OPTIMIZING CATSKILL MOUNTAIN REGIONAL BANKFULL DISCHARGE AND
HYDRAULIC GEOMETRY RELATIONSHIPS

Sarah J. Miller and Dan Davis[*]

ABSTRACT: The NYCDEP Stream Management Program (SMP) is responsible for developing stream management plans for NYC water supply watersheds in the Catskill Mountains, New York State. This mostly forested region of Pleistocene glacial deposits over sedimentary rocks ranges in elevation from approximately 600 to 4,120 feet above sea level; average annual precipitation ranges from 36 to >60 inches/year. The SMP uses fluvial geomorphology as a framework for stream assessment, restoration and monitoring. Bankfull discharge, a common surrogate for channel forming discharge, forms a basis for assessing and classifying stream morphology (Rosgen, 1994). The SMP documented bankfull discharge and associated stream geometry for 41 cross sections at 18 USGS stream gage stations, which produce statistically significant regression models as a function of drainage area. Coefficients of determination (R^2) for bankfull discharge, cross-sectional area, width, and depth are 0.81, 0.90, 0.88, and 0.85, respectively. Stratifying the data using either of two co-variables – hydrologic region (Lumia, 1991) or mean annual runoff (MAR) – significantly improves regional models. Observed scatter is best explained by variation in MAR, a measure of water availability largely dependent on the distribution of precipitation, enabling optimization of the data set to generate more specific regional curves for the Catskill Mountains.
KEY TERMS: bankfull discharge, gage calibration, hydraulic geometry, regional curves, fluvial geomorphology

INTRODUCTION

The New York City (NYC) Department of Environmental Protection (DEP) Stream Management Program (SMP) is one of many partnership programs managing the NYC water supply watershed in the Catskill Mountains (Figure 1). The central methodological framework for the SMP's work is fluvial geomorphology - the science describing stream form and function in relation to the landscape. Because multi-objective management is a priority for NYC, the SMP is interested in channel-forming processes impacting water quality, flooding behavior, aquatic habitat, and stream-related erosion. The SMP applies fluvial geomorphology to stream classification, stability assessment, and restoration design, construction and monitoring.

A basic premise of fluvial geomorphology is that there is a direct relationship between the shape (or morphology) of streams and their valleys and the way in which they function to conduct water and sediment through their watersheds. Each stream has a statistically significant discharge, commonly known as the effective or dominant discharge (Wolman and Miller, 1960; Andrews, 1980; Whiting, et al 1999; Emmet and Wolman, 2001), that moves the largest quantity of sediment over time owing to its frequent occurrence and its sediment transport capacity. This discharge is often equated with the channel forming flow, being statistically "responsible" for the channel form by transporting and depositing the greatest amount of bed material. The bankfull discharge, commonly described as the moderate, frequent flood event that fills an alluvial channel to the elevation of the active floodplain, is another widely used surrogate for the channel forming flow (Leopold, et al., 1964; Williams, 1978; Andrews and Nankervis, 1995; Rosgen, 1994; Moody and Odem, 1999; Harman et al., 1999). Various researchers report bankfull discharge to occur every one to two years, or 1.5 years on average (Dunne and Leopold, 1978; Rosgen, 1994; Moody and Odem, 1999; Harman, et al., 1999). A system for classifying and assessing streams has been developed based on bankfull channel dimensions and the hypothesis that bankfull stage can be consistently identified in the field (Rosgen, 1994). The SMP uses this system in support of stream management plans and restoration projects.

In practice, not all stream reaches show consistent or reliable field indicators of bankfull stage, and may often have conflicting indicators. Because accurate identification of bankfull stage is a necessary first step in any detailed geomorphic stream assessment, a dependable field tool is essential. Dunne and Leopold (1978) suggest there is a significant relationship between stream drainage area and bankfull discharge and associated morphology (hydraulic geometry), and this relationship differs regionally with hydrologic and basin characteristics. Regional regression models of these relationships (often called "regional curves") developed by Dunne and Leopold (1978), and reproduced with minor changes by Rosgen (1998), depict several generalized regions of the United States. These relationships are used in the field to help the researcher identify and confirm field indicators of bankfull stage. This paper summarizes a more comprehensive technical report documenting initial development and optimization of Catskill-specific models of bankfull discharge and hydraulic geometry (width, depth and cross sectional area) as a function of drainage area (Miller and Davis, 2003).

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[*] Respectively, Fluvial Geomorphologist, Geologist, NYCDEP Stream Management Program, 71 Smith Avenue, Kingston, NY 12401, Phone: (845) 340-7518; Fax: (845)340-7504; E-mail: smiller@dep.nyc.gov; ddavis@dep.nyc.gov

OBJECTIVES

The objectives of this study are: (1) test the hypothesis that bankfull stage indicators can be reliably identified in Catskill Mountains streams within a broad range of drainage area and variable states of channel equilibrium, (2) develop regional relationships for bankfull discharge and associated hydraulic geometry, and (3) test whether these regional relationships can be optimized by further stratifying by appropriate geographic variables.

An influential assumption in this study is that bankfull discharge typically occurs with average RI between 1 to 2 years. While this is consistent with other similar studies, it does preclude consideration of bankfull stage indicators that correspond to a discharge with much higher RI. Recent research has shown that in headwater mountain streams effective discharge RI may exceed 3 years (Wohl, 2000; Emmet and Wolman, 2001). This study was designed to determine whether a discrete set of confirmable bankfull stage indicators could be defined in the Catskills consistent with similar studies elsewhere.

STUDY AREA

The study area is a mostly forested region of the Catskill Mountains of New York State, containing approximately 1,600 square miles of watersheds feeding 5 reservoirs comprising the West of Hudson portion of the New York City water supply system (Figure 1). The Catskill region is comprised of four main escarpments forming the principal basin divides. Elevations in the study area range from 600 to 4,120 ft above mean sea level. Many of the peaks along the escarpments are above 3,500 ft in elevation.
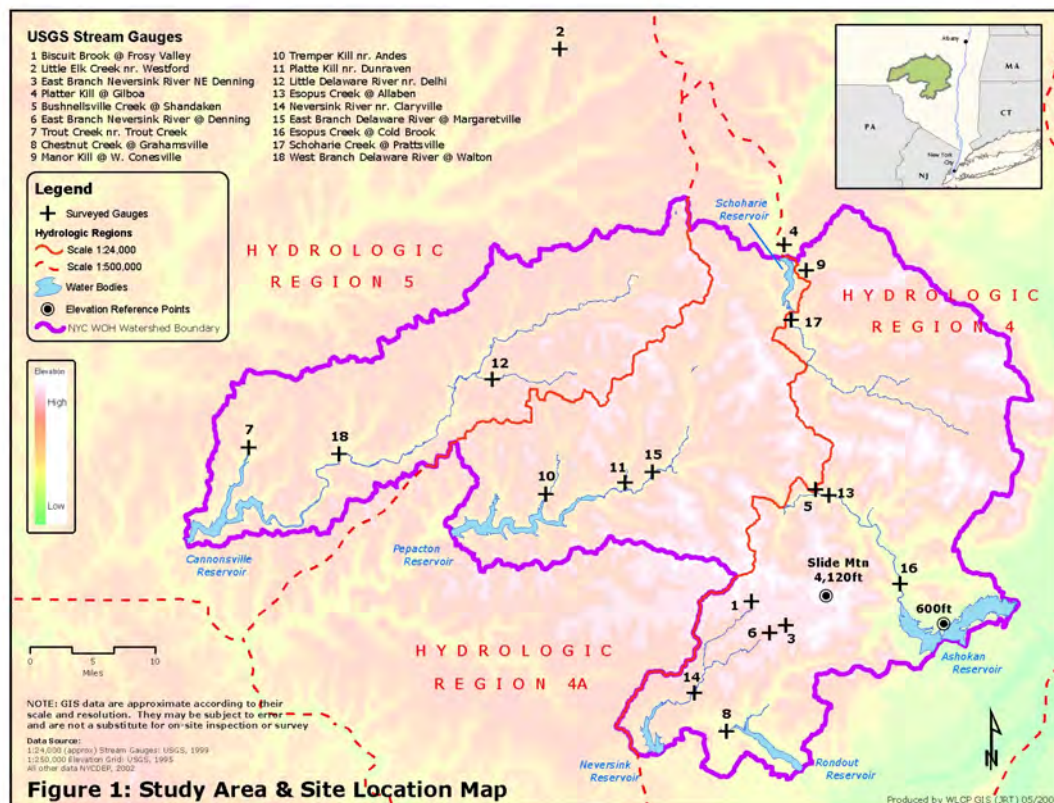

Figure 1. Study Area and Site Location Map.

The Catskill Mountains are an erosionally-dissected plateau of flat to gently dipping sedimentary bedrock. The Devonian-age sediments are repeated cycles of conglomerate and sandstone overlain by siltstones and shales, and are largely fluvial in origin. Modern Catskill Mountain stream deposits are principally derived from erosion of well-bedded sedimentary bedrock. As a result, stream clasts have low spherocity, typically forming platy or disk-shaped particles, which strongly influence the degree of stream substrate imbrication and the magnitude of flows required for mobilization. The complex Pleistocene glaciation of the Catskills (continental and alpine) has significantly modified the landscape, leaving varying deposits of clay-rich to bouldery till, silts, sands, gravels, and cobbles of glaciofluvial and ice-contact deposits, and easily erodible glaciolacustrine clays.

Water runoff to Catskill region streams, though influenced in part by localized differences in geology and land use, is principally influenced by the amount and distribution of precipitation. Average annual precipitation increases from a regional 36 to 42 inches in the northwest, to a "bullseye" of 45 to >60 inches in the high peaks region (Figure 2). Higher precipitation amounts are largely a result of a combination of orographic effect on precipitation and storm tracks from the southeast and southwest that extend into the eastern Catskills.
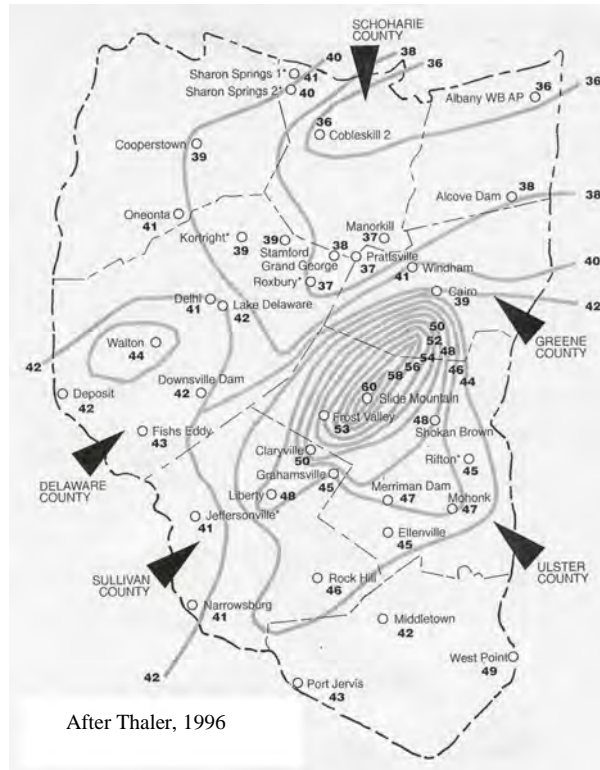

Figure 2. Average Annual Precipitation in the Catskill Mountains Region (inches; 1961-1990).

METHODOLOGY

The SMP used a detailed protocol to select sites, collect and analyze field data for bankfull discharge identification surveys at USGS stream gaging stations (Miller and Powell, 1999). A brief summary of the methodology is presented below.

Regional curves are developed using both field gathered and previously recorded data from stream reaches connected to USGS stream gaging stations. We selected stream reaches and associated gages according to the following criteria. The reach must be primarily alluvial, uncontrolled and single channel at bankfull stage and include at least two (2) meander wavelengths, two riffle/pool sequences, or an average of 20 bankfull widths in length. The reach should represent a single stream type, if possible, and must be in sufficient equilibrium that bankfull indicators are identifiable. The reach must cross the gage to associate bankfull indicators, channel morphology and discharge. The gage must be active, with at least 10 years of continuous peak flow record fitted to a Log Pearson Type III flood frequency distribution (Benson, 1968; U.S. Geological Survey, 1981). The gage must have a current rating table, preferably with little recent shift, and not represent a regulated basin, especially if the control impacts flood peaks.

Reaches chosen for this study are not necessarily "stable". Many gaging stations are located at bridges or other controls that may produce localized channel instability or obscure natural channel features. In addition, because roads and development patterns in the Catskills tend to follow streams, many gages represent intermittently straightened, hardened or otherwise impacted reaches. Nonetheless, we hypothesize that many streams have adjusted to these changes enough to show clear and confirmable bankfull stage indicators.

Preliminary reconnaissance is performed at each reach to evaluate site suitability, identify bankfull stage indicators and flag study reach limits. Investigators in similar studies typically look for a clear break between stream channel banks and an active flood plain (also referred to as the point of incipient flooding). However, an active flood plain is not a typical feature in mountain streams (Wohl, 2000). Bankfull stage indicators in our study reaches include significant breaks in cross section slope, back of point/lateral bars or low benches, and edge or base of cut banks. During reconnaissance, selected features are compared for consistency with other flagged indicators and localized conditions, and compared with the flood frequency distribution to check for anomalously high or low recurrence interval (RI) associated with the corresponding discharge.

Following reconnaissance, the study reach is surveyed, consistent with methods detailed in Harrelson et al. (1994). Longitudinal profile elevation survey follows the channel thalweg (for stationing) and includes thalweg channel bottom at feature breaks and deepest pool locations, current water surface at feature breaks and bankfull flags, and bankfull stage at flagged indicators. Cross sections are surveyed for derivation of hydraulic geometry, and include flood prone area for Rosgen (1994) stream classification. Bankfull channel bed material grain size distribution is characterized by modified Wolman pebble counts (Wolman, 1954; Rosgen, 1996) for selected riffle sections, and the reach as a whole for classification.

Elevation survey data are entered into standardized spreadsheets and plotted for graphic analysis. Bankfull stage profile through the gage is delineated by plotting a "smoothed" line through surveyed bankfull stage indicators (rather than connecting each point sequentially). Elevation of bankfull stage at the gage (staff plate) is identified, and corresponding discharge from the current rating table is determined. Bankfull discharge RI is obtained from the flood frequency distribution.

Cross sections are analyzed to determine bankfull hydraulic geometry (width, depth, cross sectional area) and Rosgen stream classification parameters (entrenchment, width/depth). The D_{50} and D_{84} particle sizes (for which 50% and 84% of the sample is smaller, respectively) are determined from grain size distributions. Bankfull discharge and hydraulic geometry estimates are checked by comparing velocity and geometry reported on USGS 9-207 forms (documenting actual and estimated discharge measurements), and by comparing velocity through surveyed cross sections where USGS discharge measurement location is unknown. Bankfull flow velocity is calculated by the continuity equation (velocity = discharge/cross-sectional area).

There are two primary categories of variation in the data: 1) actual variability in bankfull stage and discharge parameters, and 2) sample variability. Actual variability can be further categorized: a) local variability within the study reach, and b) natural variability between study reaches due to regional variables influencing hydrology and stream morphology. Sampling variability can be grouped as: a) measurement error, b) calculation error, and c) investigator bias.

We minimize bias in field bankfull indicator identification by corroborating a number of indicators through a reach, rather than taking a single point at the staff plate, especially if the reach shows local differences in morphology or control at the gage (such as a bridge or bedrock control). In addition, in locations with a recent high flow event, flood marks are surveyed with bankfull stage to demonstrate actual variations in water surface at a single high discharge to explain some local variations seen in bankfull indicators.

We use several approaches to minimize sources of sampling error, bias and subsequent variability in the data. A number of Quality Assurance and Quality Control measures are provided in the survey protocol (Miller and Powell, 1999). One or two people are responsible for identifying and flagging all bankfull locations, reach limits, and cross section locations, to minimize bias introduced by multiple investigator interpretations of field evidence. Consistent methodology, training programs, staff and equipment are used.

RESULTS

Between 1999 and 2002 field crews surveyed 18 gaged stream reaches, with drainage areas ranging from 3.7 to 332 square miles (Figure 1; Table 1). Study reaches range from steep, narrow headwater streams to wide, meandering valley-bottom streams; from stable reaches in thick forest to streams running through villages or managed agricultural land; and from boulder and intermittent bedrock beds to gravel and intermittent clay beds. The inclusion of two particular gages requires some explanation. The Little Elk Creek gage, while outside the NYC watershed (Figure 1), represents a small basin in a setting similar to the western Catskills. Discharge measured at the Esopus Creek at Cold Brook gage includes additional flows from the Shandaken tunnel (portal), which transfers water from Schoharie Reservoir to the Esopus basin at Shandaken, NY. Portal discharge ranges from 250 cfs to about 900 cfs, almost an order of magnitude less than bankfull discharge at the Cold Brook gage. DEP reduces portal flows during floods on the Esopus Creek, so maximum portal discharge rarely, if ever, occurs during a peak flow event.

Each study reach is classified using the Rosgen (1994) system, based on current water surface slope, bankfull width/depth ratio, entrenchment ratio, sinuosity and D_{50} of the bed surface material (Table 1). Rosgen stream types B, Bc, C, F, and Fb are represented in the data set.

Average bankfull discharge recurrence interval (RI) for the 18 study streams is 1.5 years, ranging from 1.2 to 2.7 years. We were able to confirm a set of stage indicators at each stream reach corresponding to a flow with 1 to 3 year recurrence, though we do not rule out the potential for a higher morphologically significant flow to be influential in the streams we studied.

Table 1. USGS Gaged Stream Reaches and Bankfull Channel Data, Catskill Mountain Region, NY.

Mean Annual Runoff (cfsm) calculated from mean annual discharge / drainage area for period of record to water year 2000. Italicized values are estimated.

Stream/Gage	Period of Record	Rosgen Stream Type	Hydrologic Region	Drainage Area (mi2)	Mean Annual Runoff (cfsm)	Bankfull Discharge (cfs)	Return Interval (yr)	Mean Depth (ft)	Width (ft)	Cross-Sectional Area (ft2)
Biscuit Brook abv Pigeon Brk at Frost Valley, NY (01434025)	1983 - P	F3b/B3	4	3.72	2.82	270.9	1.5	1.7	36.0	61.3
Little Elk Creek nr Westford, NY (01497805)	1977 - P	C4/F4	5	3.73	*1.55*	68	1.24	1.3	16.1	20.5
East Branch Neversink River ne of Denning, NY (0143400680)	1990 - P	F3/B3	4	8.93	3.52	1187	1.25	2.6	50.1	127
Platter Kill at Gilboa, NY (01350120)	1975 - 1989; 1989 - P	F3b/B3	4	10.9	1.26	342	2.7	1.6	39.7	64.3
Bushnellsville Creek at Shandaken, NY (01362197)	1971 - 1986; 1993 - P; CSG	B3c/C3	4a	11.4	*2.2*	297	1.5	2.1	35.7	76.6
East Branch Neversink River at Denning, NY (01434010)	1983 - P; CSG	B3c	4	13.3	*3.26*	1982	1.65	2.4	71.2	169.2
Trout Creek nr Trout Creek, NY (0142400103)	1952 – 1967; 1996 - P	C4	5	20.2	1.51	630	1.25	2.8	54.1	151.7
Chestnut Creek at Grahamsville, NY (01365500)	1937 - 1987; 1998 - P	B4c	4	20.9	1.86	1228	2.15	2.6	68.5	178.7
Manor Kill at W. Conesville nr Gilboa, NY (01350080)	1986 - P	F3b	4	32.4	1.52	803.3	1.2	2.3	56.0	129.5
Tremper Kill near Andes, NY (01415000)	1937 - P	F3/B3	4a	33.2	1.77	913.9	1.4	2.3	65.5	151.0
Platte Kill near Dunraven, NY (01414000)	1941 - 1962; 1996 - P	C3	4a	34.9	1.84	1172	1.45	2.5	55.7	135.7
Little Delaware River nr Delhi, NY (01422500)	1930 - 1970; 1997 - P	C4	5	49.8	1.78	1700	1.48	3.3	75.3	246.2
Esopus Creek at Allaben, NY (01362200)	1963 - P	F3	4	63.7	2.23	2772	1.65	4.3	80.5	342.9
Neversink River nr Claryville (01435000)	1951 - P	C3	4	66.6	2.84	4182	1.3	4.2	102.2	426.5
East Branch Delaware River at Margaretville, NY (01413500)	1937 - P	C4	4a	163	1.88	4047	1.32	5.0	149.6	747.1
Esopus Creek at Cold Brook, NY (01362500)	1931 - P	B3c/F3	4	192	2.72	7069	1.2	6.2	194.7	1201.0
Schoharie Creek at Prattsville, NY (01350000)	1905 - P	B4c/B3/c	4	237	1.96	8344	1.25	5.8	320.1	1814.6
West Branch Delaware River at Walton, NY (01423000)	1950 - P	C4	5	332	1.75	6644	1.33	4.6	243.6	1121.2

Regional Relationships

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

$$Q_{bf} = c(DA)^b \qquad\qquad (1)$$

where Q_{bf} is bankfull discharge (cfs), c is a coefficient related to watershed conditions (determined by regression), DA is drainage area (sq mi), and b is an exponent of the regression (slope of the regression line). The power function is derived from regression of log-transformed values of Q_{bf} and DA. Similar power functions are developed for bankfull hydraulic geometry parameters – width (W_{bf}, ft), depth, (D_{bf}, ft), and cross-sectional area (A_{bf}, sq. ft).

Equations derived for all study gages show statistically significant relationships between the independent variable (DA) and the dependent variables (Q_{bf}, W_{bf}, D_{bf}, A_{bf}, Table 2; Figure 3). The coefficient of determination (R^2) of 0.81 for the Q_{bf} curve indicates the model as fitted explains 81% of the variability in observed bankfull discharge. Similarly, R^2 of 0.88, 0.85, and 0.90 indicate the models for width, depth and cross-sectional area are reasonable fits to observed variability. The points plotted for hydraulic geometry are the average values based on a total of 41 cross sections surveyed at the 18 study sites.

We used standard error of estimate (residual standard deviation) to compute 95% confidence intervals for regression (Figure 3). Several "observed" bankfull parameter values fall outside this range. For some gages, even within the 95% confidence limits, the error of estimate is high.
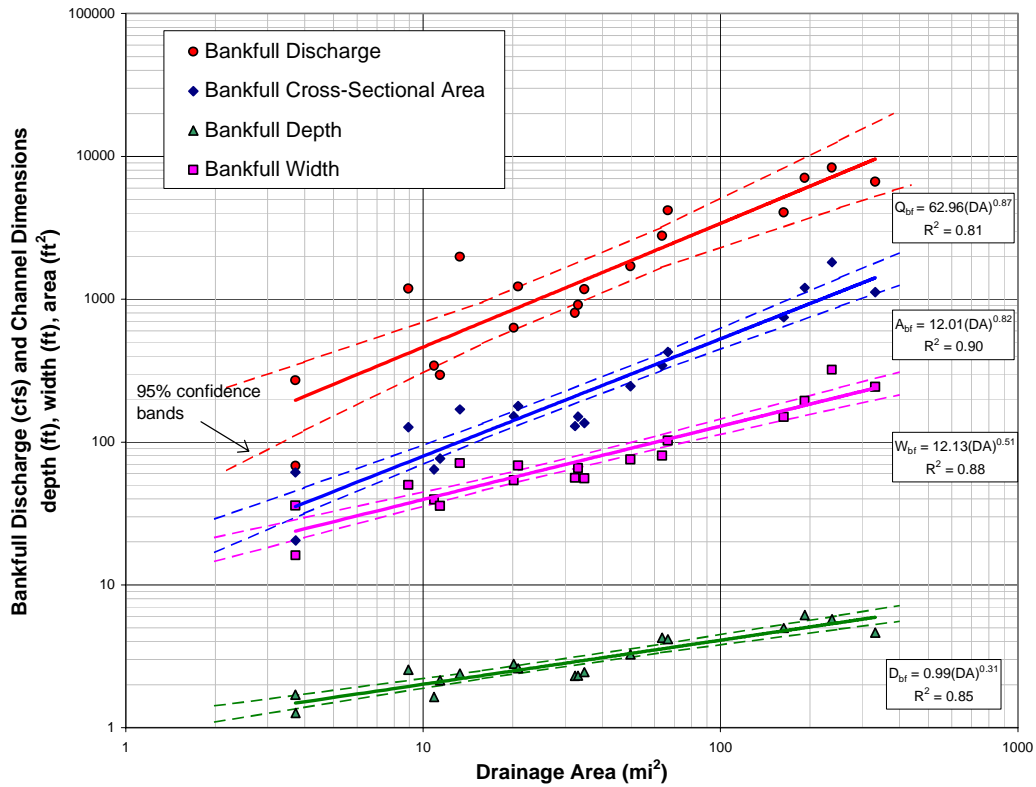
Figure 3. Bankfull Discharge and Hydraulic Geometry Regional Relationships for 18 USGS Stream Gages, Catskill Mountains, NY

Table 2. Bankfull Discharge and Hydraulic Geometry Regional Relationships for 18 USGS Stream Gages in the Catskill Mountains, NY: Regression Equations and Coefficients of Determination.

Parameter	Equation	Coefficient of Determination (R^2)	Sample Size (N)
Bankfull Discharge	$Q_{bf} = 62.96(DA)^{0.87}$	0.81	18
Width	$W_{bf} = 12.51(DA)^{0.51}$	0.88	18
Depth	$D_{bf} = 1.01(DA)^{0.31}$	0.85	18
Cross-Sectional Area	$A_{bf} = 12.67(DA)^{0.81}$	0.90	18

We presume some variability in the data set is due to actual natural variability of field conditions controlling bankfull discharge. Some variability may be attributable to bias, perhaps associated with using a specific RI range as a field check for bankfull stage. Scatter in geometry relationships is likely in part due to stream type and degree of stability, influenced by differing geology, vegetation, land use, sediment load, and runoff characteristics. In addition, cross section location is influential, as local variations in hydraulic geometry variables within a reach can vary with changes in local riffle slope, sediment size, roughness and vegetative characteristics.

Close examination of the scatter about the curves shows that most reaches with bankfull discharge parameter values above the regression line are in the Neversink, Esopus, Rondout and upper Schoharie basins (draining the high peaks region), while most reaches with bankfull discharge parameter values below the regression line are in the Delaware or mid-Schoharie basins (draining less mountainous terrain). The notable exception is the Bushnellsville Creek, which is in the Esopus basin but lies below the regression line. To capitalize on this regional pattern and improve the power of our models, we stratified the data by two regional variables: hydrologic region and water availability (represented by mean annual runoff). We also evaluated the effect of Rosgen Stream type on the hydraulic geometry relationships.

Stratifying by Hydrologic Region

Similar studies have stratified gage data by hydrophysiographic provinces, delineated on the basis of hydrologic and physiographic characteristics (e.g. Harmen et al, 1999; Moody and Odem, 1999). There are no previously delineated

hydrophysiographic provinces for the study area, however, hydrologic regions have been developed by USGS for New York State (Lumia, 1991, Figure 1). Lumia delineated flood frequency (2 to 500 year RI) hydrologic regions using multi-variate regression analysis, including climatic, geologic and physiographic data for each region. The Catskills study area is represented by regions 4, 4a, and 5 (Figure 1). Regions 4 and 4a include the high peaks region, Schoharie, Neversink and East Branch Delaware River basins. Region 5 includes West Branch Delaware River basin.

Because regions 4a and 5 include 4 gages each, stratifying our Q_{bf} data by hydrologic region is limited, though we can reasonably stratify hydraulic geometry using 41 cross sections. For demonstration purposes, we present stratified hydraulic geometry regression curves for A_{bf} in addition to preliminary stratification for Q_{bf}, showing improvement in R^2 for regions 4a and 5, and no change in region 4 (Figures 4a and 4b; Table 3). The regression results indicate that there is negligible distinction between regions 4a and 5. Platter Kill and Manor Kill sites, both in region 4, appear to better match 4a and 5 curves, limiting applicability of stratifying by hydrologic region.
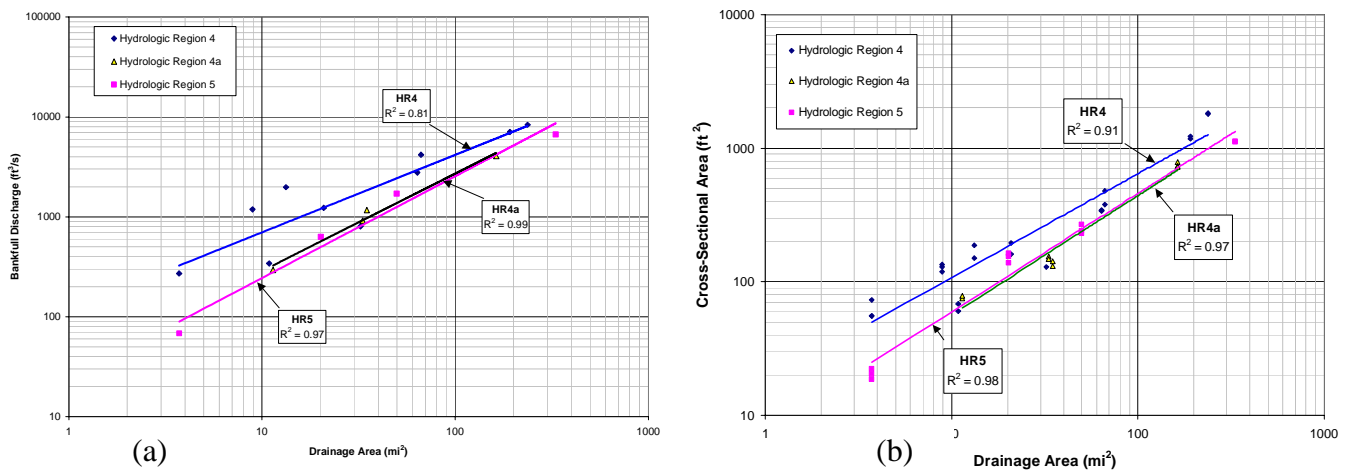

Figure 4. Regional Relationships for 18 USGS Stream Gages in the Catskill Mountains, NY Stratified by Hydrologic Region: (a) Bankfull Discharge; (b) Cross-sectional Area.

Stratifying by Mean Annual Runoff

The Catskill Mountains high peaks region receives significantly more precipitation than surrounding regions (Figure 2). Considering precipitation concentration and basin characteristics that influence runoff amount and timing may reduce regression scatter. Mean annual discharge at continuous recording gages can serve as an index of water availability in a basin (Wandle and Randall, 1994), and therefore may be a used to segregate gage data into groups with similar characteristics.

Mean annual runoff (MAR) expressed as the ratio of mean annual discharge to drainage area, in cubic feet per second per square mile (cfsm) represents a unit runoff for the basin upstream of the gage. MAR accounts for precipitation and basin characteristics affecting annual runoff volume (e.g. imperviousness, slope, basin storage, geology), and normalized by drainage area, enables comparison between streams of different size. MAR values for the period of record for study gages range from 1.26 cfsm to 3.52 cfsm (USGS, 2001), with a systematic pattern of relatively high MAR values for gages with bankfull discharge above the regression line, and relatively low MAR values for gages with bankfull discharge below the predicted value (Figure 3; Table 1). Hydraulic geometry plots show a similar pattern (Figure 3).

Stratifying the data by MAR is limited because MAR cannot be computed for crest stage or regulated gages. We estimated MAR for the East Branch Neversink River at Denning crest stage gage (3.26 cfsm) by interpolating between two continuous gages upstream and downstream. Estimated MAR is relatively high, following the same pattern shown above. We used the MAR map for the glaciated northeastern U.S. (Randall, 1996) to estimate MAR for Bushnellsville Creek (2.2 cfsm) and Little Elk Creek (1.55 cfsm), because there are no other gages in either basin. Little Elk Creek MAR is similar to basins in the western Catskills. Though Bushnellsville Creek is in the high peaks region, estimated bankfull discharge and hydraulic geometry are quite low compared to other gages with high MAR value (Table 1). Actual MAR for Bushnellsville Creek may be lower than 2.2 cfsm, or flows may be suppressed by extensive relatively permeable glacial lake deltaic deposits and kame terrace deposits present throughout the basin.

To estimate MAR for Esopus Creek at Cold Brook (2.73 cfsm), we had to remove intra-basin flow from the Shandaken portal. Only 4 years of portal flow records are available, potentially compromising the accuracy of these calculations. Estimated MAR for the Esopus is higher than MAR for the Esopus Creek at Allaben (upstream of the portal). Though this value may be in error, for the purpose of this investigation the value is used to test the hypothesis of stratifying by MAR.

Stratifying by MAR requires segregating the data into groups or classes. To define a clear MAR class break in the data requires analysis of a larger set of Catskills gages, comparing the same water years to minimize the influence of wetter or

drier years in longer periods of record. There are 38 USGS continuous recording gaging stations in the Catskill Region with complete water year flow records for 1998 and 1999. Our analysis shows average MAR for these two years (1998 was wetter than average, and 1999 was drier than average), represent a reasonable surrogate for gages with 6 or more years of record (regression of 1998/1999 to the full record yielded $R^2=0.94$). Histogram analysis reveals a bimodal distribution, suggesting a class break between 2.3 to 2.5 cfsm (mean MAR is 2.3 cfsm). We stratified the data using a 2.3 cfsm class break.

Stratifying bankfull discharge and hydraulic geometry data by MAR significantly improves predictive relationships and reduces errors of estimate (Figures 5a and 5b; Table 3). High MAR streams, with greater Q_{bf}, tend to be headwater streams in the high peaks region, typically with larger channels and higher sediment loads than streams in less mountainous areas. For example, A_{bf} predicted for a stream with DA=10mi^2 in the high MAR class is 129 ft^2 while A_{bf} for a stream in a similarly-sized basin in the low MAR class is 60 ft^2 (Figure 5b). The observed values generally closely correspond to the predicted values (Figures 5a and 5b; Table 1).
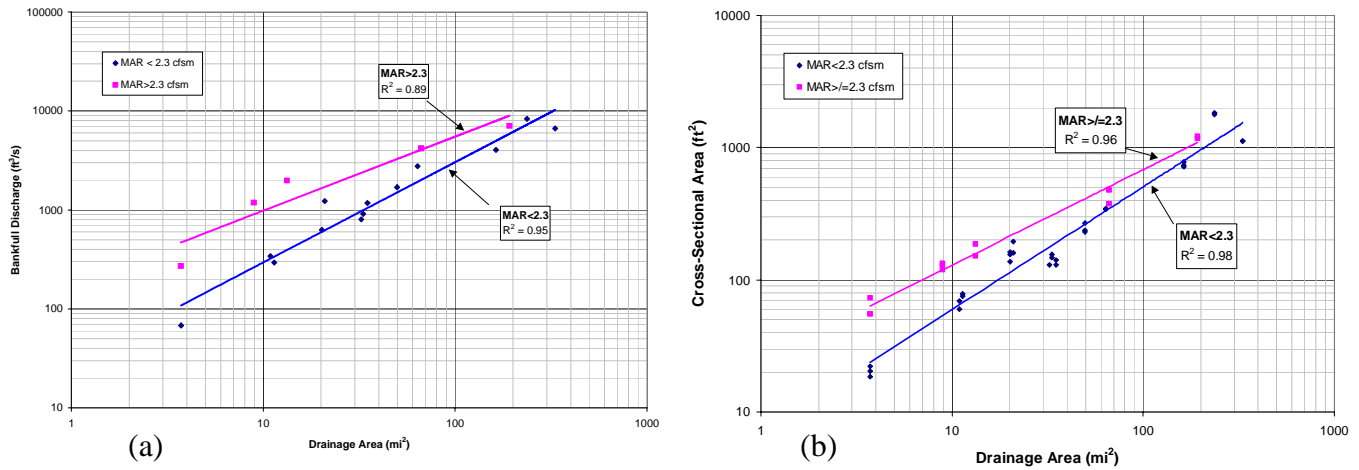

Figure 5a and 5b. Regional Relationships for 18 USGS Stream Gages in the Catskill Mountains, NY, Stratified by Mean Annual Runoff (MAR): (7a) Bankfull Discharge; (7b) Cross-sectional Area.

Stratifying by Rosgen Stream Type

Stratifying the data set by stream type (B, C, and F), we found 3 distinct trends with reasonable R^2 can be distinguished, though there is still considerable variability and potential error (Table 3). B- and C-type geometry increase at similar rates, though B-type streams tend to have higher hydraulic geometry values for a given drainage area. F-, B- and C-type streams have similarly sloping cross-sectional area curves, though depth and width show uniquely sloping trends.

Table 3. Bankfull Discharge and Hydraulic Geometry Stratified Regional Relationships for 41 cross sections at 18 USGS Stream Gages in the Catskill Mountains, NY: Regression Equations and Coefficients of Determination.

Stratifying Variable	Bankfull Discharge	Width	Depth	Cross-Sectional Area
Hydrologic Region 4	$Q_{bf} = 117.25(DA)^{0.78}$ $R^2 = 0.81$; N= 10	$W_{bf} = 17.07(DA)^{0.46}$ $R^2 = 0.87$; N= 21	$D_{bf} = 1.05(DA)^{0.32}$ $R^2 = 0.85$; N= 21	$A_{bf} = 17.93(DA)^{0.78}$ $R^2 = 0.91$; N=21
Hydrologic Region 4a	$Q_{bf} = 30.35(DA)^{0.98}$ $R^2 = 0.99$; N= 4	$W_{bf} = 9.12(DA)^{0.55}$ $R^2 = 0.87$; N= 9	$D_{bf} = 0.79(DA)^{0.35}$ $R^2 = 0.88$; N= 9	$A_{bf} = 7.19(DA)^{0.89}$ $R^2 = 0.97$; N=9
Hydrologic Region 5	$Q_{bf} = 23.39(DA)^{1.02}$ $R^2 = 0.97$; N= 4	$W_{bf} = 7.79(DA)^{0.60}$ $R^2 = 0.98$; N= 11	$D_{bf} = 0.98(DA)^{0.29}$ $R^2 = 0.90$; N=11	$A_{bf} = 7.69(DA)^{0.89}$ $R^2 = 0.98$; N=11
MAR<2.3 cfsm	$Q_{bf} = 28.65(DA)^{1.01}$ $R^2 = 0.95$; N= 13	$W_{bf} = 8.07(DA)^{0.60}$ $R^2 = 0.94$; N= 29	$D_{bf} = 0.87(DA)^{0.33}$ $R^2 = 0.88$; N=29	$A_{bf} = 7.04(DA)^{0.93}$ $R^2 = 0.96$; N=12
MAR∃2.3 cfsm	$Q_{bf} = 175.62(DA)^{0.75}$ $R^2 = 0.89$ N= 5	$W_{bf} = 21.25(DA)^{0.41}$ $R^2 = 0.96$; N= 12	$D_{bf} = 1.15(DA)^{0.31}$ $R^2 = 0.93$; N=12	$A_{bf} = 24.53(DA)^{0.72}$ $R^2 = 0.98$; N=29
B Stream Type		$W_{bf} = 13.26(DA)^{0.54}$ $R^2 = 0.84$; N= 12	$D_{bf} = 1.15(DA)^{0.29}$ $R^2 = 0.83$; N=12	$A_{bf} = 15.23(DA)^{0.82}$ $R^2 = 0.89$; N=12
C Stream Type		$W_{bf} = 7.99(DA)^{0.58}$ $R^2 = 0.98$; N= 18	$D_{bf} = 1.03(DA)^{0.29}$ $R^2 = 0.88$; N=18	$A_{bf} = 8.31(DA)^{0.88}$ $R^2 = 0.97$; N=18
F Stream Type		$W_{bf} = 15.56(DA)^{0.45}$ $R^2 = 0.87$; N= 11	$D_{bf} = 0.86(DA)^{0.35}$ $R^2 = 0.83$; N=11	$A_{bf} = 13.42(DA)^{0.81}$ $R^2 = 0.87$; N=11

CONCLUSIONS

Based on analysis of 41 cross sections at 18 gaged stream reaches we show there is a statistically significant relationship between drainage area and bankfull discharge and its associated hydraulic geometry in the Catskill Mountain region. Though many streams in the data set include sections of previously, or even presently, disturbed morphology, we were able to consistently identify a clear set of dominant channel features representing a narrow discharge range in each study site. This shows identification of bankfull stage seems to depend on the degree to which a stream is functioning under the current hydrologic regime, rather than on strict channel stability, and that this set of relationships accurately represents stream processes and morphology.

We improved the relationships by accounting for geographic location and corresponding climate conditions by using either of two stratifying variables – hydrologic region or mean annual runoff (MAR). Stratifying by hydrologic region improves the predictive relationships for regions 4a and 5 yet is problematic, however, given limited representation in our dataset for regions 4a and 5, and different precipitation zones represented in region 4.

We found stronger correlation when stratifying our data using MAR, with less variability in the lower MAR class than in the higher MAR class. In smaller, steeper watersheds of headwater mountains streams, geologic control on boundary resistance likely exerts a greater effect on the magnitude of channel forming flows and associated channel dimensions. Stratifying by MAR allows a more flexible grouping of gage sites with the opportunity to optimize data sets to match expected conditions of a given area. We believe the best use of the available dataset is to optimize the range of applicable MAR values for development of predictive equations for a particular watershed. For example, a researcher might exclude high to very high MAR gages to derive regional relationships for streams in moderate to lower MAR watersheds. In high MAR watersheds, especially, the researcher needs to consider watershed geologic similarity. We recommend initially comparing field-identified bankfull parameters with unstratified curves, and using stratified curves (e.g. Table 3) as appropriate when working in specific areas of the Catskill Mountain region.

Since MAR is measured only at continuous recording stream gages, resultant curves may have limited field application for ungaged sites where MAR is unknown. The MAR map for the glaciated northeastern US (Randall, 1996) can be used as an initial guide to determine MAR class for ungaged basins. However, the case of Bushnellsvile Creek indicates this method has the potential for locally high predictive error. Should further research confirm MAR is a useful stratifying variable for regional curves, additional research should focus on producing detailed Catskill Mountains regional MAR maps for field use.

We also found that considering stream type can improve the relationship between drainage area and bankfull hydraulic geometry for the Catskill region, particularly for C-type streams, with some improvement for B- and F-type streams.

Regional curves developed through this and continuing research will be used to assist development of a set of hydraulic geometry relationships for stable reference reaches alone, stratified by stream type. In particular, gage-derived curves will be useful for identifying and confirming bankfull stage at reference reaches by comparison with discharge (for roughness and velocity calculations), and cross sectional area in particular. Stable hydraulic geometry curves will be valuable in identification and confirmation of bankfull stage at stable reference reaches in the field for stability assessment, design survey, and monitoring at restored reaches. These curves could also be valuable in permit review to guide initial assessment of proposed stream related projects, to determine whether proposed morphology deviates markedly from stable geometry for a particular stream type and setting.

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