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DEVELOPMENT AND EVALUATION OF BANKFULL HYDRAULIC GEOMETRY RELATIONSHIPS FOR THE PHYSIOGRAPHIC REGIONS OF THE UNITED STATES[1]

Katrin Bieger, Hendrik Rathjens, Peter M. Allen, and Jeffrey G. Arnold[2]

ABSTRACT: Bankfull hydraulic geometry relationships are used to estimate channel dimensions for streamflow simulation models, which require channel geometry data as input parameters. Often, one nationwide curve is used across the entire United States (U.S.) (e.g., in Soil and Water Assessment Tool), even though studies have shown that the use of regional curves can improve the reliability of predictions considerably. In this study, regional regression equations predicting bankfull width, depth, and cross-sectional area as a function of drainage area are developed for the Physiographic Divisions and Provinces of the U.S. and compared to a nationwide equation. Results show that the regional curves at division level are more reliable than the nationwide curve. Reliability of the curves depends largely on the number of observations per region and how well the sample represents the population. Regional regression equations at province level yield even better results than the division-level models, but because of small sample sizes, the development of meaningful regression models is not possible in some provinces. Results also show that drainage area is a less reliable predictor of bankfull channel dimensions than bankfull discharge. It is likely that the regional curves can be improved using multiple regression models to incorporate additional explanatory variables.

(KEY TERMS: streams; fluvial geomorphology; bankfull discharge; nationwide and regional regression equations; hydrologic modeling.)

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INTRODUCTION

Attempts to predict processes at regional scales are often limited by the spatial information that is available. Obtaining representative channel geometries is crucial for improving the predictive capabilities of watershed models. Many hydrologic models, such as the Soil and Water Assessment Tool (SWAT) (Arnold *et al.*, 1998) and Hydrologic Simulation Program-Fortran (HSPF) (Bicknell *et al.*, 1997), require channel dimensions, e.g., bankfull width, depth, and cross-sectional area, as input parameters (Ames *et al.*, 2009). Hydraulic geometry (HG) relationships are frequently used not only for stream classification and natural channel design but also to provide such data for hydrologic modeling studies.

The concept of HG was first introduced by Leopold and Maddock (1953) to describe the dependency of channel dimensions on discharge within specific river

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[2] Postdoctoral Research Associate (Bieger), Blackland Research and Extension Center, Texas A&M AgriLife, 720 E. Blackland Road, Temple, Texas 76502; Postdoctoral Research Associate (Rathjens), Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, Indiana 47907; Professor (Allen), Department of Geology, Baylor University, Waco, Texas 76798; and Research Agricultural Engineer (Arnold), Grassland, Soil and Water Research Laboratory, USDA-ARS, Temple, Texas 76502 (E-Mail/Bieger: kbieger@brc.tamus.edu).

basins. Based on a study of gauging station records for 20 large rivers in the Great Plains and in the southwestern United States (U.S.), they expressed the relationship between average annual discharge and channel width, depth, and flow velocity in terms of simple power functions (Dingman, 2007). Bankfull HG relationships use bankfull discharge instead of average annual discharge as the independent variable to predict channel dimensions (Leopold *et al.*, 1964). Bankfull discharge is a deterministic discharge representing the channel-forming discharge in a stream (Copeland *et al.*, 2000). It is defined as the highest flow a channel can convey before it starts to spill onto its floodplain (Leopold *et al.*, 1964) and can be identified in the field using physical indicators (Mulvihill and Baldigo, 2012).

As the use of discharge as the independent variable limits the applicability of HG equations to gauged stream reaches (Ames *et al.*, 2009), Dunne and Leopold (1978) introduced the use of drainage area as a surrogate for discharge. Acquiring complete channel geometry measurements can be time consuming and cost prohibitive, while bankfull HG curves can provide the channel dimensions that are required by hydrologic models by using only the drainage area, which can be derived from readily available Digital Elevation Models (Cinotto, 2003; Chaplin, 2005; Faustini *et al.*, 2009). In addition, Dunne and Leopold (1978) developed HG relationships on a regional level. Based on the assumption that within a physiographic region the geology, soil, climate, and hydrology are similar, they expected HG relationships to be similar within these definable regions. These regional curves illustrate channel dimensions as a function of drainage area on log-log plots.

Regional HG curves such as those developed by Dunne and Leopold (1978) were never widely applied for hydrologic models as they lacked applicable equations for larger geographic use. Allen *et al.* (1994) pointed out that measured channel dimensions required to develop such equations are usually not available over large geographic areas. Nevertheless, the data presented by Dunne and Leopold (1978) indicated major regional differences in channel dimensions, which justifies recent trends toward more detailed regional curves in order to more accurately assess HG in areas of varying physiography and climate. Recently, more localized HG curves have been developed for many areas across the country to address classification and natural channel design restoration needs (Mulvihill and Baldigo, 2012). An increasing use of bankfull HG relationships for the design of stream restoration projects has resulted in a number of studies carried out all over the U.S. (Harman *et al.*, 1999; Smith and Turrini-Smith, 1999; Harman *et al.*, 2000; Castro and Jackson, 2001; White, 2001; McCandless and Everett, 2002; Cinotto, 2003; McCandless, 2003a, b; Sweet and Geratz, 2003; Emmert, 2004; Messinger and Wiley, 2004; Powell *et al.*, 2004; Babbit, 2005; Keaton *et al.*, 2005; Mohamoud and Parmar, 2006; Mulvihill *et al.*, 2006; Vesely *et al.*, 2008; Padmanabhan and Johnson, 2010).

The studies listed above provide a useful dataset to develop regional bankfull HG equations that can be used in hydrologic models. Currently, many models use bankfull HG relationships that were developed for large geographic areas. For example, the SWAT (Arnold *et al.*, 1998), which is also integrated in the environmental analysis system BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) developed by the U.S. Environmental Protection Agency, uses nationwide equations to estimate bankfull channel width and depth (Raghavan Srinivasan, personal communication, 2014).

In this study, we hypothesize that regional equations provide more reliable predictions of bankfull channel dimensions than a nationwide curve and therefore should be used in hydrologic models to predict channel dimensions. Therefore, the objectives were to use a large database of bankfull HG data compiled from over 50 different publications (1) to develop bankfull HG relationships for the conterminous U.S. and for physiographic regions at different spatial levels, (2) to compare the regional regression equations and determine if they are more accurate than the nationwide equation, and (3) to assess the performance of drainage area as a surrogate for bankfull discharge.

MATERIALS AND METHODS

Database

We used a large dataset comprising bankfull HG data for sites in the conterminous U.S. published by almost 50 different authors over the past 50 years (Table 1). The original database compiled from these literature sources contained data for a total of 1,861 sites. However, the selected datasets were inconsistent in the number and type of variables they contained. Datasets were only considered suitable for analysis in this study when data on latitude and longitude, drainage area, and at least one of the variables bankfull width, depth, and cross-sectional area were available. Datasets that did not meet the above criteria were omitted from analysis. Also, no urban streams were included in the database. There

TABLE 1. Sources of Bankfull Hydraulic Geometry Data Compiled in This Study.

References	Number of Sites	States
Andrews (1984)	24	Colorado
Babbit (2005)	10	Tennessee
Brockman (2010)	29	Kentucky
Castro and Jackson (2001)	75	Idaho, Oregon, Washington
Chaplin (2005)	52	Maryland, Pennsylvania
Cinotto (2003)	14	Maryland, Pennsylvania
Doll *et al.* (2003)	16	North Carolina
Dudley (2004)	10	Maine
Dutnell (2000)	48	Kansas, Missouri, Oklahoma, Texas
Eash (1993)	111	Iowa
Elliott and Cartier (1986)	18	Colorado
Emmett (1975)	39	Idaho
Harman *et al.* (1999)	13	North Carolina
Harman *et al.* (2000)	14	North Carolina
Haucke and Clancy (2011)	12	Wisconsin
Howell (2009)	8	California
Jaquith and Kline (2006)	20	Vermont
Johnson and Padmanabhan (2010); Padmanabhan and Johnson (2010)	22	Minnesota, North Dakota
Keaton *et al.* (2005)	41	Maryland, Virginia, West Virginia
King *et al.* (2004)	33	Idaho
Krstolic and Chaplin (2007)	8	Maryland, Virginia
Lawlor (2004)	41	Montana
Leopold and Wolman (1957)	19	Maryland, Montana, Nebraska, Wyoming
Lotspeich (2009)	17	Virginia
Mater *et al.* (2009)	20	Kentucky
McCandless (2003a)	14	Maryland, Pennsylvania
McCandless (2003b)	14	Delaware, Maryland
McCandless and Everett (2002)	25	Maryland
McPherson (2011)	16	Tennessee
Messinger (2009)	37	West Virginia
Metcalf (2004)	26	Alabama, Florida, Georgia
Mistak and Stille (2008)	5	Michigan, Wisconsin
Moody *et al.* (2003)	183	Arizona, New Mexico, Navajo Nation
Mulvihill and Baldigo (2007)	12	New York
Mulvihill *et al.* (2005)	14	New York
Mulvihill *et al.* (2006)	10	New York
Mulvihill *et al.* (2007)	16	New York
Miller and Davis (2003); Mulvihill *et al.* (2009)	14	New York
Osterkamp *et al.* (1982)	17	Kansas
Parola *et al.* (2005a)	13	Kentucky
Parola *et al.* (2005b)	5	Kentucky
Parola *et al.* (2007)	20	Kentucky
Parrett *et al.* (1983)	209	Montana
Pruitt (2001)	6	Georgia
Pugh *et al.* (2008)	9	Arkansas
Rachol and Boley-Morse (2009)	40	Michigan
Sherwood and Huitger (2005)	50	Ohio
Sweet and Geratz (2003)	24	North Carolina
Vesely *et al.* (2008)	26	Kentucky
Westergard *et al.* (2005)	16	New York
Williams (1978)	51	Arizona, Colorado, Kentucky, Massachusetts, New Mexico, North Dakota, Oregon, Pennsylvania, Tennessee, Utah, West Virginia, Wisconsin, Wyoming

were a few sites where data from two different literature sources were available. In these cases, the more complete dataset was used for analysis while the other one was excluded.

According to McManamay *et al.* (2011), “regional frameworks inform management by relating spatial patterns to ecological and physical variables at the landscape scale.” They conclude from their study examining different regional frameworks applied to hydrology that the development of regional frameworks is appropriate and useful. Simon *et al.* (2004) point out the importance of placing existing data in a conceptual and analytical framework so that they can be used at ungauged sites. In this study, we used Physiographic Divisions and Provinces to stratify the available data. To distinguish different physiographic regions in the U.S., Fenneman and Johnson (1946) developed a classification system that is based on topography and geology. According to this system, the conterminous U.S. are divided into eight Physiographic Divisions: the Laurentian Upland, the Atlantic Plain, the Appalachian Highlands, the Interior Plains, the Interior Highlands, the Rocky Mountain System, the Intermontane Plateau, and the Pacific Mountain System. Each Physiographic Division is subdivided into Physiographic Provinces and Sections. Even though within each of the regions, there is a range of stream types, gross characteristics of the streams can be summarized and stream processes can be investigated broadly (Johnson, 2006). Johnson and Fecko (2008) used Physiographic Provinces in the Eastern U.S. as a regional framework for developing channel geometry equations and concluded that at a large scale they provide appropriate boundaries. Moyer and Bennett (2007) developed separate bankfull HG relationships for four Physiographic Provinces in the Chesapeake Bay Watershed and obtained satisfactory simulation results when using the estimated channel dimensions as input data for the model HSPF.

After exclusion of duplicate datasets and datasets that were not suitable for analysis because of a lack of critical data, the database contained a total of 1,310 sites. However, there is not necessarily data available for all the variables used for analysis at all sites. Also, the number of datasets varies considerably among the eight Physiographic Divisions. Table 2 lists the number of sites with data available for the variables drainage area and bankfull discharge, width, depth, and cross-sectional area per Physiographic Division and for the conterminous U.S. The database is available for download under http://swat.tamu.edu/publications/.

Summarizing, the data required for this assessment are available for a relatively large number of sites in the Appalachian Highlands (387), the Interior Plains (425), and the Rocky Mountain System (288) (Figure 1 and Table 2). Even though the largest number of sites is available for the Interior Plains, due to the vast extent of this Physiographic Division there are large spatial gaps in the data. In the Appalachian Highlands and the Rocky Mountain System, the sites are relatively well distributed and cover almost the entire region (Figure 1). Data are available for considerably fewer sites in the Atlantic Plain (61), the Intermontane Plateau (88), the Pacific Mountain System (48), and especially the Laurentian Upland (6) and the Interior Highlands (7), so there are considerable spatial gaps in the data. Even though the latter two are very small regions and therefore spatial gaps in the data are not larger than in the former three regions, the sites are strongly clustered, so only a small fraction of the area of each region is represented by the sample sites (Figure 1 and Table 2).

For all five variables (drainage area and bankfull discharge, width, depth, and cross-sectional area), the largest range of values occurs in the Interior Plains and the smallest in the Laurentian Upland. This is partly an effect of sample size, but the broad geographic extent of the Interior Plains spanning a large climatic gradient probably also contributes to the wide range of channel dimensions in this Physiographic Division. The second and third largest ranges of drainage areas occur in the Rocky Mountain System and in the Pacific Mountain System, while the remaining variables exhibit larger ranges in the Pacific Mountain System than in the Rocky Mountain System. The Intermontane Plateau, the Atlantic Plain, the Appalachian Highlands, and the Interior Highlands rank fourth, fifth, sixth, and seventh with regard to the maximum range of drainage areas, while their ranks with regard to the ranges of bankfull discharge, width, depth, and cross-sectional area are highly variable (Table 2). Bankfull channel dimensions are generally greater in the Laurentian Upland, the Interior Highlands, and the Pacific Mountain System than in the remaining Physiographic Divisions, which is most likely an artifact of sampling bias toward higher discharge streams.

Regression Equations

Linear regression models relating the independent variable of drainage area to the dependent variables of bankfull width, depth, and cross-sectional area were developed for the conterminous U.S. and for the Physiographic Divisions and Provinces. The regression equations express the mathematical relationships between log-transformed bankfull channel dimensions and drainage area and take the form

$$y = a \cdot \mathrm{DA}^b \tag{1}$$

where y is the dependent variable (bankfull width [m], depth [m], or cross-sectional area [m^2]), DA is the independent variable of drainage area, a is a coefficient indicating the intercept of the regression line, and b is an exponent representing the slope of the regression line.

TABLE 2. Number of Sites with Available Data and the Range and Median of Drainage Area and Bankfull Discharge, Width, Depth, and Cross-Sectional Area per Physiographic Division.

Physiographic Division	Drainage Area (km^2)	Bankfull Discharge (m^3/s)	Bankfull Width (m)	Bankfull Depth (m)	Bankfull Cross-Sectional Area (m^2)
LUP					
No. of sites	6	6	6	6	6
Range	43-948	1.4-45	14-41	0.6-1.7	8.2-69
Median	384	24	27	1.0	25
APL					
No. of sites	61	61	61	61	61
Range	0.8-2,815	0.2-75	2.3-46	0.2-3.1	0.5-108
Median	116	6	11	1.0	10
AHI					
No. of sites	387	374	377	377	377
Range	0.2-2,435	0.2-304	1.7-98	0.2-2.8	0.3-193
Median	81	24	18	0.9	17
IPL					
No. of sites	425	210	414	394	216
Range	0.5-155,213	0.3-1,182	0.8-274	0.1-5.2	0.2-1,705
Median	254	14	17	1.1	15
IHI					
No. of sites	7	5	7	7	7
Range	78-2,484	48-308	33-76	0.7-3.0	28-196
Median	344	103	52	1.3	65
RMS					
No. of sites	288	160	278	273	122
Range	0.4-25,201	0.2-534	1.3-99	0.1-3.7	0.2-243
Median	144	8	10	0.7	5
IMP					
No. of sites	88	79	88	88	88
Range	9.4-19,632	0.03-333	1.3-87	0.03-2.4	0.1-161
Median	607	26	19	0.7	12
PMS					
No. of sites	48	48	48	48	48
Range	16-20,927	5.2-1,123	7.3-183	0.5-5.1	8.7-907
Median	778	114	41	1.8	67
USA					
No. of sites	1,310	943	1,279	1,254	925
Range	0.2-155,213	0.03-1,182	0.8-274	0.03-5.2	0.1-1,705
Median	155	17	16	0.9	15

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

The values of the coefficient a and the exponent b were determined by least-squares regression analysis using the logarithms (base 10) of the empirical values of drainage area and bankfull width, depth, and cross-sectional area contained in the database. The logarithmic transformation allows the application of linear techniques even though many of the variables possess moderate positive skewness (Kolberg and Howard, 1995). In accordance with the use of log-transformed variables in the regression analysis, regional curves are illustrated on a log-log scale.

The reliability of the regression equations was analyzed using the coefficient of determination (R^2) and the standard error of estimate (SEE). R^2 is a measure of the fit of the data to the regression line and indicates how well the independent variable accounts for the variability of the dependent variable. SEE is a measure of the precision of regression equation estimates and indicates how well predicted channel dimensions agree with those measured during field surveys. For log-transformed data, an SEE value of x corresponds to a multiplicative SEE of 10^x. Thus, if an HG equation for bankfull width has an SEE of 0.15, then the back-transformed SEE is a multiplicative factor of 1.41 ($10^{0.15}$). So for a predicted width of 10.0 m, a ±1 SEE range would be from 10/1.41 to 10*1.41, i.e., from 7.1 to 14.1 m. To compare the performance of the nationwide and the regional models, the SEE values for the regional models were compared to the SEE values for the national model applied to the subset of sites within each region.

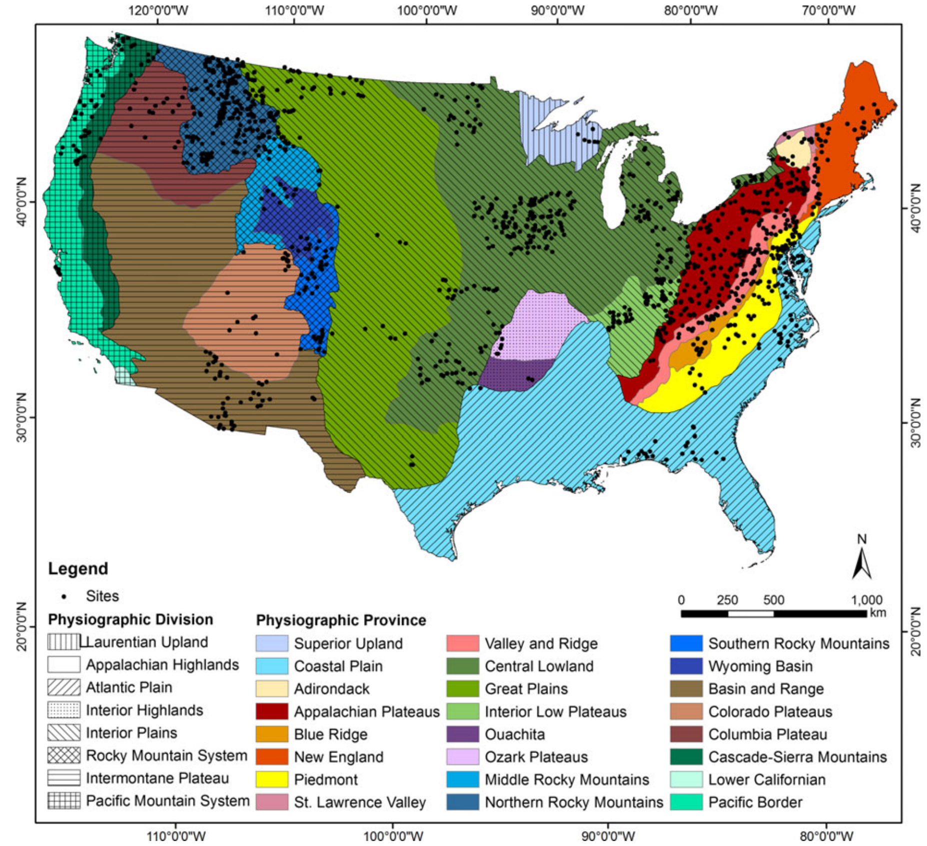

FIGURE 1. Bankfull Hydraulic Geometry Field Survey Sites and Physiographic Divisions of the U.S.

To find out if a finer stratification of the bankfull HG data based on Physiographic Provinces significantly improves the regression equations for bankfull width, depth, and cross-sectional area as a function of drainage area, the R^2, and SEE values for the Physiographic Provinces were compared to those for the corresponding Physiographic Division.

In addition, residuals plots and a table listing the standard errors of slope (SE_S) and intercept (SE_I) are available as an online supplement. SE_S and SE_I indicate the standard deviation of the slope and the intercept of a regression equation and should be smaller than slope and intercept themselves. Large SE_S and SE_I values indicate large, uncertainty in slope and intercept.

In this study, drainage area is used as a surrogate for discharge to enable the application of the regression equations not only to gaged but also to ungaged sites. Various studies have found a high correlation between drainage area and bankfull width, depth, and cross-sectional area (e.g., Dunne and Leopold, 1978; Harman *et al.*, 1999; Smith and Turrini-Smith, 1999; Harman *et al.*, 2000; Castro and Jackson, 2001; McCandless and Everett, 2002; Cinotto, 2003; McCandless, 2003a, b; Sweet and Geratz, 2003; Emmert, 2004; Powell *et al.*, 2004; Babbit, 2005; Keaton *et al.*, 2005). However, unlike discharge, drainage area is not directly responsible for shaping the channel, which makes the bankfull HG relationships based on drainage area less reliable than those based on discharge (Castro and Jackson, 2001; Johnson and Fecko, 2008). Due to differences in watershed shape, drainage pattern, slope, vegetation, land use, and management practices, magnitude and duration of bankfull discharges can vary in watersheds with similar drainage area (USDA-NRCS, 2007). To evaluate the performance of drainage area as a surrogate for bankfull discharge, an additional least-squares regression analysis was performed using bankfull discharge as the independent variable and R^2 and SEE values were compared.

RESULTS

Regional Curves for the Eight Physiographic Divisions and the Conterminous U.S.

Visual examination of the regional curves relating bankfull width, depth, and cross-sectional area to drainage area reveals that there are large differences between some of the regions, while some regions are very similar to each other (Figure 2). In the following paragraphs, the description of results follows the order (1) width, (2) depth, and (3) cross-sectional area, even though in Figure 2 the regional curves for width and depth are plotted below those for cross-sectional area to be comparable to the original plot by Dunne and Leopold (1978, p. 615) showing regional curves for four regions in the U.S.

With regard to bankfull width, the regional curves for the Atlantic Plain and the Interior Plains are very similar to the nationwide curve, whereas the regional curves for the Rocky Mountain System and the Intermontane Plateau plot below the nationwide curve, indicating that bankfull width in these Physiographic Divisions is generally smaller for a given drainage area than the nationwide average. The regional curves for the Laurentian Upland, the Appalachian Highlands, the Interior Highlands, and the Pacific Mountain System plot above the nationwide curve, indicating that bankfull width in these Physiographic Divisions is generally greater than the nationwide average for a given drainage area. The curve for the Interior Highlands, in particular, plots well above the nationwide curve and also is considerably flatter, indicating that bankfull width for streams in this Physiographic Division is considerably larger than the nationwide average for watersheds with drainage areas of about 100 km^2, although the difference becomes smaller with increasing watershed size. However, due to the small sample size, the curve is not necessarily representative of the entire Physiographic Division. The curve for the Laurentian Upland is also slightly flatter than the nationwide curve, whereas the curves for the Appalachian Highlands, the Rocky Mountain System, the Intermontane Plateau, and the Pacific Mountain System are steeper.

The regional curves for the relations between bankfull depth and drainage area for the Laurentian Upland and the Interior Plains are very similar to the nationwide curve, even though the curve for the Interior Plains is flatter than the nationwide curve, indicating that in this region, bankfull depth is larger in small watersheds than on a nationwide average. The regional curves for the Atlantic Plain, Appalachian Highlands, and the Pacific Mountain System are steeper than the nationwide curve and intersect the nationwide curve at drainage areas between about 5 and 30 km^2, indicating that bankfull depths for these Physiographic Divisions increase more rapidly with watershed area and are greater than the nationwide average for watersheds larger than a few tens of square kilometers. The curve for the Interior Highlands follows a similar pattern but does not include watersheds smaller than 78 km^2 and hence lies entirely above the national curve. The curve for the Intermontane Plateau is also considerably steeper than the nationwide curve but plots well below it, indicating that bankfull depth for streams in this Physiographic Division is considerably smaller than the nationwide average for watersheds of similar size, although this difference diminishes for very large watersheds. The curve for the Rocky Mountain System also plots slightly below the nationwide curve but has a similar slope, indicating that bankfull depth for streams in this Physiographic Division tends to be somewhat smaller than the nationwide average.

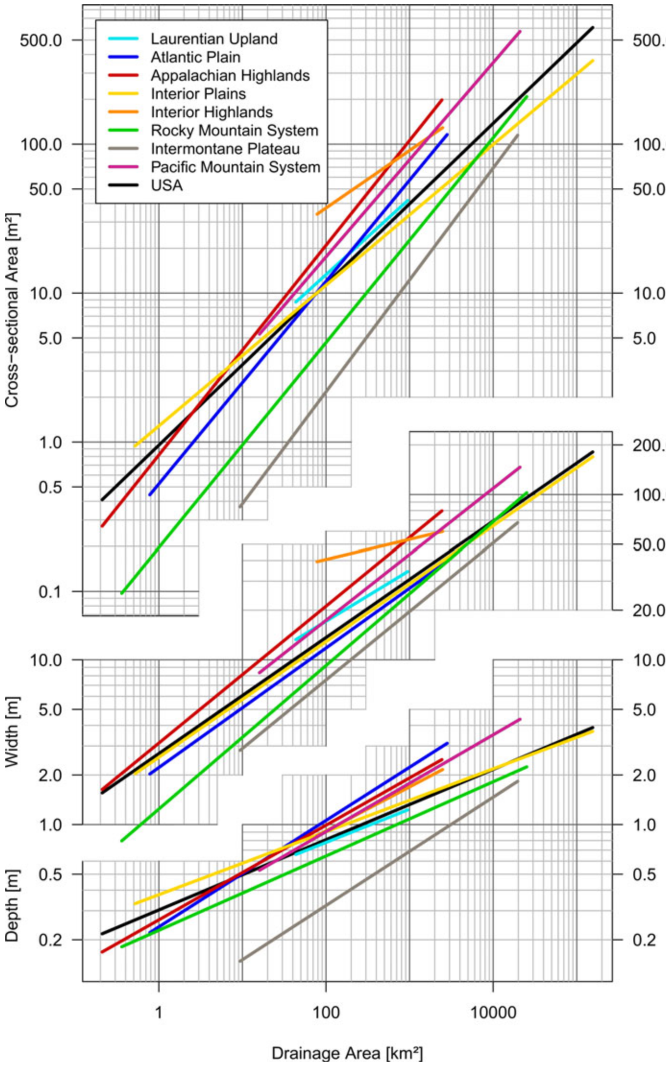

FIGURE 2. Regional and Nationwide Curves Relating Bankfull Width, Depth, and Cross-Sectional Area to Drainage Area.

Visual comparison of the regional curves relating bankfull cross-sectional area to drainage area reveals that the curve for the Laurentian Upland is very similar to the nationwide model, but slightly flatter. The curves for the Interior Highlands and the Interior Plains are also flatter than the nationwide curve and the former additionally plots well above it. The curve for the Interior Plains intersects the nationwide curve at drainage areas of about 80 km^2. The regional curves for the Atlantic Plain, Appalachian Highlands, Rocky Mountain System, Intermontane Plateau, and the Pacific Mountain System are steeper than the nationwide curve. The curves for the Rocky Mountain System and the Intermontane Plateau plot well below the nationwide curve, while the curve for the Pacific Mountain System plots above it. This indicates that bankfull cross-sectional area for streams in these Physiographic Provinces is generally larger and smaller, respectively, than the nationwide average for streams of comparable drainage area. The curves for the Atlantic Plain and the Appalachian Highlands intersect the nationwide curve at drainage areas of about 80 and 2.5 km^2, respectively.

Statistical Evaluation of the Regional and Nationwide Regression Equations

Analysis of the HG relationships and regional curves for the conterminous U.S. and for the eight Physiographic Divisions showed that drainage area is generally a good explanatory variable for bankfull width, depth, and cross-sectional area. Table 3 lists the regression equations for bankfull width, depth, and cross-sectional area as a function of drainage area and the corresponding R^2 and SEE values.

With regard to bankfull width, the regional models for the Atlantic Plain, the Appalachian Highlands, the Interior Plains, the Rocky Mountain System, and the Pacific Mountain System have higher R^2 values than the pooled nationwide model, while the R^2 values for the Laurentian Upland, the Interior Highlands, and the Intermontane Plateau are lower. The regional models predicting bankfull depth as a function of drainage area have higher R^2 values than the nationwide model in all Physiographic Divisions except for the Laurentian Upland and the Interior Plains. Regarding bankfull cross-sectional area, the regional models have higher R^2 values than the nationwide model in all Physiographic Divisions except the Laurentian Upland and the Interior Highlands (Table 3). These results indicate that in 17 of 24 regional models, the drainage area accounts for more variation in bankfull channel dimensions than

TABLE 3. Regional Regression Equations for Bankfull Width, Depth, and Cross-Sectional Area as a Function of Drainage Area and Corresponding R^2 and Standard Error of Estimate (SEE) Values (SEE$_{\mathrm{NAT}}$ = SEE for the national model applied to the subset of sites within each region, SEE$_{\mathrm{PD}}$ = SEE for the regional model, Physiographic Division abbreviations as in Table 2).

	Physiographic Division	No. of Sites	Regression Equation	R^2	SEE$_{\mathrm{NAT}}$	SEE$_{\mathrm{PD}}$
Bankfull width	LUP	6	$4.15DA^{0.308}$	0.54	0.18	0.15
	APL	61	$2.22DA^{0.363}$	0.84	0.14	0.13
	AHI	377	$3.12DA^{0.415}$	0.87	0.22	0.12
	IPL	414	$2.56DA^{0.351}$	0.75	0.22	0.22
	IHI	7	$23.23DA^{0.121}$	0.27	0.41	0.12
	RMS	278	$1.24DA^{0.435}$	0.76	0.26	0.20
	IMP	88	$1.11DA^{0.415}$	0.62	0.36	0.29
	PMS	48	$2.76DA^{0.399}$	0.74	0.22	0.15
	USA	1,279	$2.70DA^{0.352}$	0.66	0.24	—
Bankfull depth	LUP	6	$0.31DA^{0.202}$	0.37	0.14	0.14
	APL	61	$0.24DA^{0.323}$	0.75	0.20	0.15
	AHI	377	$0.26DA^{0.287}$	0.77	0.15	0.12
	IPL	394	$0.38DA^{0.191}$	0.38	0.26	0.25
	IHI	7	$0.27DA^{0.267}$	0.52	0.19	0.15
	RMS	273	$0.23DA^{0.225}$	0.49	0.21	0.19
	IMP	88	$0.07DA^{0.329}$	0.58	0.41	0.25
	PMS	48	$0.23DA^{0.294}$	0.50	0.23	0.19
	USA	1,254	$0.30DA^{0.213}$	0.43	0.23	—
Bankfull cross-sectional area	LUP	6	$1.27DA^{0.509}$	0.50	0.27	0.26
	APL	61	$0.52DA^{0.680}$	0.84	0.26	0.23
	AHI	377	$0.82DA^{0.704}$	0.90	0.31	0.18
	IPL	216	$1.28DA^{0.472}$	0.65	0.38	0.37
	IHI	7	$6.28DA^{0.387}$	0.55	0.53	0.21
	RMS	122	$0.20DA^{0.688}$	0.74	0.50	0.32
	IMP	88	$0.07DA^{0.751}$	0.64	0.78	0.50
	PMS	48	$0.87DA^{0.652}$	0.66	0.42	0.30
	USA	925	$0.95DA^{0.540}$	0.58	0.42	—

in the nationwide model. It is important to note that the Laurentian Upland and the Interior Highlands have sample sizes in the single digits, which is insufficient for the development of meaningful HG relationships. Results for these two Physiographic Divisions are included in the graphs, tables, and analysis for the sake of completeness, but are tentative at best and should only be interpreted with care.

All SEE values for the regional models are equal to or lower than those for the nationwide equation applied to the subset of sites within the corresponding Physiographic Division, indicating a lower deviation of observed data from the data predicted by the regional models than from data predicted by the nationwide model (Table 3). Accordingly, the regional models can be assumed to be more reliable in predicting bankfull channel dimensions than the nationwide model, even though in some cases, the regional models have lower R^2 values than the nationwide model. Since our interest is in predicting bankfull channel dimensions based on drainage area, SEE is in this case a more relevant criterion than R^2.

Table 4 lists the channel dimensions predicted by the regional and nationwide regression equations for watersheds with an area of 1, 10, 100, and 1,000 km^2 and their relative differences. The percentage differences indicate that the channel dimensions predicted using the regional equations differ considerably from those predicted using the nationwide curve, especially with regard to bankfull width and cross-sectional area. Relative differences are particularly high in the Interior Highlands, which can be attributed to the small number of measurement sites in this region and to extrapolating the regional relationship well beyond the range of the regional data used for model development.

Effects of Finer Stratification

To test the effects of a finer stratification of the available data, regional models were also developed for the Physiographic Provinces (Table 5). The Laurentian Upland is not subdivided into provinces and the Atlantic Plain is subdivided into the Continental

TABLE 4. Predicted Channel Dimensions Using the Regional and Nationwide Regression Equations for Bankfull Width, Depth, and Cross-Sectional Area and Relative Difference of the Dimensions (in parentheses) Predicted by the Regional Curves from the Nationwide Curve (Physiographic Division abbreviations as in Table 2).

	Physiographic Division	Predicted Channel Dimensions (m) and Relative Differences (%)			
		1 km^2	10 km^2	100 km^2	1,000 km^2
Bankfull width	LUP	4.15 (+54)*	8.43 (+39)*	17.13 (+26)	34.82 (+13)
	APL	2.22 (−18)	5.11 (−16)	11.79 (−14)	27.17 (−11)
	AHI	3.12 (+16)	8.13 (+34)	21.15 (+55)	55.03 (+79)
	IPL	2.56 (−5)	5.74 (−5)	12.88 (−6)	28.89 (−6)
	IHI	23.23 (+761)*	30.70 (+406)*	40.55 (+197)	53.58 (+75)
	RMS	1.24 (−54)	3.39 (−44)	9.23 (−32)	25.15 (−18)
	IMP	1.11 (−59)	2.90 (−52)	7.54 (−45)	19.62 (−36)
	PMS	2.76 (+2)	6.92 (+14)	17.35 (+27)	43.52 (+42)
	USA	2.70	6.07	13.65	30.70
Bankfull depth	LUP	0.31 (+1)*	0.49 (−1)*	0.78 (−4)	1.24 (−6)
	APL	0.24 (−21)	0.50 (+2)	1.06 (+31)	2.23 (+68)
	AHI	0.26 (−13)	0.51 (+3)	0.99 (+22)	1.92 (+45)
	IPL	0.38 (+24)	0.58 (+18)	0.90 (+12)	1.40 (+6)
	IHI	0.27 (−12)*	0.50 (±0)*	0.92 (+13)	1.69 (+28)
	RMS	0.23 (−25)	0.38 (−23)	0.64 (−20)	1.08 (−18)
	IMP	0.07 (−77)	0.15 (−69)	0.32 (−60)	0.69 (−48)
	PMS	0.23 (−23)	0.46 (−7)	0.91 (+12)	1.78 (+35)
	USA	0.30	0.50	0.81	1.32
Bankfull cross-sectional area	LUP	1.27 (+34)*	4.11 (+24)*	13.30 (+16)	42.98 (+8)
	APL	0.52 (−45)	2.51 (−24)	11.99 (+5)	57.36 (+44)
	AHI	0.82 (−14)	4.14 (+25)	20.94 (+83)	105.88 (+166)
	IPL	1.28 (+35)	3.81 (+15)	11.30 (−1)	33.53 (−16)
	IHI	6.28 (+559)*	15.29 (+363)*	37.25 (+225)	90.74 (+128)
	RMS	0.20 (−79)	0.96 (−71)	4.66 (−59)	22.68 (−43)
	IMP	0.07 (−93)	0.39 (−88)	2.17 (−81)	12.26 (−69)
	PMS	0.87 (−9)	3.91 (+18)	17.52 (+53)	78.62 (+98)
	USA	0.95	3.31	11.46	39.77

*Values are extrapolated outside the range of drainage areas in the regional samples.

TABLE 5. Number of Sites, R^2, and Standard Error of Estimate (SEE) Values of the Regression Models for the Physiographic Divisions and Provinces (Physiographic Division abbreviations as in Table 2). For the Physiographic Provinces, the SEE for the division-level model applied to the subset of sites within each province and the SEE for the province-level model are listed.

Physiographic Division/ Province	Bankfull Width			Bankfull Depth			Bankfull Cross-Sectional Area		
	No. of Sites	R^2	SEE	No. of Sites	R^2	SEE	No. of Sites	R^2	SEE
AHI	377	0.87	0.12	377	0.77	0.12	377	0.90	0.18
Adirondack	7	0.96	0.13/0.09	7	0.91	0.13/0.10	7	0.99	0.19/0.09
Appalachian Plateaus	178	0.88	0.13/0.13	178	0.77	0.13/0.13	178	0.91	0.19/0.19
Blue Ridge	11	0.73	0.11/0.11	11	0.70	0.10/0.09	11	0.83	0.16/0.14
New England	27	0.59	0.14/0.12	27	0.60	0.10/0.10	27	0.75	0.19/0.15
Piedmont	71	0.90	0.12/0.10	71	0.77	0.14/0.13	71	0.93	0.15/0.15
St. Lawrence Valley	5	0.42	0.09/0.07	5	0.05	0.14/0.09	5	0.76	0.13/0.05
Valley and Ridge	78	0.87	0.12/0.11	78	0.84	0.10/0.09	78	0.87	0.21/0.19
IPL	414	0.75	0.22	394	0.38	0.25	216	0.65	0.37
Central Lowland	254	0.79	0.18/0.18	250	0.34	0.23/0.23	139	0.66	0.35/0.35
Great Plains	83	0.83	0.32/0.22	76	0.25	0.34/0.29	9	0.09	0.70/0.48
Interior Low Plateaus	77	0.81	0.20/0.15	68	0.86	0.22/0.13	68	0.91	0.37/0.21
IHI	7	0.27	0.12	7	0.52	0.15	7	0.55	0.21
Ouachita	2	—	—	2	—	—	2	—	—
Ozark Plateaus	5	0.76	0.07/0.05	5	0.86	0.17/0.10	5	0.89	0.22/0.13
RMS	278	0.76	0.20	273	0.49	0.19	122	0.74	0.32
Middle Rocky M.	15	0.79	0.19/0.17	13	0.16	0.31/0.30	0	—	—
Northern Rocky M.	209	0.76	0.21/0.21	206	0.55	0.19/0.18	98	0.78	0.32/0.32
Southern Rocky M.	38	0.71	0.18/0.16	38	0.70	0.18/0.10	22	0.72	0.31/0.23
Wyoming Basin	16	0.63	0.25/0.24	16	0.47	0.24/0.20	2	—	—
IMP	88	0.62	0.29	88	0.58	0.25	88	0.64	0.50
Basin and Range	41	0.63	0.26/0.18	41	0.55	0.20/0.15	41	0.65	0.44/0.32
Colorado Plateaus	28	0.48	0.39/0.27	28	0.56	0.33/0.27	28	0.68	0.56/0.39
Columbia Plateau	19	0.88	0.17/0.14	19	0.52	0.20/0.14	19	0.51	0.57/0.55
PMS	48	0.74	0.15	48	0.50	0.19	48	0.66	0.30
Cascade-Sierra M.	19	0.60	0.17/0.16	19	0.56	0.18/0.15	19	0.66	0.29/0.27
Lower Californian	0	—	—	0	—	—	0	—	—
Pacific Border	29	0.80	0.15/0.15	29	0.56	0.20/0.19	29	0.71	0.31/0.30

Shelf and the Coastal Plain, but there is no data available for the former. Accordingly, analysis of the effects of finer stratification was not possible in these two Physiographic Divisions. Also, there were no data available for the Lower Californian Province in the Pacific Mountain System. The small number of sites in the Adirondack and St. Lawrence Valley Provinces in the Appalachian Highlands and the Ouachita and the Ozark Plateaus Provinces in the Interior Highlands prevented the development of statistically meaningful HG relationships. Therefore, these provinces were excluded from the statistical analysis of the effects of finer stratification, even though for the sake of completeness R^2 and SEE values are included in Table 5. This left a total of 17 Physiographic Provinces for statistical analysis of bankfull width and depth, 5 in the Appalachian Highlands, 3 in the Interior Plains, 4 in the Rocky Mountain System, 3 in the Intermontane Plateau, and 2 in the Pacific Mountain System (Table 5). With regard to bankfull cross-sectional area, the lack of sites with observed data in the Middle Rocky Mountains and the Wyoming Basin in the Rocky Mountain System made analysis in these two provinces impossible.

The SEE values indicate that the development of bankfull HG models for smaller regions generally improves the regression equations, even though the R^2 values are not higher in all cases (Table 5). The R^2 values for the province-level models are higher than, equal to, and lower than the R^2 values for the division-level models in 23, 5, and 21 of 49 models across the three variables, respectively, which corresponds to 47, 10, and 43%, respectively. This indicates that in only about half of the province-level models the drainage area accounts for more variation in bankfull channel dimensions than in the division-level models. The SEE values for the province-level models are equal to the SEE values for the division-level models in 12 of 49 models (24%) across the three variables and lower in 37 of 49 models (76%) across the three variables. This suggests that the province-level models generally provide more reliable predictions than the division-level models. However, it is important to note that in some provinces the data for all sites used in this study may come from a single publication and thus possibly from one individual stream or a few streams that are located very close together. Accordingly, the regression equation may not necessarily be representative for the entire Physiographic Province.

Performance of Drainage Area as a Surrogate for Bankfull Discharge

Bankfull discharge is generally considered to be a more reliable predictor of bankfull HG than drainage area, because it takes a number of watershed characteristics into account that affect runoff processes and hence the magnitude and duration of bankfull discharge. However, the use of drainage area as a surrogate for bankfull discharge allows for the use of regression equations in ungauged watersheds, which is critical for most of the stream restoration projects. In this study, it was found that bankfull discharge generally explained more variation in bankfull width, depth, and cross-sectional area than did drainage area (Table 6), except for bankfull width in the Appalachian Highlands and in the Pacific Mountain System. For the conterminous U.S., R^2 values for the models predicting bankfull width, depth, and cross-sectional area as a function of drainage area are 0.66, 0.43, and 0.58, respectively, whereas R^2 values for the models predicting bankfull width, depth, and cross-sectional area as a function of bankfull discharge are 0.84, 0.73, and 0.89, respectively. However, according to the SEE values, drainage area is a more reliable predictor of bankfull width than bankfull discharge in the Atlantic Plain, the Interior Plains, and the Rocky Mountain System. In the Interior Highlands, the model predicting bankfull depth as a function of drainage area has a lower SEE value than the model predicting bankfull depth as a function of bankfull discharge. According to the SEE values, drainage area is a better predictor of bankfull cross-sectional area than bankfull discharge in the Atlantic Plain.

DISCUSSION

Bankfull HG relationships and regional curves are useful tools for identifying bankfull channel dimensions. However, as Table 4 shows, predicted channel dimensions can vary considerably depending on the regression equation used. Therefore, it is very important to carefully analyze the uncertainty associated with the regression equations, which can be introduced by different sources of error.

The reliability of the regional regression equations is highly dependent on the correct identification of bankfull stage in the field. Williams (1978) lists more than 10 different indicators for identifying bankfull stage, including the floodplain break in slope, back of point bars, most prominent bench, top of bank, highest scour line, change in bank materials, and change in vegetation (Leopold, 1994). Johnson and Heil (1996) found considerable variability in bankfull channel dimensions and bankfull discharge when applying a range of these methods of determining bankfull stage to a river in Maryland. Ideally, a variety of indicators is used in the field (Sherwood and Huitger, 2005). Johnson and Heil (1996) suggested the use of fuzzy numbers to describe bankfull dimensions rather than a deterministic value. As the database used in this study combines data from a number of publications (Table 1), there is considerable uncertainty inherent in the regression equations because of the different indicators used for identifying bankfull stage in different studies.

Naturally occurring heterogeneity in a population is called variability (Harman *et al.*, 2008). Models

TABLE 6. Comparison of R^2 and Standard Error of Estimate (SEE) Values of the Regression Models Relating Bankfull Width, Depth, and Cross-Sectional Area to Drainage Area and Bankfull Discharge (Physiographic Division abbreviations as in Table 2).

	Bankfull Width		Bankfull Depth		Bankfull Cross-Sectional Area	
Physiographic Division	**R^2/SEE (DA)**	**R^2/SEE (Q)**	**R^2/SEE (DA)**	**R^2/SEE (Q)**	**R^2/SEE (DA)**	**R^2/SEE (Q)**
LUP	0.54/0.15	0.80/0.10	0.37/0.14	0.64/0.10	0.50/0.26	0.80/0.17
APL	0.84/0.13	0.74/0.16	0.75/0.15	0.83/0.12	0.84/0.23	0.84/0.24
AHI	0.87/0.12	0.88/0.11	0.77/0.12	0.81/0.11	0.90/0.18	0.93/0.15
IPL	0.75/0.22	0.78/0.18	0.38/0.25	0.63/0.17	0.65/0.37	0.87/0.22
IHI	0.27/0.12	0.91/0.03	0.52/0.15	0.56/0.19	0.55/0.21	0.68/0.21
RMS	0.76/0.20	0.82/0.17	0.49/0.19	0.81/0.11	0.74/0.32	0.92/0.18
IMP	0.62/0.29	0.91/0.15	0.58/0.25	0.87/0.14	0.64/0.50	0.90/0.28
PMS	0.74/0.15	0.71/0.16	0.50/0.19	0.74/0.13	0.66/0.30	0.83/0.21
USA	0.66/0.24	0.84/0.16	0.43/0.23	0.73/0.15	0.58/0.42	0.89/0.22

have to be able to account for this variability to reduce uncertainty associated with model predictions. For this, it is critical to have sufficient knowledge about the factors causing natural variability and to make sure that the sample represents the population as well as possible. The representative status of a sample depends on the sample size and the population it is supposed to represent. If any statistical significance is to be attributed to the results of bankfull HG regression equations, a suitably large sample size is very important (Park, 1977). However, in many studies, the sample size is limited by the availability of stream reaches that are suitable for conducting bankfull HG measurements. In this study, a limited number of sites with measurement data are available for some of the Physiographic Divisions, especially for the small ones (Laurentian Upland and Interior Highlands) (Figure 1 and Table 2). In large, topographically and climatically diverse divisions even a large number of sites may not be sufficient if the natural variability is too high to be accounted for by a single equation, especially when the sample locations are clustered and likely not representative of the region as a whole (e.g., in the Interior Plains and the Intermontane Plateau). The regression equations developed in this study should be applied with caution to streams in areas, from which no sites were used for model development, e.g., the Mississippi Alluvial Plain and the West Gulf Coastal Plain in the Atlantic Plain, the Great Basin Section in the Intermontane Plateau, or the Sierra Nevada in the Pacific Mountain System.

Also, measurements often do not cover a sufficiently wide range of watershed areas to make reliable predictions especially for very small watersheds (Table 2). According to Mulvihill *et al.* (2009), this is a concern because small channels are characterized by particularly variable bankfull hydraulic dimensions. In this study, data on very small watersheds are available for some, but not all of the Physiographic Divisions. Predictions of channel dimensions from the regional curves should be limited to drainage basin sizes that were accounted for in the dataset used for model development, or at least results extrapolated beyond this range should be treated with caution (see predicted values for small watersheds in the Laurentian Upland and the Interior Highlands in Table 4).

Bankfull regional curves are a simplification of complex natural processes, which are influenced by a large number of factors including precipitation, soils, and vegetation (McCandless and Everett, 2002). Identifying the causes of natural variability can help to integrate additional independent variables in a model to explain a higher degree of variability in the dependent variable. When bankfull channel dimensions are predicted only by drainage area, all other possibly influencing factors are assumed to vary consistently within the region of interest. Accordingly, it is widely recognized that bankfull HG relationships are only valid within relatively homogenous regions (McCandless and Everett, 2002). Discharge is assumed to scale systematically with drainage area (Ames *et al.*, 2009). However, as discharge is directly influenced by spatial variations in climate, topography, soils, land cover, and in-stream factors, drainage area is not necessarily a suitable surrogate for discharge. Results of this study show that drainage area performs reasonably well in predicting channel dimensions (Table 3). However, when using bankfull discharge as the independent variable, most of the regional curves for all three dependent variables (bankfull width, depth, and cross-sectional area) have higher R^2 and lower SEE values compared to the regional curves that are based on drainage area (Table 6), since discharge accounts for variability caused by factors other than drainage area. He and Wilkerson (2011) found that in some cases using the two-year return-period discharge (Q_2) instead of drainage area to predict bankfull width, depth, and cross-sectional area results in more reliable models, which they attribute to the fact that Q_2 estimates (like bankfull discharge, which Q_2 approximates) integrate not only the drainage area but also climate and geology. According to Wilkerson (2008), estimates of Q_2 are available for large parts of the U.S.

Many authors have tried to reduce the variability of a population by regionalizing the available data according to a number of criteria to minimize the variability of influencing factors. Data have been stratified by ecoregions (Castro and Jackson, 2001; Faustini *et al.*, 2009; Splinter *et al.*, 2010), hydrologic regions (Mulvihill and Baldigo, 2012), water resources regions (Faustini *et al.*, 2009), and physiographic regions (Castro and Jackson, 2001; Johnson and Fecko, 2008). However, only Faustini *et al.* (2009) evaluated the effects of regionalization for the entire conterminous U.S. They found that both approaches to regionalization they evaluated (ecoregions and water resources regions) performed equally well in developing reliable regression equations relating bankfull width to drainage area. In this study, it was shown that regionalization based on Physiographic Divisions also results in reliable bankfull HG relationships, not only for bankfull width but also for bankfull depth and cross-sectional area, and improves the regression equations as compared to a nationwide model (Table 3).

Some authors have tried stratifying data according to mean annual precipitation, mean annual runoff, channel slope, or stream type (Rosgen, 1996; Miller and Davis, 2003; Lawlor, 2004; Powell *et al.*, 2004; Mulvihill *et al.*, 2009). The USDA-NRCS (2007) suggests constructing separate regional curves for forested/rangeland, agricultural, and urban areas. Others have used these additional influencing factors for multiple linear regression analysis to better explain the natural variability of a population that is not explained by drainage area and thereby improve regional predictive relationships for bankfull channel dimensions (e.g., Elliott and Cartier, 1986; Hey and Thorne, 1986; Julien and Wargadalam, 1995; Lee and Julien, 2006; Faustini *et al.*, 2009). Some of these authors included variables like the median grain size of the bed material (D_{50}), the density of bank vegetation, the channel slope, or the Shields parameter in their regression equations. Even though these variables have shown to impact channel dimensions (Leopold *et al.*, 1964; Allen *et al.*, 1994; Hession *et al.*, 2003; Anderson *et al.*, 2004), observed data required to develop reliable equations over large geographic areas is not available. For modeling purposes, a comprehensive set of regression equations to predict channel dimensions based on readily available data is of greater significance than more advanced equations accounting for local variability. Wilkerson *et al.* (2014) showed that precipitation is a factor influencing the relationship between bankfull width and drainage area. Precipitation is one of the basic model inputs for hydrologic models like SWAT, so it should generally be available even for poorly gauged watersheds. Therefore, it is a variable that could be used for improving the prediction of bankfull channel dimensions for hydrologic models without limiting the applicability of the equations to well-gauged watersheds.

Faustini *et al.* (2009) used a large national dataset on HG in wadeable streams to examine the impact of different regionalization schemes and to analyze the potential of incorporating additional independent variables using multiple regression analysis. They concluded from their study that a finer stratification into smaller, more homogenous regions has a higher potential of improving regional predictive relationships than the incorporation of additional independent variables. In contrast, Ames *et al.* (2009) concluded from their study that both regionalization and the integration of additional watershed variables can improve regression equations predicting stream width and depth. Anderson *et al.* (2004) and Mulvihill and Baldigo (2012) argue that even highly regionalized curves are often subject to substantial variability and error. Also, finer stratification leads to a smaller number of representative data points per region, which results in less robust equations (Johnson and Fecko, 2008). However, it should be considered an option when there are a sufficient number of sites within a province to develop a reasonably robust HG equation and when R^2 and SEE values are considerably higher and lower, respectively. In this study, finer stratification of data and the development of regional curves for Physiographic Provinces instead of Physiographic Divisions resulted in an improvement of R^2 and SEE values in more than half of the provinces when compared to the corresponding divisions (Table 5). The integration of additional variables in multiple regression analysis has not been tested yet, but may further improve the reliability of bankfull HG relationships. An additional approach suggested by Wilkerson *et al.* (2014) is developing a linear-piecewise model to predict bankfull width based on drainage area. Using a similar dataset as the one used in this study and the wadeable streams data also used by Faustini *et al.* (2009), they found out that a two-segment linear-piecewise model provides more reliable predictions of bankfull width than a simple linear model, since it accounts for differences between small and large watersheds (Wilkerson *et al.*, 2014).

SUMMARY AND CONCLUSION

This study presents a large database integrating bankfull HG data from almost 50 publications. In total, observed data are available for more than 1,300 sites across the conterminous U.S. The data were stratified based on the Physiographic Divisions of the U.S. and bankfull HG regression equations were developed for each of the eight divisions and for the entire conterminous U.S. The equations relate the independent variable drainage area to the dependent variables bankfull width, depth, and cross-sectional area. The reliability of the regional curves was evaluated using the coefficient of determination (R^2) and the SEE. In addition, the effect of finer stratification of data on the basis of Physiographic Provinces and the performance of drainage area as a surrogate for bankfull discharge were assessed.

In conclusion, results indicate the following:

1. In most cases, regional curves for each of the Physiographic Divisions have higher R^2 values and lower SEE values and thus perform better than the nationwide curve, which confirms the central hypothesis of this study.
2. A finer stratification of data based on Physiographic Provinces improves the reliability of the regression equations in approximately three-quarters of the provinces as compared to the corresponding divisions.
3. Despite the large amount of data available in the literature, there are large geographic areas within most of the Physiographic Divisions that are not represented within the dataset used in

this study, which demands careful consideration of the geographic applicability of the regression equations and points to the need for additional studies to fill the data gaps.

4. Bankfull discharge accounts for a considerably higher degree of variability in bankfull width, depth, and cross-sectional area than does drainage area, which indicates a need for further improvement of the regression equations.

Various authors have improved regional regression equations by either identifying the most suitable means of regionalization or by using multiple linear regression analysis to integrate additional independent variables in the equations. While the first approach focuses on minimizing the variability within the population to improve the representative status of the sample, the second approach aims at identifying and integrating variables that explain variability in the sample that is not explained by drainage area. There is no consensus among researchers with regard to the question, which approach is more appropriate to improve the reliability of bankfull HG relationships. Either way, when a consistent set of bankfull HG relationships across the conterminous U.S. is supposed to be used in hydrologic models, it is not necessarily expedient to use the variables that are best suited to predicting channel dimensions, but rather to use data that is commonly available or can be derived from GIS data layers with national coverage. In the future, the results of this study will be used as a basis for improving the regional curves by integrating additional readily available variables in the regression equations.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

A table listing the regression equations and standard errors of intercept and slope for all Physiographic Divisions and Provinces and seven figures, showing the residuals (predicted-observed bankfull channel dimensions) and their frequency distribution for the Physiographic Divisions and Provinces.

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