting a good fit and four a moderate fit (HLRs 4, 5, 8, and 17). HLRs 5, 8, and 17 are located in arid or semiarid environments while HLR 4 is located in a humid environment. These regression results are not surprising as prior studies have shown that drainage area is a good predictor of bankfull width across a variety of landscapes (Johnson and Fecko, 2008; Faustini *et al.*, 2009; Bieger *et al.*, 2015). The mean value for the exponent of the bankfull width regression equation (h in $W_{\mathrm{bkf}} = gA_w{}^h$) was 0.37 with a minimum value of 0.25 for HLR 6 and a maximum value of 0.49 for HLR 10. Brockman *et al.* (2012) reported that for the southeastern U.S., exponents of regional curves for bankfull width typically ranged between 0.28 and 0.47. A similar range, as that of the southeastern U.S., was found in studies focusing on the western portion of the U.S. (Dutnell, 2000; Castro and Jackson, 2001; Lawrence, 2003; Moody *et al.*, 2003; Emmert, 2004; Lawlor, 2004) though Elliott and Cartier (1986) reported a value of 0.2.

Bankfull Mean Depth. In all instances except six, drainage area and mean bankfull depth had poor relationships. HLRs 9 and 16 had good fits while HLRs 1, 3, 7, and 11 had moderate fits. All of these HLRs are located in the eastern U.S. and experience subhumid or humid climates. The mean value of the exponent of the bankfull mean depth regression

TABLE 9. Comparison of Physiographic Province Regional Curves Where $Q_{\mathrm{bkf}} = aA_w{}^b$, $A_{\mathrm{bkf}} = cA_w{}^d$, $W_{\mathrm{bkf}} = gA_w{}^h$, and $D_{\mathrm{bkf}} = jA_w{}^k$.

	Bankfull Discharge (m^3/s)						Bankfull Cross-sectional Area (m^2)						Bankfull Width (m)						Bankfull Mean Depth (m)					
Physiographic Province	No. of Sites	*a*	*b*	R^2	SE_r	Fit[1]	No. of Sites	*c*	*d*	R^2	SE_r	Fit[1]	No. of Sites	*g*	*h*	R^2	SE_r	Fit[1]	No. of Sites	*j*	*k*	R^2	SE_r	Fit[1]
U.S.	1,055	0.86	0.63	0.53	0.51	**M**	2,805	0.75	0.53	0.56	0.44	**M**	2,832	2.44	0.34	0.58	0.27	**M**	2,806	0.27	0.21	0.39	0.25	P
Adirondack	8	0.66	0.86	0.99	0.08	**G**	12	1.18	0.67	0.90	0.28	**G**	12	4.81	0.37	0.88	0.16	**G**	12	0.25	0.30	0.72	0.22	**G**
Appalachian Plateaus	171	0.85	0.81	0.79	0.32	**G**	260	0.75	0.70	0.81	0.28	**G**	260	2.81	0.43	0.81	0.17	**G**	260	0.25	0.28	0.64	0.17	**G**
Basin and Range	4	20.76	0.04	0.00	0.50	P	92	0.47	0.47	0.60	0.43	**G**	92	1.75	0.32	0.64	0.27	**G**	92	0.27	0.15	0.30	0.25	P
Blue Ridge	11	0.93	0.85	0.83	0.17	**G**	32	1.03	0.58	0.78	0.29	**G**	32	2.98	0.40	0.88	0.14	**G**	32	0.35	0.17	0.38	0.21	P
Cascade-Sierra Mountains	23	1.65	0.62	0.35	0.50	P	140	0.78	0.59	0.75	0.34	**G**	140	2.39	0.40	0.79	0.21	**G**	140	0.33	0.19	0.44	0.21	P
Central Lowland	156	1.51	0.46	0.40	0.50	P	443	0.92	0.53	0.62	0.34	**G**	445	2.46	0.35	0.68	0.21	**G**	443	0.33	0.20	0.34	0.21	P
Coastal Plain[2]	73	0.37	0.64	0.72	0.30	**G**	150	1.84	0.43	0.38	0.45	P	150	2.03	0.33	0.45	0.30	P	150	0.21	0.27	0.31	0.33	P
Colorado Plateaus	21	0.00	1.04	0.62	0.53	**G**	75	0.46	0.39	0.28	0.57	P	75	2.04	0.25	0.38	0.29	P	75	0.22	0.14	0.12	0.36	P
Columbia Plateau	19	0.15	0.79	0.84	0.08	**G**	112	0.01	4.71	0.76	0.37	**G**	112	1.30	0.39	0.73	0.24	**G**	112	0.25	0.18	0.44	0.21	P
Great Plains	16	3.68	0.25	0.06	0.56	P	277	0.36	0.54	0.63	0.39	**G**	287	1.33	0.35	0.66	0.24	**G**	277	0.26	0.19	0.35	0.25	P
Interior Low Plateaus	62	0.47	0.86	0.85	0.32	**G**	82	0.65	0.77	0.88	0.25	**G**	91	2.98	0.39	0.81	0.16	**G**	82	0.21	0.37	0.78	0.17	**G**
Lower Californian	0	ND	ND	ND	ND	ND	9	0.19	0.53	0.36	0.17	P	9	0.62	0.53	0.85	0.09	**G**	9	0.30	0.00	0.00	0.24	P
Middle Rocky Mountains	0	ND	ND	ND	ND	ND	70	0.69	0.50	0.57	0.37	**M**	72	2.02	0.36	0.64	0.24	**G**	70	0.33	0.14	0.29	0.20	P
New England	73	0.59	0.76	0.65	0.31	**G**	109	0.62	0.68	0.71	0.24	**G**	109	3.08	0.39	0.67	0.15	**G**	109	0.20	0.29	0.50	0.15	**M**
Northern Rocky Mountains	110	0.15	0.87	0.83	0.32	**G**	293	0.33	0.65	0.72	0.35	**G**	297	1.38	0.42	0.76	0.21	**G**	294	0.24	0.23	0.49	0.20	P
Ouachita	0	ND	ND	ND	ND	ND	17	1.30	0.58	0.63	0.29	**G**	17	3.13	0.45	0.61	0.24	**G**	17	0.41	0.13	0.32	0.12	P
Ozark Plateaus	5	3.33	0.51	0.58	0.22	**M**	20	3.58	0.40	0.50	0.32	**M**	20	5.83	0.29	0.71	0.15	**G**	20	0.61	0.11	0.17	0.20	P
Pacific Border	43	0.72	0.76	0.57	0.42	**M**	212	0.45	0.63	0.62	0.44	**G**	212	2.22	0.38	0.73	0.21	**G**	212	0.20	0.25	0.37	0.28	P
Piedmont	107	0.62	0.86	0.76	0.35	**G**	149	0.69	0.72	0.77	0.30	**G**	149	2.62	0.41	0.76	0.18	**G**	149	0.24	0.32	0.56	0.22	**M**
Southern Rocky Mountains	45	0.37	0.60	0.63	0.33	**G**	77	0.41	0.50	0.63	0.32	**G**	77	1.79	0.34	0.65	0.21	**G**	77	0.23	0.16	0.41	0.16	P
St. Lawrence Valley	5	0.60	0.78	0.70	0.13	**G**	8	0.42	0.79	0.76	0.23	**G**	8	1.62	0.53	0.76	0.15	**G**	8	0.26	0.25	0.41	0.16	P
Superior Upland[2]	9	0.03	1.05	0.81	0.22	**G**	22	1.14	0.46	0.41	0.41	P	22	1.96	0.42	0.77	0.17	**G**	22	0.21	0.22	0.30	0.26	P
Valley and Ridge	84	0.66	0.78	0.88	0.20	**G**	116	0.42	0.77	0.83	0.26	**G**	116	2.35	0.45	0.88	0.13	**G**	116	0.17	0.33	0.66	0.18	**G**
Wyoming	10	0.38	0.70	0.62	0.27	**G**	28	0.06	0.84	0.83	0.33	**G**	28	0.46	0.56	0.79	0.25	**G**	28	0.14	0.28	0.68	0.17	**G**
Mean		1.83	0.71	0.64	0.32			0.78	0.77	0.66	0.33			2.33	0.40	0.72	0.20			0.27	0.21	0.42	0.21	

Notes: ND; no data were available; SE_r, standard error of regression.

[1]Fit refers to the quality of the regression fit using criteria specified by Faustini *et al.* (2009). Good: $R^2 \geq 0.6$, Moderate: $0.5 \leq R^2 < 0.6$, and Poor: $R^2 < 0.5$. Regressions with Good or Moderate fits are in bold.

[2]Coastal Plain is same as Atlantic Plain and Superior Upland is same as Laurentian Upland.

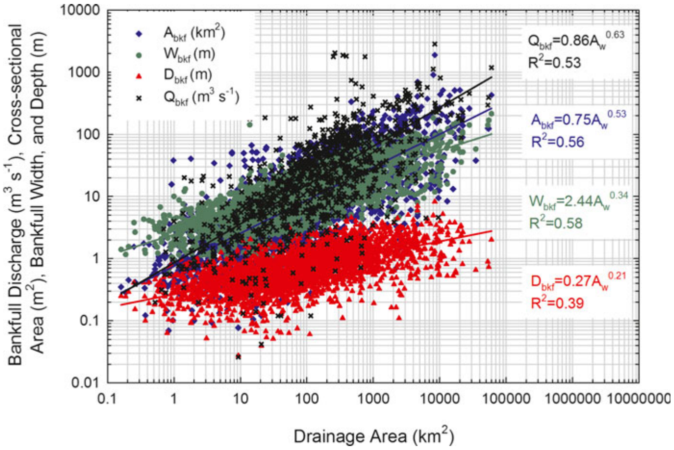

FIGURE 4. Drainage Area *vs.* Bankfull Discharge, Cross-sectional Area, Width, and Mean Depth for the Contiguous U.S.

equation (k in $D_{\mathrm{bkf}} = jA_w{}^k$) was 0.21 and ranged from 0.10 for HLR 8 and a maximum of 0.30 for HLR 9. For the southeastern portion of the U.S., Brockman *et al.* (2012) reported that exponents of regional curves for bankfull mean depth typically ranged between 0.25 and 0.43. Based on prior studies, it was expected that mean bankfull depth would exhibit a greater number of poor fits than the other bankfull parameters (Table 7) (Chaplin, 2005; Keaton *et al.*, 2005; Krstolic and Chaplin, 2007; Mistak and Stille, 2008; Brockman *et al.*, 2012). In some instances, drainage area explained almost none of the variability in bankfull mean depth such as with HLRs 8, 14, 17, and 20, which had R^2 values of 0.10, 0.23, 0.22, and 0.22, respectively.

The poorer fitting regression equations were for HLRs located in the arid and semiarid western portion of the U.S. In arid and semiarid environments, ephemeral channels often incise to form arroyos (Nordin, 1963). Arroyos evolve through a process of incision followed by aggradation (Elliot *et al.*, 1999). With arroyos, incision is rapid. The maximum channel depth is reached quickly and is followed by the lateral eroding of alluvium to create a wide, shallow stream (Leopold and Miller, 1954). The widening process is followed by aggradation with the cycle of re-incision, widening, and aggradation continuing (Elliot *et al.*, 1999). Post-incision, the location of the stream channel can change noticeably even over a short time span (Gellis, 1988; Meyer, 1989; Elliot *et al.*, 1999). In these arid and semiarid environments, the rapid incision-aggradation cycle would likely add a greater level of variability to mean bankfull depth regional curves.

Other factors not captured in this study are likely influencing bankfull mean depth across and within HLRs, potentially more so than the other bankfull parameters. More refined information such as the type of channel bed material (*e.g.*, clay, sand, gravel, cobble, bedrock) and type of streamside vegetation (*e.g.*, forest *vs.* grass) may help explain some of the variability in bankfull mean depth. For instance, Schumm (1977) noted that channel shape, expressed as the width-to-depth ratio, is related to the percentage of fine sediment (silt and clay) in the stream bed and banks. Schumm (1977) showed that streams with higher percentages of fines in their beds and banks tend to have lower width-to-depth ratios, meaning such streams are narrow and deep, and are generally characterized as lower bedload transport systems. Leopold and Maddock (1953) concluded that streams with high levels of bedload transport tended to have high width-to-depth ratios meaning such streams are wide and shallow. These studies suggest that, holding drainage area constant, a stream with bed material that is more resistant to movement (*e.g.*, bedrock) will have a smaller mean bankfull depth than a stream with a bed comprised of less resistant material (*e.g.*, sand). Streamside vegetation type also influences channel geometry. Hession *et al.* (2003) found that streams with forested riparian buffers had wider and shallower channels. Anderson *et al.* (2004) found, for watersheds >10 km^2, streams with forested riparian buffers were more narrow and deeper as compared to streams with grass riparian buffers. Hence, two streams with the same drainage area may have different geometries due to streamside vegetation type. Neither channel bed material nor streamside vegetation type were specifically considered in the Wolock *et al.* (2004) HLU classification though bedrock and sand are mapped.

Regionalization by Physiographic Division. Results indicated the relationships $h + k = d$ and $g{\cdot}j = c$ occurred for all of the physiographic provinces except the Atlantic Plain and Laurentian Upland (Table 8). For the Atlantic Plain, the sum of the coefficients h and k was 0.60 while the value for the coefficient d was 0.43, a difference of 33%. The product of the exponents g and j was 0.43 while the value for the exponent c was 1.84, which was a difference of 124%. A similar trend was seen for the Laurentian Upland where the sum of the coefficients h and k was 0.64 while the value for the coefficient d was 0.46, a difference of 33%. The product of the exponents g and j was 0.41 while the value for the exponent c was 1.14, which was a difference of 94%.

Bankfull Discharge. For bankfull discharge, five of the physiographic divisions had a good fit, two a moderate fit, and one a poor fit (Table 8). As with the HLR regional curves, bankfull discharge was the parameter with the fewest data points. The mean value for the exponent of the bankfull discharge regression equation (b in $Q_{\mathrm{bkf}} = aA_w{}^b$) was 0.77. The Interior Highlands and Interior Plains had the smallest exponent values at 0.51 and 0.49, respectively. The Intermontane Plateau and Laurentian Upland had exponent values >1, which indicates these bankfull discharge regional curves are questionable (Dunne and Leopold, 1978). The remaining physiographic divisions (Appalachian Highlands, Atlantic Plain, Pacific Mountain System, and Rocky Mountain System) all had exponent values between 0.64 and 0.80, which is a similar range reported by Brockman *et al.* (2012) for the southeastern U.S. and in studies conducted in the western U.S. (Elliott and Cartier, 1986; Dutnell, 2000; Castro and Jackson, 2001; Moody *et al.*, 2003; Emmert, 2004; Lawlor, 2004).

Bankfull Cross-sectional Area. For bankfull cross-sectional area, four of the physiographic divisions had a good fit, two a moderate fit, and two a poor fit (Table 8). The mean value for the exponent of the bankfull cross-sectional area regression equations (d in $A_{\mathrm{bkf}} = cA_w{}^d$) was 0.54. The Atlantic Plains had the lowest exponent value at 0.43 while the Appalachian Highlands had the highest value at 0.69. With the exception of the Appalachian Highlands, exponents were lower than the range (0.62-0.81) reported by Brockman *et al.* (2012) for the eastern U.S. and by others for the western U.S. (Elliott and Cartier, 1986; Dutnell, 2000; Castro and Jackson, 2001; Moody *et al.*, 2003; Emmert, 2004; Lawlor, 2004).

Bieger *et al.* (2015) developed bankfull cross-sectional area regional curves for the physiographic divisions of the U.S. using data from 1,566 sites, all of which are included in this study. The curves developed by Bieger *et al.* (2015) had higher R^2 values in all cases except the Interior Highlands. Exponent and coefficient values were different in all cases. Percent differences between exponent values presented in this study and the Bieger *et al.* (2015) study were greater or equal to 25% for the Atlantic Plain (45%), Interior Highlands (25%), and Intermontane Plateau (44%). In some instances, exponent values were larger from this study while in others exponents presented in Bieger *et al.* (2015) were larger. Similar trends were seen with the coefficient values though the percent differences were generally larger than those for the exponents. Including 1,290 more sites in the dataset (this study's dataset *vs.* the Bieger *et al.* (2015) dataset) generally resulted in smaller R^2 values and produced less reliable regional curves, possibly due to the introduction of more variability. The inclusion of additional sites allowed for a greater spatial representation of each physiographic province, meaning the nonuniformities of each physiographic province were captured more readily.

Bankfull Width. For bankfull width, six of the physiographic divisions had a good fit, one a moderate fit, and one a poor fit (Table 8). The mean value for the exponent of the bankfull width regression equation (h in $W_{\mathrm{bkf}} = gA_w{}^h$) was 0.37. The Intermontane Plateau and Interior Plains had the lowest exponent values at 0.32 each while the Appalachian Highlands and Laurentian Upland had the highest values at 0.42 each. The ranges of exponents from the bankfull width regional curves developed for the physiographic divisions agrees with the expected range of exponent values (0.28-0.47) provided in the literature (Elliott and Cartier, 1986; Dutnell, 2000; Castro and Jackson, 2001; Moody *et al.*, 2003; Emmert, 2004; Lawlor, 2004; Brockman *et al.*, 2012).

The bankfull width regional curves developed by Bieger *et al.* (2015) had higher R^2 values in all cases except the Interior Highlands, Laurentian Upland, and Pacific Mountain System. As with bankfull cross-sectional area, the exponent and coefficient values differed though the percent differences were smaller. For the exponent values, the percent differences between this and the Bieger *et al.* (2015) study were >25% only for the Intermontane Plateau (27%) and the Laurentian Upland (30%). Similar trends were present with the coefficient values though the percent differences were generally larger. As with bankfull cross-sectional area, the addition of more sites in each physiographic division tended to produce less reliable curves with lower R^2 values. This finding suggests a broader spatial representation of a physiographic division is reducing the R^2 values of the regression equations.

Bankfull Mean Depth. For mean bankfull depth, one physiographic division had a moderate fit while the remaining seven had poor fits (Table 8). The mean value for the exponent of the bankfull mean depth regression equation (k in $D_{\mathrm{bkf}} = jA_w{}^k$) was 0.21. The Intermontane Plateau had the lowest value at 0.25 while the Appalachian Highlands had the highest value at 0.57. The ranges of exponents from the bankfull mean depth regional curves developed for the physiographic divisions were generally lower than the expected range of exponent values (0.25-0.43) provided in the literature (Elliott and Cartier, 1986; Dutnell, 2000; Castro and Jackson, 2001; Moody *et al.*, 2003; Emmert, 2004; Lawlor, 2004; Brockman *et al.*, 2012). The only two physiographic provinces to fall within this range were the Appalachian Highlands and the Atlantic Plain.

The bankfull mean depth regional curves developed by Bieger *et al.* (2015) had higher R^2 values for all physiographic divisions. The exponent and coefficient values developed for this study differed from those presented in Bieger *et al.* (2015). Percent differences between exponent values in this and the Bieger *et al.* (2015) study were >15% for the Appalachian Plains (17%), Interior Highlands (51%), Intermontane

Plateau (75%), and Pacific Mountain System (28%). As with bankfull cross-sectional area and width, the larger dataset produced regional curves with lower R^2 values.

Regionalization by Physiographic Province. The results indicate that the relationship $h + k = d$ and $g{\cdot}j = c$ occurred for all of the physiographic divisions except the Coastal Plain, Columbia Plateau, and Superior Upland (Table 9). For the Coastal Plain, the sum of the coefficients h and k was 0.60 while the value for the coefficient d was 0.43, a difference of 33%. The product of the exponents g and j was 0.43 while the value for the exponent c was 1.84, which was a difference of 124%. For the Columbia Plateau, the sum of the coefficients h and k was 0.57 while the value for the coefficient d was 4.71, a difference of 157%. The product of the exponents g and j was 0.33 while the value for the exponent c was 0.01, which was a difference of 188%. Lastly, for the Superior Upland, the sum of the coefficients h and k was 0.64 while the value for the coefficient d was 0.46, a difference of 33%. The product of the exponents g and j was 0.41 while the value for the exponent c was 1.14, which was a difference of 44%.

Bankfull Discharge. Due to lack of discharge data for each physiographic province, bankfull discharge regional curves were developed for only 21 of the 24 areas. Fifteen physiographic provinces had a good fit, two a moderate fit, and four a poor fit (Table 9). The mean value for the exponent of the bankfull discharge regression equation (b in $Q_{\mathrm{bkf}} = aA_w{}^b$) was 0.71. This mean value agrees well with values presented in the literature for bankfull discharge regional curves developed in the eastern and western portions of the U.S. (Dunne and Leopold, 1978; Elliott and Cartier, 1986; Dutnell, 2000; Castro and Jackson, 2001; Moody *et al.*, 2003; Emmert, 2004; Lawlor, 2004; Brockman *et al.*, 2012). Exponent values ranged between a low of 0.01 for the Basin and Range physiographic province to a high of 1.05 for the Superior Upland.

Bankfull Cross-sectional Area. For bankfull cross-sectional area, 18 of the physiographic province regional curves had a good fit, two a moderate fit, and four a poor fit (Table 9). The mean value for the exponents of the bankfull cross-sectional area regression equations (d in $A_{\mathrm{bkf}} = cA_w{}^d$) was 0.77. Exponent values generally ranged between 0.40 and 0.80 though the Columbia Plateau had a much higher exponent at 4.71. This range extends lower than typical values presented in the literature (0.62-0.81) for bankfull cross-sectional area regional curves developed in the eastern and western portions of the U.S. (Dunne and Leopold, 1978; Elliott and Cartier, 1986; Dutnell, 2000; Castro and Jackson, 2001; Moody *et al.*, 2003; Emmert, 2004; Lawlor, 2004; Brockman *et al.*, 2012).

Bieger *et al.* (2015) developed bankfull cross-sectional area regional curves of 18 of the 24 physiographic provinces (the authors presented R^2 values, but not regression equations, for Adirondack and St. Lawrence Valley). As the Laurentian Plain has only one physiographic province, the regional curve for the Superior Upland is the same as the regional curve for the Laurentian Plain physiographic province. The Atlantic Plain consists of two physiographic provinces, the Continental Shelf and the Coastal Plain. Since no data were available for the Continental Shelf, the regional curves for the Coastal Plain are the same as those for the Atlantic Plain physiographic province. Insufficient data were available to develop regional curves for the Adirondack, St. Lawrence Valley, Ouachita, Lower Californian, Middle Rocky Mountains, or Southern Rocky Mountains physiographic provinces. As with the physiographic division regional curves, the exponents and coefficients for the physiographic province regional curves differed between this study and Bieger *et al.* (2015). In some cases, the values were greater for this study; in others, they were greater for Bieger *et al.* (2015). R^2 values were higher for the Bieger *et al.* (2015) regional curves except for the St. Lawrence Valley, Great Plains, Columbia Plateau, and Cascade-Sierra Mountains physiographic provinces where R^2 values were higher for this study.

Bankfull Width. For bankfull width, 22 of the physiographic province regional curves had a good fit and two (Coastal Plain and Colorado Plateaus) had a poor fit (Table 9). The mean value for the exponents of the bankfull width regression equations (h in $A_{\mathrm{bkf}} = gA_w{}^h$) was 0.40. Exponent values were generally between 0.30 and 0.50 and agree well with values presented in the literature (0.28-0.47) for bankfull width regional curves developed in the eastern and western portions of the U.S. (Dunne and Leopold, 1978; Elliott and Cartier, 1986; Dutnell, 2000; Castro and Jackson, 2001; Moody *et al.*, 2003; Emmert, 2004; Lawlor, 2004; Brockman *et al.*, 2012). The Colorado Plateaus physiographic province had the lowest exponent at 0.25 and the Wyoming physiographic province had the highest at 0.56.

Bieger *et al.* (2015) developed bankfull width regional curves for 20 of the 24 physiographic provinces (same physiographic provinces used to develop the bankfull cross-sectional area regional curves with the addition of the Middle Rocky Mountains and Wyoming Basin physiographic provinces). Exponents and coefficients differed between the two studies for all physiographic provinces though regression equations for Appalachian Plateaus, Piedmont, Interior Low Plateaus, Northern Rocky Mountains, and Southern

Rocky Mountains were quite similar. R^2 values were higher for the Bieger *et al.* (2015) study for 12 physiographic provinces while this study had higher R^2 values for eight studies (two R^2 values did not differ between the studies).

Bankfull Mean Depth. As with the other sets of regional curves (contiguous U.S., HLR, and physiographic province), the physiographic province bankfull mean depth regional curves had many poor fits (17) with only a few good (5) and moderate (2) fits. The mean value for the bankfull mean depth regression equations (k in $A_{\mathrm{bkf}} = jA_w{}^k$) was 0.21. The range of exponents found in this study (0.00-0.37) extends lower than typical values presented in the literature (0.25-0.43) for bankfull mean depth regional curves developed in the eastern and western portions of the U.S. (Dunne and Leopold, 1978; Elliott and Cartier, 1986; Dutnell, 2000; Castro and Jackson, 2001; Moody *et al.*, 2003; Emmert, 2004; Lawlor, 2004; Brockman *et al.*, 2012).

As with bankfull width, Bieger *et al.* (2015) developed bankfull mean depth regional curves for the same 20 physiographic provinces. In most instances, R^2 values were higher for the Bieger *et al.* (2015) regional curves except for the Central Lowland, Great Plains, Middle Rocky Mountains, and Wyoming physiographic provinces.

Comparison of Regional Curves. Contiguous U.S. *vs*. HLR. Localized regional curves for individual HLRs tended to outperform (*i.e.*, higher R^2 and lower SE_r) the contiguous U.S. regional curves for bankfull discharge, cross-sectional area, and width, however, the majority (70%) of regional curves (HLRs and contiguous U.S.) had poor fits for bankfull mean depth. Only two HLR regional curves had poorer fits for bankfull discharge (HLRs 4 and 10), four for bankfull cross-sectional area (HLRs 4, 8, 14, and 17), three for bankfull width (HLRs 4, 5, and 17), and seven for bankfull mean depth (HLRs 2, 4, 8, 10, 14, 17, and 20) as compared to the contiguous U.S. About 63% of the HLRs that exhibited a poorer fit than the contiguous U.S. for bankfull discharge, cross-sectional area and/or width occur in arid (HLRs 5, 10, and 14) or semiarid (HLRs 8 and 17) climates. Not all HLRs with semiarid climates exhibited poor fits for bankfull discharge, cross-sectional area and/or width. HLRs 12, 13, 15, and 18 occur in semiarid climates and displayed good fits, in all but one instance, for bankfull discharge, cross-sectional area, and width (all had poor fits for bankfull mean depth).

The reason why some semiarid HLRs had poor fits for bankfull cross-sectional area and width while others had good/moderate fits is unknown. One difference between the arid and semiarid HLRs with good/moderate fits and the arid and semiarid HLRs with poor fits is the number of sites available for analysis. With the exception of HLRs 8 and 17, all arid and semiarid HLRs with poor fits were comprised of data from <75 sites (40 for HLR 5, 34 for HLR 10, and 73 for HLR 14). A similar aspect was noted with HLR 2 (83 sites) and 20 (76 sites), both of which are located in humid climates. However, not all HLRs with lower numbers of sites produced poorer fits (*e.g.*, HLRs 1, 3, 15, and 19). The higher levels of variability associated with bankfull parameters is possibly linked to landscape factors such as the number and location of reservoirs upgradient in the watershed (Deitch *et al.*, 2013), level of irrigation or water withdrawal within the watershed (Kendy and Bredehoeft, 2006; Caskey *et al.*, 2014), reliance or lack thereof on snowmelt (USGS, 2005; Miller and Piechota, 2011), type of streamside vegetation (Hession *et al.*, 2003), and degree of urbanization (Doll *et al.*, 2002; Cianfrani *et al.*, 2006; Annable *et al.*, 2010). These factors may have influenced assessed streams unequally within and across these arid and semiarid HLRs, more so than the humid and subhumid HLRs. Faustini *et al.* (2009) had a similar result in the western U.S. using physiographic regions. Wolman and Gerson (1978) found that temperate zone streams that were widened by extreme floods could recover their original shape within a period of months while the period of recovery for streams located in arid and semiarid regions could be on the order of decades. Copeland *et al.* (2000) found that streams located in arid and semiarid environments where vegetation was lacking were prone to adjustment with each major flood event.

Contiguous U.S. *vs*. Physiographic Division/Physiographic Province. Regional curves developed for individual physiographic divisions tended to outperform the contiguous U.S. regional curves for bankfull discharge, cross-sectional area, width, and mean depth (Table 8). For bankfull discharge, R^2 values were higher and SE_r values were lower for all physiographic divisions except the Interior Plains (R^2 was lower and SE_r was higher) and Pacific Mountain System (R^2 was lower and SE_r was lower). Bankfull cross-sectional area regional curve R^2 values were higher and SE_r values were lower for five physiographic divisions as compared to the contiguous U.S. R^2 values were lower and SE_r values were higher for the Atlantic Plain and Intermontane Plateau. R^2 values were lower and SE_r values were lower for the Laurentian Upland. For bankfull width, R^2 values where higher and SE_r values lower or the same for six physiographic province regional curves. Lower R^2 and higher SE_r values were noted for the Atlantic Plain while a lower R^2 and equal SE_r were noted for the Interior Plains. For bankfull mean depth, R^2 values were higher and SE_r values were lower for only two physiographic divisions (Appalachian Highlands and Rocky Mountain System) as compared to the contiguous U.S. Across all bankfull parameters, regional curves developed for physiographic divisions in the Midwest or western U.S. tended to perform more poorly than those developed for the eastern U.S.

Regional curves developed for individual physiographic provinces also tended to outperform the regional curves developed for the contiguous U.S. (Table 9). For bankfull discharge, R^2 values were higher and SE_r values were lower for 76% of the physiographic provinces for which data were available to develop bankfull discharge regional curves. The exceptions were Basin and Range, Central Lowland, and Cascade-Sierra Mountains, which had lower R^2 values and lower SE_r values. The Colorado Plateaus had higher R^2 and higher SE_r values while the Great Plains had lower R^2 and higher SE_r values. For bankfull cross-sectional area, the physiographic province regional curves had higher R^2 and lower SE_r values for 75% of the models. Only the Coastal Plain and Colorado Plateaus had both lower R^2 and higher SE_r values as compared to the contiguous U.S. The Lower Californian, Ozark Plateaus, and Superior Upland physiographic provinces had lower R^2 and lower SE_r values. Only the Pacific Border had higher R^2 and lower SE_r values. Similar to bankfull cross-sectional area, the physiographic province bankfull width regional curves posted higher R^2 and lower SE_r values for 88% of the models. Again, only the Coastal Plain and Colorado Plateaus physiographic provinces had lower R^2 and higher SE_r values. The Basin and Range physiographic province had a higher R^2 value and the same SE_r value. The physiographic province bankfull mean depth models outperformed the contiguous U.S. model at the lowest rate (50%) with six physiographic provinces (Basin and Range, Coastal Plain, Colorado Plateaus, Great Plains, Pacific Border, and Superior Upland) posting both lower R^2 and higher SE_r values. The Blue Ridge, Central Lowland, Lower Californian, Middle Rocky Mountains, Ouachita, and Ozark Plateaus physiographic regions had lower R^2 and lower SE_r values. As with physiographic divisions, bankfull regional curves developed for physiographic provinces located in midwestern or western portions of the U.S. did not perform as well as models developed for the eastern U.S.

Physiographic Division *vs.* Physiographic Province. The effect of separating physiographic divisions into physiographic provinces was investigated. For this analysis, the Laurentian Upland (Superior Upland) and Atlantic Plain (Coastal Plain) were not considered as these physiographic divisions could not be further separated. For bankfull discharge, the Interior Highlands (Ouachita and Ozark Plateaus) was not included as insufficient discharge data were available. Further stratification of physiographic divisions into physiographic provinces both increased R^2 values and lowered or maintained SE_r values for 35% of the bankfull discharge, 55% of the bankfull cross-sectional area, 59% of the bankfull width, and 41% of the bankfull mean depth regional equations. Bieger *et al.* (2015) also noted that increased stratification improved bankfull regional curve models provided sufficient data are available (*i.e.*, dataset size limits the levels of stratification).

HLR *vs.* Physiographic Division/Physiographic Province. Regional curves developed using HLR as a basis performed equivalently as regional curves developed using physiographic province as a basis. For HLR regional curves, increases in R^2 and decreases in SE_r, as compared to the contiguous U.S., were noted for 75% of the bankfull discharge, 75% of bankfull cross-sectional area, 75% of bankfull width, and 55% of mean bankfull depth regional curves. Using physiographic provinces as a basis, R^2 value increased and SE_r values decreased for 65% of the bankfull discharge, 82% of the bankfull cross-sectional area, 91% of the bankfull width, and 55% of the bankfull mean depth regional curves. The mean R^2 and SE_r values for bankfull discharge, cross-sectional area, width, and mean depth for HLR-based regional curves ($R^2 = 0.66$ and $SE_r = 0.41$ for Q_{bkf}; $R^2 = 0.66$ and $SE_r = 0.38$ for A_{bkf}; $R^2 = 0.71$ and $SE_r = 0.22$ for W_{bkf}; and $R^2 = 0.41$ and $SE_r = 0.24$ for D_{bkf}) were similar to those for the physiographic province regional curves ($R^2 = 0.64$ and $SE_r = 0.32$ for Q_{bkf}; $R^2 = 0.66$ and $SE_r = 0.33$ for A_{bkf}; $R^2 = 0.72$ and $SE_r = 0.20$ for W_{bkf}; and $R^2 = 0.42$ and $SE_r = 0.21$ for D_{bkf}).

Effect of Physiographic Province Stratification by HLR. The effect of further stratifying physiographic province by HLR was investigated by developing these regional curves provided sufficient data were available. For this analysis, the minimum threshold was set at eight data points. Table S1 contains the resultant regional curves for the bankfull parameters discharge, cross-sectional area, width, and mean depth. This additional level of stratification increased R^2 values, above those for the physiographic province regional curves, by 57% for bankfull discharge, 61% for bankfull cross-sectional area, 61% for bankfull width, and 57% for bankfull mean depth. Different HLRs within the same physiographic province may have markedly different exponents and coefficients. When these HLRs are aggregated over a larger area, such as a physiographic province, these differences are oftentimes “lost,” particularly if an HLR has a small percentage of data points as compared to other HLRs. For example, the bankfull cross-sectional area regional curve for the Coastal Plain physiographic province is of the form $A_{bkf} = 1.84A_w^{0.43}$ ($R^2 = 0.38$).

For a 25 km^2 drainage area, this equation predicts a bankfull cross-sectional area of 7.34 m^2. Stratification of the Coastal Plain by HLR (see Table S1 for regional curves) produces four HLR-based regional curves with R^2 values of 0.92 (HLR 1), 0.89 (HLR 2), 0.77 (HLR 3), and 0.50 (HLR 6) with the following predicted bankfull cross-sectional areas for a 25 km^2 drainage area: 3.90 m^2 for HLR 1, 5.70 m^2 for HLR 2, 5.83 m^2 for HLR 3, and 4.84 m^2 for HLR 6. These bankfull cross-sectional areas are 61% (HLR 1), 25% (HLR 2), 23% (HLR 3), and 41% (HLR 6) smaller than the bankfull cross-sectional area predicted, using the Coastal Plain regional curve.

CONCLUSIONS

As noted by Leopold and Maddock (1953), drainage area is directly related to the bankfull parameters discharge, cross-sectional area, width, and mean depth. Recognition of this linkage has spurred the development of numerous regional curves throughout the U.S. (Table 2), many of which are used as aids in stream assessment and restoration designs. Little research has explored the geographic limits of regional curves outside of the physiographic region in which said curves were developed (Castro and Jackson, 2001; Bieger *et al.*, 2015). Using drainage area and bankfull discharge, cross-sectional area, width, and mean depth data from 2,856 sites, this study developed regional curves for (1) the contiguous U.S, (2) each of the 20 HLRs defined by Wolock *et al.* (2004), (3) each of the eight physiographic provinces, (4) 22 of the 25 physiographic provinces, and (5) individual HLRs within each physiographic province. Comparisons were made between these sets of regional curves and to previously published regional curves.

In most instances, localized regional curves for individual HLRs outperformed (*i.e.*, higher R^2 and lower SE_r) the contiguous U.S. regional curves for bankfull discharge, cross-sectional area, and bankfull width though 70% of developed curves showed a poor fit ($R^2 < 0.5$) for bankfull mean depth. Individual HLR regional curves with good ($R^2 \geq 0.6$) fits were developed for 70% of the HLRs for bankfull discharge; an additional 20% of the HLRs had moderate fits ($0.5 \leq R^2 < 0.6$). For bankfull cross-sectional area, 80% had good fits while an additional 5% had a moderate fit. For bankfull width, 80% of the HLRs had good fits while an additional 20% had moderate fits. Only 30% of the HLRs exhibited a good or moderate fit for bankfull mean depth. Regional curves developed for HLRs 4, 8, 10, 14, and 17 had poor fits for at least two out of the four bankfull parameters. With the exception of HLR 4, these HLRs are primarily located in the arid or semiarid climates of the western U.S. Results from this study along with those from Faustini *et al.* (2009) suggest that streams located in HLRs in arid or semiarid environments or those influenced differently by anthropogenic activities (*e.g.*, reservoirs, irrigation, grazing, and urbanization) are bound by a different stream evolution model than streams located in HLRs in humid or subhumid climates.

Regional curves developed for individual physiographic divisions and provinces tended to outperform regional curves developed for the contiguous U.S. Increased levels of stratification (U.S. to division to province) improved the bankfull regional curves, given sufficient data were available, a trend that was also noted by Bieger *et al.* (2015). The contiguous U.S., physiographic division, and physiographic province regional curves developed by Bieger *et al.* (2015) tended to outperform the regional curves developed in this study. This study used 1,290 more sites. This nearly 60% increase in sites generally resulted in smaller R^2 values and produced less reliable regional curves, possibly due to the introduction of more variability. The inclusion of additional sites allowed for a greater spatial representation of each physiographic division and province, meaning nonuniformities of each physiographic division and province were more readily captured in the dataset. As with HLRs, bankfull regional curves developed for physiographic divisions and provinces located in midwestern or western portions of the U.S. (*i.e.*, semiarid and arid environments) did not perform as well as models developed for the eastern U.S., which is characterized by humid and subhumid environments.

Using HLR as a basis to further stratify physiographic province markedly improved the reliability of the regional curves. R^2 values for the HLR-based physiographic province regional curves were higher for all bankfull parameters (57% for bankfull discharge, 61% for bankfull cross-sectional area, 61% for bankfull width, and 57% for bankfull mean depth). Separating physiographic provinces by HLR often improved R^2 values, especially if the physiographic province included HLRs that tended to have poorer fits, such as HLRs 4, 8, 10, 14, and 17.

Results from this study provide stream restoration practitioners with multiple sets of regional curves, particularly the HLR stratified physiographic province regional curves, for use in stream assessment and restoration design procedures. Regional curves assist in the identification of bankfull elevation in the field, particularly in instances when bankfull indicators are sparse (Metcalf *et al.*, 2009; Brockman *et al.*, 2012). Correct identification of bankfull elevation aids in the determination of the degree of channel incision. Regional curves are also useful for providing a starting point in the iterative natural channel design process (Hey, 2006; USDA-NRCS, 2007). Furthermore, using HLR as a basis instead of physiographic province alone (Fenneman, 1917), it (1) may be possible to develop more robust regional curves for a project site and (2) may allow the utilization of curves developed for other parts of the U.S. in areas lacking regional curves. The results of this study and the Bieger *et al.* (2015) study highlight the importance of further subdividing areas with large amounts of spatial variability, as related to geology, climate, land-surface form, riparian vegetation, and/or anthropogenic activities, into smaller more homogenous units when developing regional curves.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: A series of figures showing the bankfull regional curves (discharge, cross-sectional area, width, and mean depth) for each HLR (Figures S1-S20); and regression equations for each HLR within each physiographic province within the contiguous U.S. (Table S1).

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