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OPTIMIZING BANKFULL DISCHARGE AND HYDRAULIC GEOMETRY RELATIONS FOR STREAMS IN NEW YORK STATE[1]

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ABSTRACT: This study analyzes how various data stratification schemes can be used to optimize the accuracy and utility of regional hydraulic geometry (HG) models of bankfull discharge, width, depth, and cross-sectional area for streams in New York. Topographic surveys and discharge records from 281 cross sections at 82 gaging stations with drainage areas of 0.52-396 square miles were used to create log-log regressions of region-based relations between bankfull HG metrics and drainage area. The success with which regional models distinguished unique bankfull discharge and HG patterns was assessed by comparing each regional model to those for all other regions and a pooled statewide model. Gages were also stratified (grouped) by mean annual runoff (MAR), Rosgen stream type, and water-surface slope to test if these models were better predictors of HG to drainage area relations. Bankfull discharge models for Regions 4 and 7 were outside the 95% confidence interval bands of the statewide model, and bankfull width, depth, and cross-sectional area models for Region 3 differed significantly ($p < 0.05$) from those of other regions. This study found that statewide relations between drainage area and HG were strongest when data were stratified by hydrologic region, but that co-variable models could yield more accurate HG estimates in some local regional curve applications.

(KEY TERMS: streams; optimization; restoration; regional curves; bankfull discharge; hydraulic geometry; models.)

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INTRODUCTION

Regional hydraulic geometry (HG) curves are regression equations that estimate bankfull discharge, width, depth, and cross-sectional area as a function of drainage area. Bankfull discharge in alluvial streams with well-developed floodplains is the stage or flow at which a stream just overtops its banks, or the point of incipient flooding (Leopold *et al.*, 1964; Dunne and Leopold, 1978; Harrelson *et al.*, 1994). For many streams, bankfull discharge occurs approximately every 1-2 years, or 1.5 years on average (Dunne and Leopold, 1978; Rosgen, 1996; Harman and Jennings, 1999), although recurrence intervals (RIs) greater than 2 years have been observed in the Catskill Mountain region of New York (NY) (Miller and Davis, 2003) and the Colorado front range (Leopold, 1994); and RIs less than 1 year were recorded in the coastal plain streams of Georgia, Maryland, and North

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Carolina (McCandless, 2003; Sweet and Geratz, 2003; GDOT, 2003). Bankfull discharge is the flow that carries the largest sediment load over time (Dunne and Leopold, 1978; Emmet and Wolman, 2001) and is capable of moving most particle sizes in poorly sorted gravel-bed streams (Andrews and Parker, 1987; Leopold and Rosgen, 1991; Lisle *et al.*, 2000). Bankfull discharge is often used as a surrogate for the channel-forming discharge because it is considered to be the morphologic transition between the active stream channel and the floodplain and the flow which defines channel shape, size, and slope in most stable reaches (Leopold *et al.*, 1964; Lawlor, 2005).

Regional HG curves are important tools used by watershed planners, engineers, geomorphologists, and others interested in the management, restoration, and regulation of stream channels and floodplains. HG models are used in stream classification, assessment, monitoring, and restoration design (Andrews and Parker, 1987; Leopold, 1992; Rosgen, 1994, 1996, 2001; Harman, 2002). The utility of bankfull discharge lies in the fact that it is the only streamflow elevation that can usually be identified in the field using physical indicators (Harman, 2002). Bankfull elevations, however, can sometimes be difficult to identify in mountainous settings or disturbed watersheds, where: (1) bank top elevations can vary widely, (2) the break in slope between streambanks and floodplains is not always obvious, (3) features such as benches and terraces mask bankfull elevations, or (4) runoff events are flashy due to convective rainfall or snowmelt dominated hydrographs (Gordon *et al.*, 1992; Wohl, 2000; Miller and Davis, 2003; Doyle *et al.*, 2007). In these situations, the only way to confirm apparent bankfull elevations is through the use of regional curves.

Regional HG curves were first developed in the mid-1900s to help analyze and interpret sediment-flow models at U.S. Geological Survey (USGS) gages (Leopold and Maddock, 1953; Leopold *et al.*, 1964). These early models were never widely used because they were accurate only in specific study reaches and could not account for differences in geomorphic characteristics or local variations in landform, climate, and runoff. More localized (regional) HG curves have recently been developed across North America to address classification and natural channel design (NCD) restoration needs (Castro and Jackson, 2001; Doll *et al.*, 2002; Keaton *et al.*, 2005; Johnson and Fecko, 2008). However, even these highly localized regional curves are subject to variability and error due to factors influencing runoff patterns (i.e., bank vegetation, riparian condition, land use, soil type) and bankfull discharge estimates (i.e., length of record, stability of rating curve, recent flooding) at the gages used to create the models. The study presented herein describes how co-variable analysis can be used to eliminate some of this uncertainty and increase the accuracy of the predictive regional models.

The demand for regional HG curves in NY was spurred by an increase in the use of fluvial geomorphology-based stream management, NCD restoration, and Rosgen's (1994, 1996) river classification system by the New York City Department of Environmental Protection (NYCDEP). In the late 1990s, the NYCDEP and its partners began using NCD to address suspended sediment, turbidity, and bank and bed erosion issues in the New York City West-of-Hudson (Catskill-Delaware) Water Supply Watershed (Nagle, 2007). These efforts led to the development of regional curves for Regions 4 and 4a in the Catskill Mountain region (Figure 1) (Miller and Davis, 2003). As these regional curves were applied and more stream restoration projects entered the planning phase, it became obvious that existing regional curves for the Northeastern United States (U.S.) (Dunne and Leopold, 1978) did not accurately model NY's highly varied physiography, hydrology, and climate (Lyford *et al.*, 1984; Lumia, 1991). Hence, the USGS, in cooperation with the New York State Department of Environmental Conservation, New York State Department of Transportation, New York State Department of State, NYCDEP, and Greene County Soil and Water Conservation District began developing regional curves for wadeable streams in the remaining six hydrologic regions (excluding Long Island) as delineated by Lumia (1991) (Figure 1). The USGS prepared data summary reports for Regions 1 and 2 (Mulvihill *et al.*, 2007), Region 3 (Mulvihill and Baldigo, 2007), Region 5 (Westergard *et al.*, 2005), Region 6 (Mulvihill *et al.*, 2005), and Region 7 (Mulvihill *et al.*, 2006). The regional curves for streams in Regions 4 and 4a were summarized by the NYCDEP (Miller and Davis, 2003). A statewide summary report was also prepared to document model variability and differences among regions (Mulvihill *et al.*, 2009).

An underlying premise of this investigation is that multiple regional curves are needed to accurately model NY's highly variable physiography and climate. Therefore, the original objective was to optimize regional relations by creating regional models for each of NY's eight hydrologic regions (Lumia, 1991). The revision of regional boundaries in 2006 (Lumia *et al.*, 2006) reduced the number of regions from eight to six and created a single model for Regions 1 and 2 in the Adirondacks (Figure 1). After regional boundaries were redrawn some were reluctant to use regional models that appeared inaccurate and out of date. Others suggested that it would be better to mimic previous regional curve studies and group data by physiographic province (Johnson and Fecko, 2008), area of the country (Dunne and

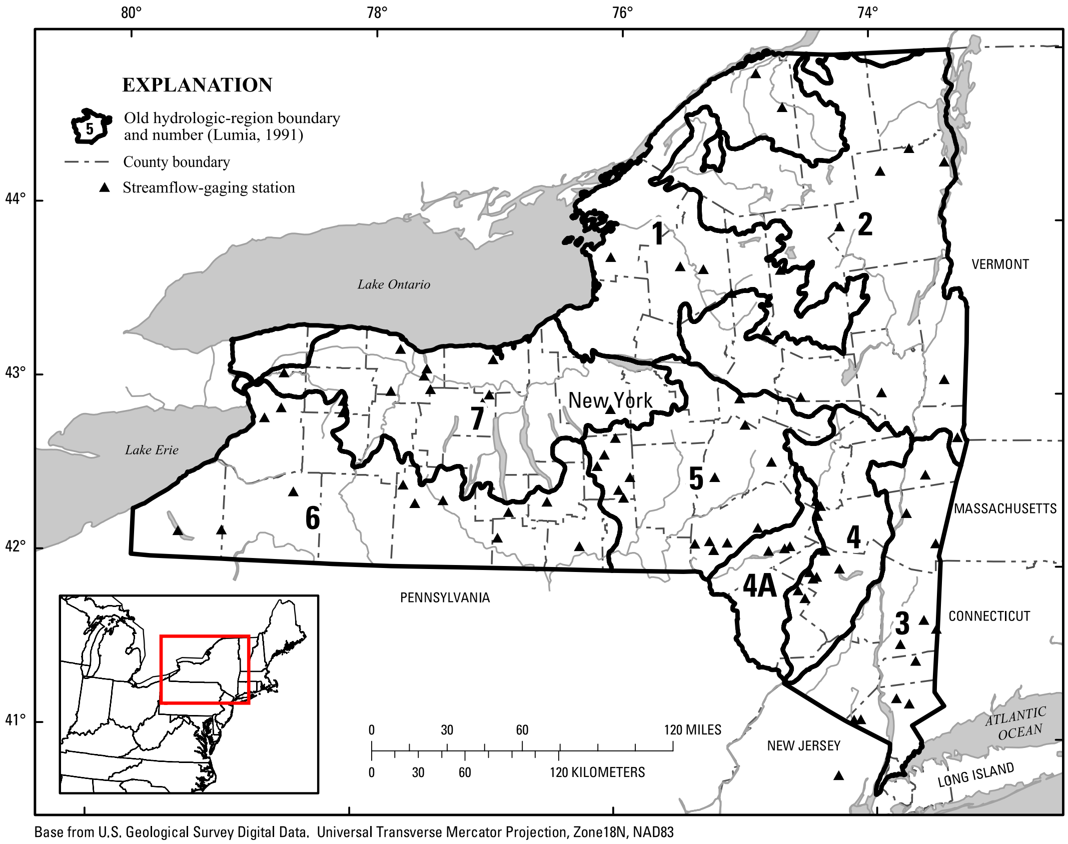

FIGURE 1. Hydrologic-Region Boundaries as Defined by Lumia (1991) and the Locations of 82 Streamflow-Gaging Stations Surveyed, 1999-2006.

Leopold, 1978; Bent, 2006), ecoregion (Castro and Jackson, 2001), mean annual precipitation (Lawlor, 2005), mean annual runoff (MAR) (Miller and Davis, 2003), or stream type (Rosgen, 1996; Powell *et al.*, 2004). The primary objective of this report is to statistically assess the effect of four data stratification co-variables — hydrologic region, MAR, Rosgen stream type, and water surface slope — to determine which model(s) most effectively minimizes variability in regional relations. A better understanding of the influence of co-variables on regional curve uncertainty and variability can only help improve model accuracy and performance and broaden the application of these valuable stream management tools.

STUDY AREA

New York State (excluding Long Island) is divided into seven physiographic provinces (Figure 2); these range from high relief in the Adirondack and Catskill Mountains to low relief along the Great Lakes and the St. Lawrence, Hudson, and Mohawk River Valleys (Lumia *et al.*, 2006). Elevations range from more than 5,000 ft (1,524 m) in the eastern half of the Adirondack Province (Fenneman, 1938) to less than 200 ft (61 m) in the St. Lawrence River Valley (Lumia *et al.*, 2006). Mean annual precipitation ranges from almost 30 inches (76 cm) along Lakes Ontario and Champlain to about 60 inches (152 cm) in the southern Catskill Mountains (Lumia *et al.*, 2006). Maximum seasonal snowfall averages more than 175 inches (444 cm) on the western and southwestern slopes of the Adirondack Mountains and Tug Hill Plateau (National Oceanic and Atmospheric Administration, 1980); the minimum seasonal snowfalls (25-35 inches) (63-89 cm) occur in extreme Southeastern New York. The minimum upstate seasonal snowfalls (40-50 inches) (102-127 cm) occur in the Chemung and mid-Genesee River Valleys and near the Hudson River from Orange, Rockland, and Westchester Counties north to southern Albany County (Figure 1) (Lumia *et al.*, 2006).

METHODS

Data collection and analysis techniques were based primarily on protocols used by the NYCDEP to

FIGURE 2. Physiographic Provinces of New York, Excluding Long Island (modified from Lyford and others, 1984).

develop bankfull discharge and HG equations for streams in the Catskill Mountain region of southeastern New York (Miller and Powell, 1999), and are summarized in Powell *et al.* (2004). These methods integrate standard USGS surveying methods (USGS, 1966; Dalrymple and Benson, 1967; Harrelson *et al.*, 1994), with those developed by Dunne and Leopold (1978) and Rosgen (1994, 1996). Several hydrologic regions in NY have only a few active gages with 10 or more years of record; therefore, techniques for identifying and confirming bankfull stage and discharge at streams with discontinued surface-water and crest-stage gages are included in Powell *et al.* (2004). The statewide investigation also modified the procedure used to construct bankfull-stage profiles by specifying the use of a "best-fit" linear regression line instead of a LOESS smooth (Miller and Powell, 1999). This procedure may be less sensitive to localized elevation profile shifts, but it helps minimize the potential investigator bias inherent in the LOESS smooth method. Specific procedures used for data collection and analysis are summarized in the sections that follow.

The hydrologic-region boundaries used in this investigation (Figure 1) were delineated by Lumia (1991) using ordinary least-squares multiple-regression techniques that related the 2- to 500-year flood discharges to statistically significant explanatory variables such as drainage area, main-channel slope, percent basin storage, mean annual precipitation, percent forested area, a basin lag factor, a ratio of main-channel slope to basin slope, MAR, maximum snow depth, and percentage of basin above 1,200 ft (366 m) (Lumia *et al.*, 2006). Regional boundaries were delineated using a generalized least squares (GLS) procedure, which took into account the time-sampling error (length of record at each site), and the spatial correlation of annual peak discharges among sites (Lumia, 1991). Although hydrologic Regions 1 and 2 in the Adirondacks (Figure 1) were originally delineated as two separate regions (Lumia, 1991), this study combined the two regions into a single model because a more recent analysis of updated basin characteristics, an additional 12 years of annual peak-discharge data, updated skews (Lumia and Baevsky, 2000), and revised data on basin characteristics indicated that peak discharges in both regions could now be estimated with a single regression equation (Lumia *et al.*, 2006).

The suitability of a stream for inclusion in regional gage calibration surveys depended on the availability of peak discharge records from USGS gages and the physical characteristics of the reach (Dunne and Leopold, 1978; Miller and Powell, 1999; Powell *et al.*, 2004). No sites with regulated flows, braided channels, stagnant pools or backwater, large amounts of rip-rap, waterfalls, or in wetlands were surveyed. However, the paucity of USGS gages in some areas, combined with the desire to create statistically robust models, occasionally made it necessary to include discontinued gages and those in residential areas and parks, as well as others that did not strictly adhere to all of the selection criteria. Four to 16 streams representing a range of drainage areas were surveyed in each hydrologic region (Table 2). When a sufficient number of suitable gages were present in a region, gages selected for gage calibration surveys had at least 10 years of annual peak-discharge data, and a current stage-to-discharge rating table. With several exceptions, the surveyed reaches were mostly single alluvial channels at bankfull stage, included at least two pool-to-riffle sequences, were at least 20 bankfull widths in length, and represented a single Rosgen (1996) stream type (Miller and Davis, 2003; Powell *et al.*, 2004). When available, reaches were selected that satisfied the minimum requirements for the slope-area method of discharge calculation (uniform channel conveyance and fall of at least 0.50 ft (.15 m); Dalrymple and Benson, 1967).

Cross-sectional and longitudinal surveys were conducted at each of the 82 study sites to determine channel dimensions and profile following methods described in Powell *et al.* (2004) and Miller and Davis (2003). Longitudinal profile elevation surveys followed the channel thalweg (for stationing) and included thalweg channel bottom at feature breaks, current water surface at feature breaks and bankfull flags, and bankfull stage at flagged indicators. Bankfull indicators consisted primarily of (1) topographic breaks from vertical bank to flat floodplain; (2) topographic breaks from steep slope to gentle slope or from gentle to steep (as in undercut banks or terraces); (3) changes in vegetation density or type (for example, from treeless to trees); (4) textural changes in sediment; (5) scour breaks, or elevations below which no fine debris such as needles, leaves, cones, or seeds were found; and (6) backs of point bars, lateral bars, or low benches (Castro and Jackson, 2001; Miller and Davis, 2003). Cross sections were surveyed for derivation of HG metrics, and included flood prone width for stream classification (Rosgen, 1994). Bankfull channel bed material grain size distribution was characterized by modified Wolman pebble counts and used for stream classification (Wolman, 1954; Rosgen, 1996).

Recurrence interval is the average interval of time within which the magnitude of a streamflow event is equaled or exceeded once (Chow, 1964). Bankfull-discharge RIs were calculated by fitting a log-Pearson Type III distribution to the annual peak-flow data for each site through procedures defined by U.S. Water Resources Council (1981). USGS guidelines recommend a minimum of 10 years of peak-flow record for accurate calculation of flood frequencies (U.S. Water Resources Council, 1981). However, as the objective of this study was to determine bankfull frequencies and develop statistically robust regional relations one gage with slightly less than 10 years of record was surveyed in Regions 1 and 2 (Mulvihill *et al.*, 2007) and two gages with slightly less than 10 years of record were surveyed in Region 3 (Mulvihill and Baldigo, 2007). Current recalculation of RIs revealed no significant changes; either because the gage was discontinued or because a few more years of peak discharge data did not change bankfull RI.

Preliminary estimates of bankfull discharge entailed matching the bankfull stage from the best-fit line through bankfull indicators to a corresponding discharge on the gages' most current stage-to-discharge rating table. However, the field identification of bankfull stage can be confounded by uncertainty regarding the RI of bankfull discharge (Johnson and Heil, 1996; Rosgen, 1996). Causes of this uncertainty include natural variability in streamflow patterns, obstruction of streamflow at the gage by culverts or bridge piers (Rantz, 1982), and/or calculation of RIs from peak-flow records that were too short (from new gages) or out of date (historic data from discontinued gages). These potential errors in bankfull-discharge estimates were minimized by first using the best fit profile method to make preliminary estimates and then confirming or adjusting these estimates through a hydraulic analysis of the bankfull geomorphic data collected during the gage-calibration survey using the computer programs NCALC (to compute Manning's n) (Jarrett and Petsch, 1985) and HEC-RAS (to calculate bankfull-discharge from the water-surface elevation at surveyed cross sections) (Brunner, 1997). This independent verification of bankfull discharge at sections where streamflow was unobstructed ensured that the modeled stage and associated HG metrics were representative of those encountered in undisturbed streams.

The relation between drainage area and bankfull discharge is described by the power function:

$$Q_{\mathrm{bkf}} = c(\mathrm{DA})^b \quad (1)$$

where Q_{bkf} is bankfull discharge (ft^3/s), DA is drainage area (mi^2), c is the amplitude, and b is the exponent of the fitting function for the log-log regression. Comparable regional HG equations were also developed for bankfull width (W_{bkf}, in ft), average depth (D_{bkf}, in ft), and cross-sectional area (A_{bkf}, in ft^2).

The relations between drainage area and bankfull discharge and associated HGs were evaluated by grouping sites by four predictor variables: (1) hydrologic region, whereby each stream was assigned to a specific region according to physiography, flood frequency, and climate (Lumia, 1991); (2) MAR, whereby streams were grouped into three classes according to precipitation and basin characteristics that affect runoff (Miller and Davis, 2003); (3) Rosgen stream type, whereby streams were grouped into four classes according to channel characteristics (Rosgen, 1994); and (4) water-surface slope, whereby streams were grouped into four classes according to topography. The goal of the analysis was to identify which, if any, predictor variables produced statistical relations more powerful than that given by either the statewide model that was created by pooling all bankfull discharge and associated HG data, or by other predictor variables. Additional analysis was done to test whether regionalization of the relations between drainage area and bankfull width, depth, and cross-sectional area was justified.

Both analyses were done through analysis of covariance (ANCOVA) procedures in Statgraphics (StatPoint Technologies, Inc., 2009) to test for differences in the slopes (b in Equation 1) and intercepts (c in Equation 1) of the regression lines. It was assumed that when a data stratification variable produced multiple models with statistically similar slopes and intercepts, more robust relations could be achieved by combining the data (Chaplin, 2005). In contrast, a significant difference ($p < 0.05$) in slope or intercept would indicate that separate curves are appropriate (Chaplin, 2005). Coefficients of determination (R^2) were used to measure how well the independent variable (DA in Equation 1) accounted for variability in the dependent variable (Q_{bkf} in Equation 1). In addition, standard errors of estimate (SEEs) were examined to measure how well model predicted HG metrics agreed with those measured during gage calibration surveys.

RESULTS

Comparison of curves for groupings by hydrologic region confirmed the existence of regional variations in bankfull discharge and associated RIs (Figure 3a and Table 1). The RIs ranged from 1.01 to 3.80 years (Table 1). The average statewide RI of bankfull discharge was 1.77 years; the highest average RIs are in Regions 1-2, 3, and 7 (2.08-2.13 years) (Table 1), and the lowest are in Regions 4, 4a, 5, and 6 (1.42-1.58 years) (Table 1). Bankfull discharge curves for all hydrologic regions except 4 and 7 were within the 95% confidence limits of the statewide curve (Figure 3a). Six of the seven regional bankfull discharge curves had lower SEEs (16-52%) and higher R^2 values (0.90-0.99) than the statewide curve (SEE = 54%, R^2 = 0.89) (Table 2). The ANCOVA confirmed that the Region 7 bankfull discharge curve was significantly different ($p < 0.05$) from the other six curves (Table 3), because of its very low intercept (37.1) (Table 3). There were no significant differences between the Region 4 and 4a bankfull discharge curves, probably because the sample sizes were small (n = 10 in Region 4, n = 4 in Region 4a) (Table 2).

Bankfull-width curves differed widely among regions; the entire Region 7 curve and parts of those for the other six regions plotted outside the 95% confidence interval bands of the statewide curve (Figure 3b). Six of the seven regional bankfull-width curves had lower SEEs (10-30%) (Table 2) and higher R^2 values (0.85-0.98) than the statewide curve (SEE = 32%, R^2 = 0.84) (Table 2). The ANCOVA demonstrated that the Region 7 bankfull-width curve was significantly different from every other curve except that for Region 4a (Table 3). The slope for the relation between bankfull width and drainage area in Region 3 also was lower than in the other regions (0.292) (Table 3), indicating that streams widen more slowly with increasing drainage area in this region than they do elsewhere in New York.

Bankfull-depth curves showed moderate regional variability; parts of every curve fell outside the 95% confidence-interval bands of the statewide curve (Figure 3c). Six regional bankfull-depth curves had slightly lower SEE (14-30%) and five had slightly higher R^2 values (0.77-0.92) than the statewide curve (SEE = 31%, R^2 = 0.76) (Table 2). Here again, ANCOVA confirmed that the Region 3 bankfull-depth curve was significantly different from the other six curves due to its high intercept (1.66) and low slope (0.210) (Table 3). No significant differences were found between the bankfull-depth curves for Region 6 and that for Region 4a, even though much of the Region 6 curve fell below the lower 95% confidence-interval band of the statewide curve (Figure 3c and Table 3).

Bankfull cross-sectional area curves varied among regions, and all or part of every curve fell outside the 95% confidence-interval bands of the statewide curve (Figure 3d). All regional bankfull cross-sectional area curves had lower SEEs (18-38%) than the statewide curve (41%), and five had higher R^2 values (0.92-0.98) than the statewide curve (0.91) (Table 2). Here again, ANCOVA indicated that the Region 3 bankfull cross-sectional area curve was significantly different from the other six curves in its high intercept (39.8) and low slope (0.503) (Table 3). No significant differences were found between the bankfull cross-sectional area curve for Region 5 and that for Region 4a (Table 3), even though much of the Region 5 curve fell below the lower 95% confidence-interval band of the statewide curve (Figure 3d).

Estimates of MAR at the 82 gages ranged from 0.8 to 3.6 (ft^3/s)/mi^2 (0.009-0.039 (m^3/s)/km^2) and had a

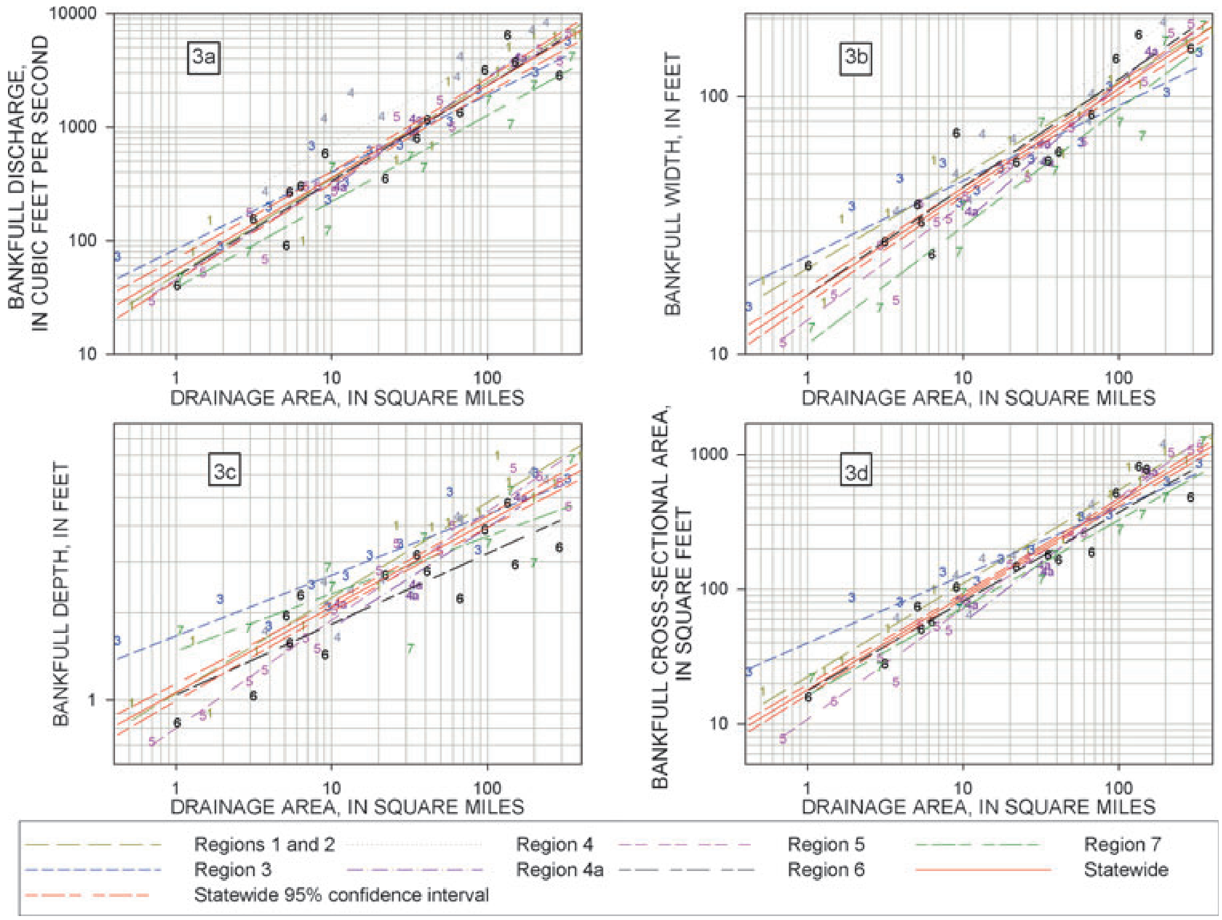

FIGURE 3. Bankfull Discharge (a), Width (b), Average Depth (c), and Cross-sectional Area (d) as a Function of Drainage Area for Seven Hydrologic Regions in New York and Statewide.

TABLE 1. Bankfull Discharge Recurrence Interval (RI) Ranges and Means.

Hydrologic Region	RI Range (years)	RI Mean (years)	Reference
1 and 2	1.01-3.80	2.13	Mulvihill *et al.* (2007)
3	1.16-3.35	2.08	Mulvihill and Baldigo (2007)
4	1.20-2.70	1.58	Miller and Davis (2003)
4a	1.32-1.50	1.42	Miller and Davis (2003)
5	1.11-3.40	1.51	Westergard *et al.* (2005)
6	1.01-2.35	1.54	Mulvihill *et al.* (2005)
7	1.05-3.60	2.13	Mulvihill *et al.* (2006)

roughly bell-shaped distribution with the majority of the gages having a MAR between 1.8 and 2.0 $(ft^3/s)/mi^2$ (0.020-0.022 $(m^3/s)/km^2$) (Mulvihill *et al.*, 2009). This distribution suggested that stratifying MAR into low (0.8-1.7 $[ft^3/s]/mi^2$) (0.009-0.019 $(m^3/s)/km^2$), moderate (1.8-2.0 $[ft^3/s]/mi^2$) (0.020-0.022 $(m^3/s)/km^2$), and high (2.1-3.6 $[ft^3/s]/mi^2$) (0.023-0.039 $(m^3/s)/km^2$) categories would be appropriate (Figure 4 and Table 4). The R^2 values of 0.88-0.93 for the three MAR curves (Table 4) confirm that MAR is a significant explanatory variable in bankfull-discharge to drainage-area relations. The SEE and R^2 values for low and moderate MAR curves were comparable to those of the hydrologic region curves, although SEE for the high-MAR curve was higher than even that of the statewide curve (Tables 2 and 4). The ANCOVA showed that the low-MAR curve was significantly different from the moderate- and high-MAR curves (Table 5).

TABLE 2. Regional and Statewide Bankfull Discharge and Hydraulic-Geometry (HG) Regression Equations, Standard Errors of Estimate, and R^2 for Streams in New York.

Hydrologic-Region Model	Number of Streamflow-Gaging Stations or Cross Sections	Regression Equation	Standard Error of Estimate (percent)	R^2
Bankfull discharge (cubic ft per second)				
1 and 2	16	49.6 DA$^{0.849}$	45	0.95
3	12	83.8 DA$^{0.679}$	40	0.93
4	10	117.2 DA$^{0.780}$	59	0.81
4a	4	30.3 DA$^{0.980}$	16	0.99
5	16	45.3 DA$^{0.856}$	36	0.96
6	14	48.0 DA$^{0.842}$	52	0.90
7	10	37.1 DA$^{0.765}$	39	0.94
Statewide	82	55.4 DA$^{0.810}$	54	0.89
Bankfull width (ft)				
1 and 2	55	21.5 DA$^{0.362}$	28	0.89
3	40	24.0 DA$^{0.292}$	23	0.85
4	21	17.1 DA$^{0.460}$	26	0.87
4a	9	9.1 DA$^{0.545}$	10	0.98
5	73	13.5 DA$^{0.449}$	27	0.92
6	50	16.9 DA$^{0.419}$	36	0.79
7	33	10.8 DA$^{0.458}$	30	0.89
Statewide	281	16.9 DA$^{0.401}$	32	0.84
Bankfull depth (ft)				
1 and 2	55	1.06 DA$^{0.329}$	25	0.89
3	40	1.66 DA$^{0.210}$	21	0.77
4	21	1.07 DA$^{0.314}$	19	0.84
4a	9	0.79 DA$^{0.350}$	14	0.88
5	73	0.82 DA$^{0.373}$	20	0.92
6	50	1.04 DA$^{0.244}$	30	0.64
7	33	1.47 DA$^{0.199}$	35	0.52
Statewide	281	1.06 DA$^{0.294}$	31	0.76
Bankfull cross-sectional area (square ft)				
1 and 2	55	22.3 DA$^{0.694}$	24	0.97
3	40	39.8 DA$^{0.503}$	27	0.92
4	21	17.9 DA$^{0.777}$	35	0.91
4a	9	7.2 DA$^{0.894}$	18	0.97
5	73	10.8 DA$^{0.823}$	24	0.98
6	50	17.6 DA$^{0.662}$	38	0.89
7	33	15.9 DA$^{0.656}$	25	0.95
Statewide	281	17.9 DA$^{0.696}$	41	0.91

The Rosgen classification system (Rosgen, 1994, 1996) grouped 44 reaches as C-type, 12 as B-type, 4 as E-type, and 5 as F-type (Table 4); the remaining 17 reaches were eliminated from the analysis because multiple stream types were present in the surveyed reaches and the classification that most accurately represented the geomorphic characteristics of the reach could not be determined (Mulvihill *et al.*, 2009). In general, the relations between bankfull discharge and Rosgen stream type were weaker than those between bankfull discharge and hydrologic region (Tables 2 and 4). Although the SEEs for most stream-type curves were comparable to those for the hydrologic-region curves, they accounted for less variability (had lower R^2 values; see Tables 2 and 4). The ANCOVA indicated no significant differences existed between curves for B- and F-type streams, or between curves for C- and F-type streams (Table 5). The low slope of the E-type curve (0.211) made it significantly different from the other three stream types (Table 5); but this model had a small sample size (4) and a moderate R^2 (0.51) (Table 4).

When streams were grouped by water-surface slope the number with gentle slopes greatly exceeded the number with steep slopes (Mulvihill *et al.*, 2009). Bankfull discharge was stratified into four water-surface slope categories: very low (<0.006), low (0.006-0.014), moderate (0.015-0.025), and high (0.026-0.074) (Figure 4 and Table 4). Curves for the low and moderate slopes had slightly higher SEEs and slightly lower R^2 values than the hydrologic-region curves (Tables 2 and 4). The ANCOVA determined that the slopes and intercepts of the <0.006 curve were significantly different from those of the 0.026-0.074 curve (Table 5).

TABLE 3. Results of ANCOVA Analysis of Similarities in the Intercepts and Slopes of Regional Bankfull Discharge and Hydraulic-Geometry (HG) Models.

		***p*-values for Similarities Between Models**						
Region and Parameter	**Equation Coefficients**	**1, 2**	**3**	**4**	**4a**	**5**	**6**	**7**
Bankfull discharge (cubic ft per second)								
1,2 Intercept	49.6							
Slope	0.849							
3 Intercept	83.8	0.945						
Slope	0.679	0.046						
4 Intercept	117.2	0.004	0.005					
Slope	0.780	0.580	0.483					
4a Intercept	30.3	**0.902**	**0.822**	**0.058**				
Slope	0.980	**0.581**	**0.159**	**0.511**				
5 Intercept	45.3	**0.627**	0.434	0.001	**0.863**			
Slope	0.856	**0.921**	0.026	0.513	**0.525**			
6 Intercept	48.0	**0.750**	**0.673**	0.005	**0.928**	**0.918**		
Slope	0.842	**0.944**	**0.119**	0.666	**0.615**	**0.879**		
7 Intercept	37.1	0.003	0.005	0.001	0.029	0.004	0.017	
Slope	0.765	0.322	0.396	0.908	0.317	0.243	0.454	
Bankfull width (ft)								
1,2 Intercept	21.5							
Slope	0.362							
3 Intercept	24.0	0.132						
Slope	0.292	0.016						
4 Intercept	17.1	**0.433**	0.038					
Slope	0.460	**0.131**	0.007					
4a Intercept	9.1	**0.187**	0.660	**0.081**				
Slope	0.545	**0.221**	0.046	**0.639**				
5 Intercept	13.5	<0.001	<0.001	0.015	**0.671**			
Slope	0.449	<0.001	<0.001	0.879	**0.562**			
6 Intercept	16.9	**0.348**	0.882	**0.324**	**0.374**	0.020		
Slope	0.419	**0.104**	0.001	**0.569**	**0.507**	0.235		
7 Intercept	10.8	<0.001	<0.001	<0.001	**0.326**	0.001	<0.001	
Slope	0.458	0.005	<0.001	0.875	**0.583**	0.963	0.379	
Bankfull depth (ft)								
1,2 Intercept	1.06							
Slope	0.329							
3 Intercept	1.66	0.014						
Slope	0.210	<0.001						
4 Intercept	1.07	**0.412**	0.098					
Slope	0.314	**0.995**	0.033					
4a Intercept	0.79	**0.070**	0.029	**0.165**				
Slope	0.350	**0.923**	0.248	**0.913**				
5 Intercept	0.820	<0.001	<0.001	**0.230**	**0.377**			
Slope	0.373	0.062	<0.001	**0.459**	**0.809**			
6 Intercept	1.04	<0.001	<0.001	0.019	**0.540**	0.045		
Slope	0.244	0.005	0.301	0.245	**0.527**	<0.001		
7 Intercept	1.47	0.076	0.021	**0.670**	**0.640**	0.159	0.007	
Slope	0.199	<0.001	0.760	**0.130**	**0.434**	<0.001	0.286	
Bankfull cross-sectional area (square ft)								
1,2 Intercept	22.3							
Slope	0.694							
3 Intercept	39.8	0.425						
Slope	0.503	<0.001						
4 Intercept	17.9	**0.943**	0.611					
Slope	0.777	**0.134**	<0.001					
4a Intercept	7.2	0.001	0.037	**0.064**				
Slope	0.894	0.160	0.013	**0.717**				
5 Intercept	10.8	<0.001	<0.001	<0.001	**0.198**			
Slope	0.823	<0.001	<0.001	0.635	**0.681**			
6 Intercept	17.6	<0.001	<0.001	0.009	**0.727**	0.461		
Slope	0.662	0.347	<0.001	0.173	**0.278**	<0.001		
7 Intercept	15.9	<0.001	<0.001	<0.001	**0.627**	0.011	**0.090**	
Slope	0.656	0.186	<0.001	0.068	**0.103**	<0.001	**0.888**	

Note: Boldface values indicate that both the slope and intercept are not significantly different at $p = 0.05$.

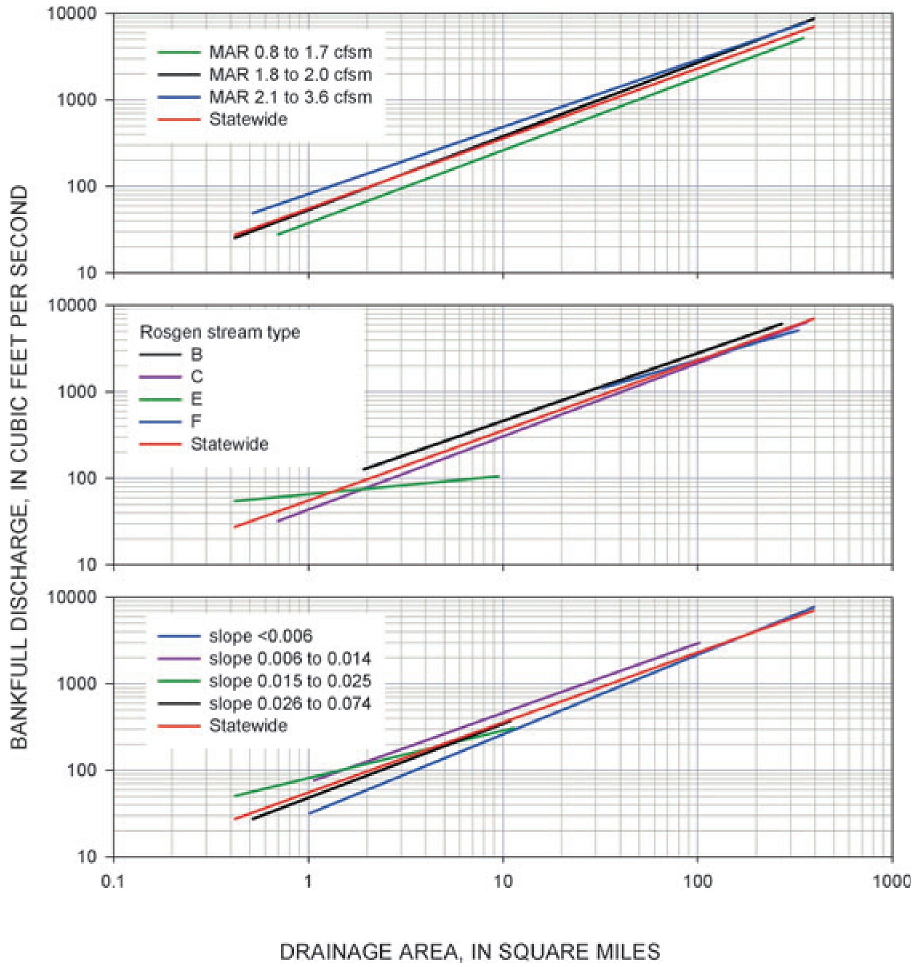

FIGURE 4. Bankfull Discharge as a Function of Drainage Area Stratified by Mean Annual Runoff (MAR), Rosgen Stream Type, and Water-Surface Slope.

TABLE 4. Bankfull Discharge Regression Equations, Standard Errors of Estimate, and R^2 for Mean Annual Runoff (MAR), Rosgen Stream Type, and Water-Surface Slope Models.

Co-variable	Model	Number of Streamflow-Gaging Stations Surveyed	Regression Equation for Bankfull Discharge	Standard Error of Estimate (percent)	R^2
MAR	0.8-1.7	30	$37.6\ DA^{0.842}$	43	0.93
	1.8-2.0	34	$53.3\ DA^{0.852}$	44	0.93
	2.1-3.6	18	$81.8\ DA^{0.775}$	64	0.88
Stream Type	Type B	12	$75.9\ DA^{0.784}$	56	0.89
	Type C	44	$43.6\ DA^{0.846}$	48	0.89
	Type E	4	$65.6\ DA^{0.211}$	35	0.51
	Type F	5	$109.1\ DA^{0.665}$	43	0.82
Water-surface slope	<0.006	46	$31.3\ DA^{0.920}$	48	0.89
	0.006-0.014	20	$72.6\ DA^{0.803}$	50	0.81
	0.015-0.025	11	$81.4\ DA^{0.549}$	70	0.43
	0.026-0.074	5	$48.2\ DA^{0.854}$	21	0.97

DISCUSSION

This study evaluates how various data stratification schemes can be used to optimize the accuracy and utility of regional HG curves in NY. Statistical analysis determined that the strength of the relations between bankfull discharge and drainage area varies depending on how the data were grouped. Causes for this variability between models can be grouped into

TABLE 5. Results of ANCOVA Analysis of Similarities in the Slopes and Intercepts of Regional Curves Relating Bankfull Discharge to Drainage Area, Stratified by Mean Annual Runoff (MAR), Rosgen Stream Type, and Water-Surface Slope.

MAR Range

		p-values for Similarities Between Models		
Region and Parameter	**Equation Coefficients**	**0.8-1.75**	**1.76-2.04**	**2.05-3.63**
0.8-1.75 Intercept	37.6			
Slope	0.842			
1.76-2.04 Intercept	53.3	<0.001		
Slope	0.852	0.869		
2.05-3.63 Intercept	81.8	<0.001	**0.161**	
Slope	0.775	0.397	**0.314**	

Stream Type

Region and Parameter	**Equation Coefficients**	**B-type**	**C-type**	**E-type**	**F-type**
B-type Intercept	75.9				
Slope	0.784				
C-type Intercept	43.6	0.029			
Slope	0.846	0.491			
E-type Intercept	65.6	0.070	0.755		
Slope	0.211	0.029	0.003		
F-type Intercept	109.1	**0.550**	**0.751**	0.017	
Slope	0.665	**0.659**	**0.432**	0.107	

Slope Range

Region and Parameter	**Equation Coefficients**	**<0.006**	**0.006-0.014**	**0.015-0.025**	**0.026-0.074**
<0.006 Intercept	31.3				
Slope	0.920				
0.006-0.014 Intercept	72.6	<0.001			
Slope	0.803	0.260			
0.015-0.025 Intercept	81.4	0.085	**0.212**		
Slope	0.549	0.035	**0.225**		
0.026-0.074 Intercept	48.2	**0.161**	**0.199**	**0.386**	
Slope	0.854	**0.734**	**0.803**	**0.324**	

Note: Boldface Values Indicate that Both the Slope and Intercept are not Significantly Different at $p = 0.05$.

two categories: factors that can be controlled by investigators, and factors that are due to natural variations in the field conditions controlling bankfull discharge. Examples of factors that could be controlled by investigators include favoring bankfull indicators with a predetermined RI, cross section location, and surveying gages that were inactive, in unstable reaches, or had less than 10 years of record. Factors that investigators could not control include the number of stable gages available with a suitable period of record, the location of those gages, and natural variability in the hydrologic and physiographic characteristics that influence streamflow patterns.

Although the specific source of variability among models are not always evident, knowledge of trends in regional bankfull discharge and HG relations is critical in model selection and application. For example, the bankfull discharge models for Regions 4 and 7 were the only models that fell outside the 95% confidence interval bounds of the statewide model, yet bankfull discharge data for several gages in Regions 3, 5, and 6 also plotted outside the confidence intervals of the statewide model (Figure 3a). Bankfull discharge in Region 4 is probably higher than for similarly sized streams in the rest of NY because this region includes basins with the greatest main channel slopes, mean annual precipitation, greatest mean and standard deviations of annual peak discharges, and the maximum 50-year peak discharge runoff rate (Lumia, 1991). Bankfull discharge in Region 7 is probably lower than for similarly sized streams in the rest of NY because this region includes basins with the greatest basin shape index values (ratio of basin length to average basin width, or basin elongation) (Lumia, 1991). Although localized regional curves eliminate some of the variability in bankfull discharge to drainage area relations, a high amount of natural variability is expected due to the large number of geomorphic, climatic, and physiographic variables that influence bankfull discharge and the logarithmic nature of these relations. These logarithmic relations translate into large ranges in the 95% confidence and 95% prediction limits of the regional curves (Miller and Davis, 2003; Mulvihill *et al.*, 2005, 2006, 2007; Westergard *et al.*, 2005; Mulvihill and Baldigo, 2007). Finally, although bankfull discharge RIs in NY were either equal to, or slightly higher than, the 1-2 year range documented by previous studies (Dunne and Leopold, 1978; Rosgen, 1996; Harman and Jennings, 1999; Castro and Jackson, 2001), this relation can possibly change as more peak-discharge data become available and RIs are recalculated.

Variability in stream-channel characteristics was even more pronounced with part or all of regionalized bankfull width, depth, and cross-sectional area curves plotting outside the 95% confidence interval bands of the statewide models (Figures 3b-3d). Although some HG models were similar to each other (Table 3) and to those of the Northeastern U.S. (Dunne and Leopold, 1978), the models for bankfull width, depth, and cross-sectional area in Region 3 were significantly different from those in other regions and statewide (Table 3). This could be related to the fact that Region 3 is in the Valley and Ridge province (Figures 1 and 2), which is the dominant physiographic province in southeastern Pennsylvania and the source of data used for the Northeastern U.S. model (Dunne and Leopold, 1978). The logarithmic nature of these relations, and the fact that a single extreme flood event can dramatically alter a stream's cross section, highlights the need to verify bankfull elevations in the field.

An important objective of this study was to test if variability in bankfull discharge to drainage area relations could be reduced if data were stratified by MAR, water surface slope, or Rosgen stream type instead of by hydrologic region. Six out of 11 co-variable models had R^2 values equal to or greater than 0.89, the R^2 of the statewide bankfull discharge model, suggesting that using a single co-variable to stratify data works at least as well as combining all the data into a single model approximately half the time. In many cases, however, co-variable models required data that were not readily available and most gages were placed in one or two co-variable data-stratification categories. This limited the strength of the ANCOVA analysis and appears to be partly responsible for the lack of significant differences between many co-variable models (Table 5). This was unexpected because previous investigations optimized regional curve relations by stratifying data by physiographic province (Johnson and Fecko, 2008), area of the country (Dunne and Leopold, 1978; Bent, 2006), ecoregion (Castro and Jackson, 2001), MAR (Miller and Davis, 2003), and mean annual precipitation (Lawlor, 2005).

Regardless of known limitations, co-variable regional models can be invaluable in certain applications. For example, the work of Miller and Davis (2003) in the Catskill Mountain region found that bankfull discharge MAR models reduced variability in areas with high precipitation. Historic flooding in the Catskills had recently caused channel erosion, over-widening, incision, and/or aggradation, which required emergency bank stabilization and channel excavation or filling to replace bridges and culverts, reopen roads, and protect private property and public infrastructure. Traditionally, emergency channel manipulations such as construction of rock walls and berms; removal of riparian trees; filling of floodplains; and widening, straightening, and deepening of channels were used with little consideration of how the stream would respond after the floodwaters receded. Regional curves and MAR models for Regions 4 and 4a were first used during flood-recovery efforts in 2006 and 2007 to ensure that resized channels were large enough to convey predicted bankfull flows. To date almost all of these resized channels have successfully conveyed subsequent peak-flows.

Stratifying bankfull discharge results by Rosgen stream type was originally hypothesized to strengthen relationships by grouping geomorphically similar streams together. This did not work as well as expected, however, because: (1) 17 of the 82 surveyed reaches contained more than one stream type and were therefore eliminated from the analysis; (2) sample size was highly variable: 44 reaches were C type, 12 were B type, 4 were E type, and 5 were F type; and (3) all E type streams had drainage area <10 mi^2, and all F type streams had drainage area >30 mi^2 (Mulvihill *et al.*, 2009). Nonetheless, bankfull discharge curve R^2 values and SEE for B and C type streams (Table 4) were comparable to that of the statewide model (Table 2). This suggests that the best use of Rosgen stream type models would be to prioritize remediation projects by assessing the extent to which measured HG metrics deviate from geomorphically similar streams (same stream type) in the same region. Another use would be to help permitting agencies decide whether channel dimensions in proposed remediation designs are capable of successfully conveying flood discharges. Using Rosgen stream type models to design stream restorations that mimic stable reaches of a specific stream type in the area could increase the success rate of stream restorations and facilitate efforts to maintain stable and healthy streams.

It has been hypothesized that because slope controls water velocity it is the most influential variable in discharge to drainage area relations. The results of this study, however, did not support this hypothesis because most USGS gages are in valleys with low to moderate slopes (Randall, 1996) and low gradient pools and high gradient riffles were unequally distributed among the study reaches. However, an R^2 of 0.97 for the 5 gages with high slopes (Table 4) clearly demonstrates that slope controls streamflow patterns in high relief areas. From this it can be inferred that the most reliable bankfull discharge estimates in high relief areas would come from slope models.

This study highlights some important issues that must be considered when generating regional HG curves. First, when this project was still in its early stages it was assumed that stratifying data by MAR, Rosgen stream type, or water surface slope would always improve regional relations; but the results of the statewide investigation did not support this hypothesis. This demonstrates the importance of working with as large a dataset as possible, even though in some areas of NY this could only be done by surveying discontinued gages, those with less than 10 years of record, or a stream in a neighboring state or province with a similar physical setting.

This study found that stratifying bankfull discharge and HG data by hydrologic region has several advantages over the other data stratification schemes examined in this study. For example, hydrologic region models were found to have the highest overall R^2 values and lowest overall SEEs. More importantly, flood-frequency regions are derived using statistical and deterministic procedures that have been proven unbiased, reproducible, and easy to apply (Ries and Crouse, 2002). Regional boundaries are also relatively easy to locate because the National Flood Frequency (NFF) Program provides software for estimating the magnitude and frequency of flood characteristics for rural, unregulated watersheds in the 50 States, the Commonwealth of Puerto Rico, and American Samoa (Ries and Crouse, 2002). NY recently made regional curves more accessible by adding them to StreamStats (http://water.usgs.gov/osw/streamstats/new_york.html), a USGS web-based tool that allows users to obtain streamflow statistics, drainage-basin characteristics, and other information for user-selected sites on streams (Ries *et al.*, 2004). Collocating streamflow statistics and regional curves will facilitate the work of engineers, land managers, biologists, and others who use this information in dam, bridge, and culvert design, as well as other water-supply planning and management applications.

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