Hydraulic Geometry Curves in the Pee Dee Watershed

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Abstract. Hydraulic bankfull geometry or regional curves are a useful metric for evaluating stream stability and planning stream restoration projects. Streams and tributaries within the Middle Pee Dee River Basin (MPDRB) in South Carolina drain an agrarian and forested landscape characterized by water conveyance structures, such as active and historical ditches which support forestry and agriculture. While streams in the region are generally stable, pockets of this landscape are beginning to face increasing pressure from development with signs of stream instability apparent in several locations as evidenced by streams in and around the urbanizing areas around Darlington and Florence, SC. In order to provide a foundation for potential stream restoration projects in the area, 15 sites in the MPDRB were selected on the basis of catchment area, in categories of small (<50 km²), small-medium (50-500 km²), medium (500-1000 km²), and large (>1000 km²). Bankfull geometries, channel substrate, flow and water temperature were measured at all the sites and a set of regional hydraulic geometry curves developed. The frequency of bankfull flows that occurred over the period of sampling were also estimated to document floodplain connectivity. Results suggest that bankfull dimensions in the MPDRB were well correlated with bankfull discharge and drainage area. The results showed that hydraulic geometry in the region were similar to those measured in a similar physiographic region in North Carolina. The study also shows that streams in the MPDRB experience bankfull exceeding flows much more frequently than streams in other parts of the country, but at a frequency that is comparable to streams in the coastal plains of North Carolina.

INTRODUCTION

Hydraulic bankfull geometry relationships are essential to the geomorphological characterization of stable streams that might potentially be subject to perturbations of flow and sediment regime. These perturbations could arise as a function of land use change (short term) or climate change (long term) and can significantly alter the fluvial form and function of stream channels. By establishing a reference condition for

channel form and function based upon hydraulic geometry, one might potentially quantify the extent of departure from that stable state and possibly provide a basis for future restoration efforts (Sweet and Geratz, 2003).

The existence of hydraulic geometry in streams with topographically similar watersheds has been well documented and the relationship is referred to as regional curves or hydraulic geometry curves (Metcalf et al., 2009; Sweet and Geratz, 2003; Leopold, 1994; Dunne and Leopold, 1978). Hydraulic geometry curves have been developed for various regions across the United States and are generally represented in the form of a power equation (e.g. Dunne and Leopold, 1978). While Dunne and Leopold's (1978) hydraulic geometry curves relied on a bankfull flow rate (Q_{bkf}) as the independent term in a power relationship of the form $W_{bkf} = a Q_{bkf}^b$, recent studies (Metcalf et al., 2009; Cinotto, 2003; Sweet and Geratz, 2003; Doll et al., 2002; Castro and Jackson, 2001) employ drainage area (A_c) as a predictor of hydraulic geometry ($W_{bkf} = a A_c^b$) as a consequence of the close correlation between drainage area and bankfull flow (Doll et al., 2002; Castro and Jackson, 2001).

The development of hydraulic geometry curves have been carried out within specific geographical boundaries, boundaries defined by ecoregion (Sweet and Geratz, 2003), physiographic province (Cinotto, 2003), and the regions with similar average yearly rainfall and runoff patterns (Metcalf et al., 2009). Initially reported by Dunne and Leopold (1978) and later modified by Leopold (1994), hydraulic geometry curves have since been developed across the country for various topographic regions. These include studies in the Pacific NW (Castro and Jackson, 2001), Pennsylvania and Maryland (Cinotto, 2003), northern Florida (Metcalf et al., 2009), Midwestern agricultural streams (Jayakaran et al., 2005) and the piedmont (Doll et al., 2002) and coastal plains (Sweet and Geratz, 2003) regions of North Carolina.

There has also been considerable interest in relating bankfull flow to a recurrence interval. Sweet and Geratz (2003) summarized several published studies (e.g. Castro and Jackson, 2001; Harman et al., 2000, 1999; Rosgen, 1996; Leopold, 1994; Dunne and Leopold, 1978) on streams across the continental U.S., the piedmont, and mountain

regions of North Carolina, reporting bankfull flows associated with a recurrence intervals ranging between 1.4 and 1.6 years. All those studies employed annual duration series (USGS, 1982) with several decades of flow record per study. However, in a study on streams in the coastal plains of North Carolina, Sweet and Geratz (2003) reported a bankfull flow recurrence interval of less than a year based on an annual duration series. However, recurrence intervals based on a partial duration series averaged only 0.19 years for those same streams. In other words, streams in the North Carolina coastal plain tended to overtop their bankfull elevation several times a year.

With the increase in stream restoration projects in neighboring states (Sweet and Geratz, 2003: North Carolina), it is likely that stream restoration projects in South Carolina will soon follow suit. However, to date no regional hydraulic geometry curves have been derived for streams in the MPDRB. As landscape and climate changes impact the streams that drain these watersheds and the need to restore potentially degraded reaches increase, the defining of hydraulic geometries that characterize stable streams in the region become critical. The objectives of this study were to derive bankfull curves for a coastal plain watershed using 15 sites in the MPDRB, as well as to quantify the annual average number of times bankfull exceeding events that took place over the period of available data.

PROJECT DESCRIPTION

Streams in the MPDRB are non-tidal low gradient coastal plain streams with bed substrates comprising a sand or sand-gravel mix. Study sites were selected to represent a wide range of watershed drainage areas, ranging from 17 to 1,718 km². Sixteen sites were selected on the basis of catchment area, in categories of small (<50 km²), medium-small (50-500 km²), medium (500-1000 km²), and large (>1000 km²). Only sites deemed geomorphologically stable based on visual surveys of channel bed, banks, and vegetation were chosen (e.g. Sweet and Geratz, 2003). The selection process also evaluated each possible site on the basis of land use within the watershed, ease of access and security of instrumentation. Study sites were all located within the Southeastern Plains EPA Level III ecoregion (Griffith et al., 2002) though some watersheds had upper sections of their catchment in the Piedmont Level IV ecoregion. At the Level IV scale, watersheds spanned six ecoregions: Atlantic Southern Loam Plains, Southeastern Floodplains and Low Terraces Sand Hills, Southern Outer Piedmont, Carolina Slate Belt, and Triassic Basins (Figure 1). Stream densities in all the study watersheds averaged 0.22 km of stream per square kilometer and varied between 0.13 and 0.37 km of stream length per square kilometer of catchment area (A_c). Six of the chosen sites utilized United States Geological Survey (USGS) flow monitoring gauges. These sites included Big Black Creek below Chesterfield (02130840), Black Creek near McBee (02130900), Black Creek near Quinby (02130980), Jeffries Creek (02131110), Lynches River near Bishopville (02131500), and Little Fork Creek at

Jefferson (02131320). Four sites were chosen in conjunction with the SCDNR's fish monitoring program (Figure 1). One of the sixteen sites was subsequently abandoned as a colony of beavers built a dam just downstream of the site, impacting our ability to reasonably quantify flow rates. Ultimately, 15 sites were used to develop hydraulic geometry for the MPDRB.

METHODS

Stream Morphology

For the wadeable stream sites, a total station was used to measure channel pattern, profile, and dimension per Harrelson et al. (1994). Stream surveys ranged from 100 to 300m along the stream profile depending upon the size of the stream including at least three representative cross sections. Cross sections were chosen based on the presence of a stable riffle with well-defined bankfull features. Depending on the size of the stream, cross sections ranged from 30 to a 120m apart. Elevations for channel thalweg, water surface and bankfull features were also recorded. Bankfull features were identified, taking careful note of indicators of bankfull level, grade changes, changes in vegetation, significant changes in particle size, level of organic debris, and scour lines (Dunne and Leopold, 1978). Specifically, evidence of bankfull elevation included a significant change in grade (i.e. steep slope to mild slope), change in vegetation (bare soil to grasses, grasses to moss, or the line where woody vegetation begins), significant changes in particle size (gravel to sand, sand to silt, etc.), level of organic debris (i.e. leaf litter), and scour lines (Dunne and Leopold, 1978). Panoramic photos taken at each site helped to corroborate selection of bankfull stage and provided photographic documentation of each site. A weight of evidence approach was used based on the above parameters, and an estimate of bankfull elevation that satisfied as many indicators as possible was made.

For non-wadeable streams, stream pattern, profile, dimension and velocities were measured with a floating acoustic doppler current profiler (ADCP). To measure stream profile and pattern, the ADCP unit (River Surveyor M9 Sontek-YSI) with Real Time Kinematic positioning (RTK-GPS) was towed behind a slow moving boat several times along the stream centerline in both upstream and downstream directions. The RTK-GPS capability allowed for tracking ADCP position in three-dimensional space providing stream sinuosity, and water surface elevations. The profiling capability of the unit provided the elevations of channel bottom along the path of travel. To measure stream dimension and average stream velocity, the ADCP unit was slowly pulled several times from bank to bank across the stream cross section being measured while ensuring that the ADCP's rate of travel never exceeded 10% of stream velocity. To ensure a complete characterization of stream morphology, total station topographic surveys were carried out to complete the above-water portions of the stream cross sections that were profiled with the ADCP

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Figure 1. Study sites in the middle Pee Dee basin. Inset box shows the Pee Dee and Lynches River watersheds, labeled with lighter and darker blues, respectively. Level IV ecoregions in this chart include: Atlantic Southern Loam Plains (ASLP), Carolina Flatwoods (CF), Carolina Slate Belt (CSB), Mid-Atlantic Flatwoods (MiAF), Sand Hills (SH), Southeastern Floodplains and Low Terraces (SFLT), Southern Outer Piedmont (SoOP), and Triassic Basins (TrB).

unit. All survey data were processed using the Reference Reach Spreadsheet for Channel Survey Data Management (Mecklenburg and Ward, 2004).

Flow Monitoring

Streamflow data for the six USGS sites were obtained from the USGS real time water website (<http://waterdata.usgs.gov/sc/nwis/rt>); data availability ranged from 3 to 52 years. For the 9 remaining sites, flow was estimated from river stage data measured with logging pressure transducers (Solinst® Leveloggers) in conjunction with stage-flow rating curves developed for each site. Site specific stage-flow rating curves were based on estimated roughness coefficients developed using measured velocity readings at various flow depths, and estimating flow using the continuity equation $Q = A \cdot V$; where Q = estimated flow, A = wetted area, V = measured stream velocity. For non-wadeable streams, velocities were estimated using a floating ADCP unit per Mueller and Wagner (2009), while in wadeable streams, a two-dimensional flow velocity meter (YSI-Sontek Flow Tracker®) was used per John (2001). For above bankfull

flow stages, a floodplain roughness coefficient was estimated using Chow (1959). Flow values were estimated for every stage sensor value on a 10-minute basis from July of 2009 through June of 2012.

Occurrence of Bankfull Flows

Bankfull discharges were calculated by estimating the amount of flow needed to fill the bankfull channel, based upon the slope and calculated roughness coefficient for each site. We also recorded the number of times flow in the stream exceeded calculated bankfull flow over the period of record. Frequency of bankfull flow exceedance enabled the calculation of an annual average bankfull occurrence rate, or simply, the average number of times in a year that flow in a stream exceeded bankfull flow. Two successive bankfull exceeding events occurred only if the stream level dropped below the bankfull elevation between the two events. Therefore multiple peaks that did not drop below the bankfull stage counted as a single bankfull exceeding event. Given that we only had 2.9 years of flow record at 9 sites (except USGS sites), we calculated bankfull occurrences per

year and not a traditional recurrence interval as calculated by Sweet and Geratz, (2003) and others. The bankfull occurrence per year metric was simply a means to relate our temporally limited dataset with other published studies.

RESULTS

Most streams in the MPDRB were swampy, sluggish, and impeded by large woody material. Stream slopes ranged from 0.023% to 0.42% and calculated Manning's roughness values ranged from 0.038 to 0.107. Hydraulic geometry for the MPDRB was based upon bankfull dimensions, in turn derived from measured cross-sections at 15 study sites with drainage areas that spanned three orders of magnitude. Given the broad range of watershed drainage areas, the four bankfull dimensions (W_{bkf} , D_{bkf} , A_{bkf} , and Q_{bkf}), also showed a broad range of values. Bankfull width ranged from 3.4 to 46.7 m, average bankfull depth ranged from 0.5 to 3.2 m, bankfull cross sectional area ranged between 1.5 and 148.0 m², and bankfull flow rate ranged between 0.5 and 68.1 m³/s. Bankfull dimensions and site parameters are summarized in Table 1.

Bankfull Occurrence

Bankfull occurrence ranged from 0.3 to almost 6.2 times per year with an average of 2.5 occurrences per year across all sites. In other words, flow rates on average met or exceeded bankfull discharge more than 2 times per year in the MPDRB.

Hydraulic Geometry

Bankfull related measurements such as bankfull width, average bankfull depth, bankfull cross sectional area and bankfull flow rate were closely correlated to the size of the contributing watershed (drainage area). Regression analyses yielded highly statistically significant relationships between all log transformed bankfull measurements and watershed drainage area values (predicted r^2 ranging from 0.85 to 0.95, $p < 0.001$) with drainage area predicting bank flow the best, and bankfull depth the worst. The resulting regional curves, in the form of the modified power functions prescribed by Dunne and Leopold (1978), are presented in Figure 2.

DISCUSSION

Bankfull occurrences per year for the MPDRB tended to be much higher than documented occurrences in other studies (e.g. Metcalf et al., 2009; Wilkerson et al., 2008; Castro and Jackson, 2001; Wolman and Miller, 1960). Annual average bankfull occurrences reported here were more similar to values reported by Jayakaran and Ward (2007) and Sweet and Geratz (2003). In fact, the Sweet and Geratz (2003) study was based on Coastal Plain stream sites in North Carolina that were physiographically most similar to those studied in this project. Sweet and Geratz (2003) report an average of 5 bankfull exceeding flow events annually in the North Carolina (NC) coastal plain, a frequency much greater than the typical 1.5 year recurrence

Table 1. Bankfull dimensions and site characteristics for 15 sites used to develop hydraulic geometry curves in the MPDRB.

Site	Drainage Area (km ²)	Bankfull Area (m ²)	Bankfull Width (m)	Bankfull Depth (m)	Bankfull Flow (m ³ /s)	Manning's N	Slope (%)	Bankfull occurrences per year
1	17.3	1.5	3.4	0.4	0.5	0.106	0.420	3.4
2	39.3	4.8	8.1	0.6	2.1	0.086	0.280	4.2
3	45.6	4.6	6.9	0.7	1.9	0.076	0.200	3.1
4	50.9	7.1	9.2	0.8	1.4	0.059	0.023	2.7
5	72.1	7.1	8.9	0.8	2.3	0.066	0.069	2.4
6	96.5	6.0	6.8	0.9	2.3	0.089	0.170	3.1
7	121.1	17.9	15.6	1.1	7.7	0.050	0.042	1.2
8	134.1	13.4	12.8	1.0	6.8	0.050	0.064	2.1
9	154.5	20.5	20.7	1.0	11.6	0.065	0.140	1.4
10	167.4	13.7	14.3	1.0	6.3	0.046	0.110	0.7
11	295.6	28.1	17.2	1.6	8.1	0.068	0.024	6.2
12	385.0	29.4	19.8	1.5	15.7	0.045	0.039	0.3
13	998.3	58.5	28.9	2.0	42.7	0.038	0.033	3.1
14	1137.1	56.6	26.7	2.1	31.5	0.107	0.141	1.2
15	1717.9	148.0	46.7	3.2	68.1	0.078	0.029	1.6
Mean	362.2	27.8	16.4	1.2	13.9	0.069	0.119	2.5
Std. dev	508.1	37.7	11.2	0.7	19.2	0.022	0.113	1.5

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Figure 2. Hydraulic geometry relationships relating (a) bankfull discharge (b) bankfull area, (c) bankfull width, and (d) bankfull depth, to drainage area. Black and blue lines represent lines of best fit and the 90% prediction intervals, respectively. Light gray lines depict a hydraulic geometry relationships derived by Sweet and Geratz (2003) for coastal plain watersheds in North Carolina.

interval that reported by studies in other part of the United States. They hypothesized this high frequency of bankfull flow events to several characteristics that typify coastal plain watersheds in Southeastern United States. There are: high precipitation, low landscape gradient, large surface storage, high water table conditions, and low flushing rates. Given the similarities in hydrologic and physiographic conditions between MPDRB and the NC coastal plain, the similarity in bankfull flow frequency in this study to the Sweet and Geratz (2003) study, is to be expected.

The investigation of hydraulic geometry relationships in the MPDRB region showed that catchment area and bankfull dimensions were significantly related. The relationships that described hydraulic geometry had coefficients of determination (see Figure 2) that fell within the range reported in the literature. Previously published curves had coefficients of determination as low as 0.54 (Castro and Jackson, 2001) to as high as 0.99 (Metcalf et al., 2009). The highest coefficients of determination typically related bankfull area and flow rate to watershed area (Sweet and Geratz, 2003; Doll et al., 2002),

and the lowest coefficients of determination consistently related average depth to watershed area (e.g. Metcalf et al., 2009; Cinotto, 2003; Sweet and Geratz, 2003; Doll et al., 2002; Castro and Jackson, 2001). The hydraulic geometry curves derived by Sweet and Geratz (2003) reproduced here as gray continuous lines in Figure 2, lie within the confidence limits of the regression lines generated by this study. The slopes of the log transformed regression lines in this study were slightly greater than those derived by Sweet and Geratz (2003) for NC coastal plain streams, but those differences in slope were statistically insignificant.

The hydraulic geometry curves derived in this study provide critical insight into stream function, providing a model that scientists and engineers can use in the classification and restoration of streams in the Middle Pee Dee region. With increasing agricultural and commercial development in the region, stream systems subject to development typically undergo changes in stream morphology driven by changing flow and sediment regimes. These morphological changes are often expressed by stream bank erosion and increased sediment export to downstream receiving waters. Stream bank erosion can cause channel incision and widening that will result in a stream losing equilibrium and deviating from its stable channel geometry. This in turn could lead to flow confinement and a loss of floodplain connectivity resulting in infrequent bank overtopping flows. The negative impacts of development upon riparian functioning have been widely documented in various geographic settings and at multiple spatial scales. (e.g. White and Greer, 2006; Booth and Jackson, 1997; Schueler, 1994; Booth, 1990; Krug and Goddard, 1986; Martens, 1968) These hydraulic relationships provide a basis for stream restoration in the region, and add to an existing framework of hydraulic geometry relationships (Metcalf et al., 2009; Jayakaran et al., 2005; Cinotto, 2003; Sweet and Geratz, 2003; and Doll et al., 2002; Castro and Jackson, 2001; Leopold, 1994) that will likely continue to expand into many other regions. An expansion of this study into the lower and upper portions of the Pee Dee River watershed, as well as an investigation of neighboring ecoregions may illuminate the optimal regional boundaries for application of these hydraulic geometry curves.

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