Hydraulic Geometry Curves and Bankfull Recurrence in the Pee Dee River Basin

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ABSTRACT. Hydraulic bankfull geometry or regional curves are a useful metric for evaluating stream stability and plan stream restoration projects. Streams and tributaries within the middle Pee Dee watershed in South Carolina drain a highly productive landscape that is characterized by forest and agricultural practices. While stream in the region are generally stable, pockets of this landscape is beginning to face increase pressure from development and showing signs of stream instability. In order provide a foundation for potential stream restoration projects in the area, sixteen sites in the watershed were selected on the basis of catchment area, in categories of small (<50 km^2), small-medium (50-500 km^2), medium (500-1000 km^2), and large (>1000 km^2). Bankfull geometries, channel substrate, flow and temperature were measured at all the sites and a set of regional hydraulic geometry curves developed. We also estimated the frequency of bankfull flows that occurred over the period of sampling to document floodplain connectivity. Bankfull dimensions in the middle Pee Dee River watershed 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.

INTRODUCTION

Hydraulic bankfull geometry relationships are essential to the geomorphological characterization of streams that are sometimes subject to perturbations of flow and sediment regime. These perturbations can 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, 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., Cinotto, 2003; Sweet and Geratz, 2003; Doll et al., 2002; Castro and Jackson, 2001) employ drainage area (Ac) as a predictor of hydraulic geometry ($W_{bkf} = a\ A_c^{\ b}$) as a function 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, 2001), 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.

With the increase in stream restoration projects in neighboring states (Sweet and Geratz, 2003: North Carolina), it is likely that stream restorations projects in South Carolina will soon follow suit. However, to date no regional hydraulic geometry curves have been derived for streams in the Upper Pee Dee River basin of South Carolina. As landscape and climate changes impact the

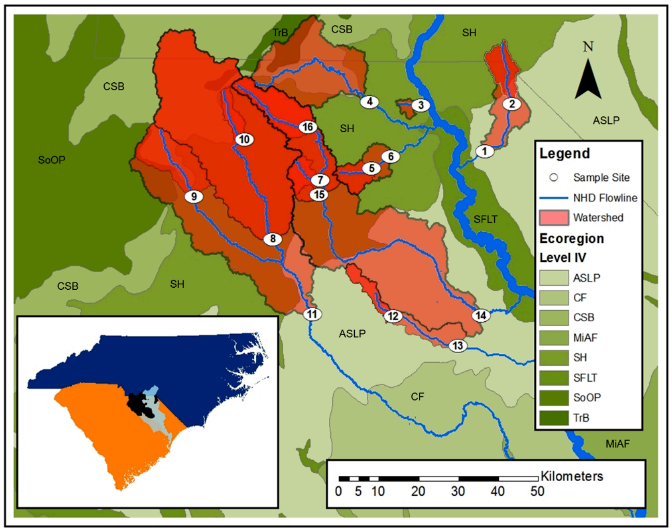

Figure 1 –Study sites in the middle Pee Dee basin. Inset box shows the Pee Dee and Lynches River watersheds, labeled with lighter and darker blues, respectively. Level IV ecoregions in this chart include Southern Outer Piedmont (SoOP), Carolina Slate Belt (CSB), Triassic Basins (TrB), Atlantic Southern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

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 was to derive bankfull curves for a coastal plain watershed using 16 sites in the Upper Pee Dee River basin, as well as to quantify how many times the annual average number of times bankfull exceeding events took place over the period of available data.

PROJECT DESCRIPTION

Streams and tributaries within the middle Pee Dee are low gradient coastal plain streams with bed substrates that are a sand or sand-gravel mix. Study sites were selected to represent a wide range of watershed drainage areas, ranging from 7 to 665 square kilometers.

Sixteen sites were selected on the basis of catchment area, in categories of small (<50 km^2), medium-small (50-500 km^2), medium (500-1000 km^2), and large (>1000 km^2). The selection process evaluated each possible site on the basis of land use within the watershed, ease of access and security of instrumentation. Study subwatersheds spanned two EPA Level III ecoregions (Olsen et al., 2001): Sand Hills (10 sites) and the Atlantic Southern Loam Plains (6 sites). At the Level IV scale, subwatersheds spanned six ecoregions: Atlantic Southern Loam Plains, 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 km 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). Five sites were chosen in conjunction with the SCDNR's fish monitoring program (Figure 1)

METHODS

Stream morphology

For the wadeable stream sites, a total station was used to measure channel pattern, profile, and dimension as 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. 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). For this study, all bankfull values are estimates based on bankfull features identified per guidelines prescribed by Dunne and Leopold (1978). Panoramic photos taken at each site helped to corroborate selection of bankfull stage and provided photographic documentation of each site. Evidence of bankfull included 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). Evidence of all these factors were weighed against each other and an estimate of bankfull elevation was made that satisfied as many indicators as possible.

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 characterize stream morphology above the water level, total station surveys were carried out to complete the above-water portions of the stream cross sections that were profiled with the ADCP unit. All survey data were processed using the Reference Reach Spreadsheet for Channel Survey Data Management (Mecklenburg and Ward, 2009).

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 10 remaining sites, flow was estimated from river stage data measured using stage recording sensors (Solinst® Leveloggers) in conjunction with stage-flow rating curves developed for each study site. The stage sensors measured absolute pressure requiring measured data to be compensated for changing atmospheric pressure by deploying three continuously logging pressure sensors (Solinst® Barologger) distributed throughout the study area.

Stage-flow rating curves at each site were based on estimated roughness coefficients developed using measured velocity readings at various flow depths, and estimating flow using the continuity equation Q =A*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 as 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 roughness coefficient calculated for each site. For this study the reported annual bankfull occurrence was simply the annual average frequency that the bankfull elevation was exceeded over the period of available data. 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.

RESULTS

Hydraulic geometry and bankfull depth (using the determined, verified bankfull) were derived from the 16 cross-sections and profiles. Slopes (S) ranged from nearly ponded ($2x10^{-5}$ %) to relatively steep (0.42 %) Manning's roughness (n) ranged from 0.038 to 0.107. Most streams were swampy, sluggish, and impeded by large woody material. Bankfull width (W_{bkf}), bankfull depth (D_{bkf}), bankfull cross sectional area (A_{bkf}) and bankfull flow rate (Q_{bkf}) varied considerably across all the sites. Bankfull width ranged from 3.6 to 195.2 m, average depth ranged from 0.6 to 3.1 m, cross sectional area ranged from 2.1 to 1195.1 m^2, and bankfull flow rate varied between 0.6 and 68.2 m^3/s.

Bankfull Occurrence

Bankfull occurrence ranged from 0.3 to almost 7.2 times per year with an average of 2.9 occurrences per year across all sites. In other words, on average flow rates met or exceeded bankfull discharge (and therefore bankfull elevation) more than 2 times per year in the middle Pee Dee region of South Carolina.

Hydraulic Geometry

Regression analyses yielded highly statistically significant relationships ($p < 0.001$) between all bankfull measurements and watershed area and R^2 values between 0.83 and 0.96. The resulting hydraulic geometry curves, in the form of the modified power function originally reported by Dunne and Leopold's (1978), are presented in Figure 1. Fifteen of the 16 sites were used in the derivation of these relationships. One site was omitted due to a downstream impoundment thought to significantly influence the calculation of bankfull discharge

DISCUSSION

Bankfull occurrences per year for the middle Pee Dee Region tended to be much higher than documented occurrence in other studies (e.g. Metcalf et al., 2009; Wilkerson et al., 2008; Castro and Jackson, 2001; Wolman and Miller, 1960). However, bankfull occurrences measured in the middle Pee Dee region are more similar to bankfull recurrence reported by (Jayakaran and Ward (2007) and Sweet and Geratz (2003). In fact the Sweet and Geratz (2003) study is based on Coastal Plain stream sites in North Carolina and are physiographically most similar to those studied in this project.

Investigation of hydraulic geometry relationships in the Pee Dee region showed that catchment area and

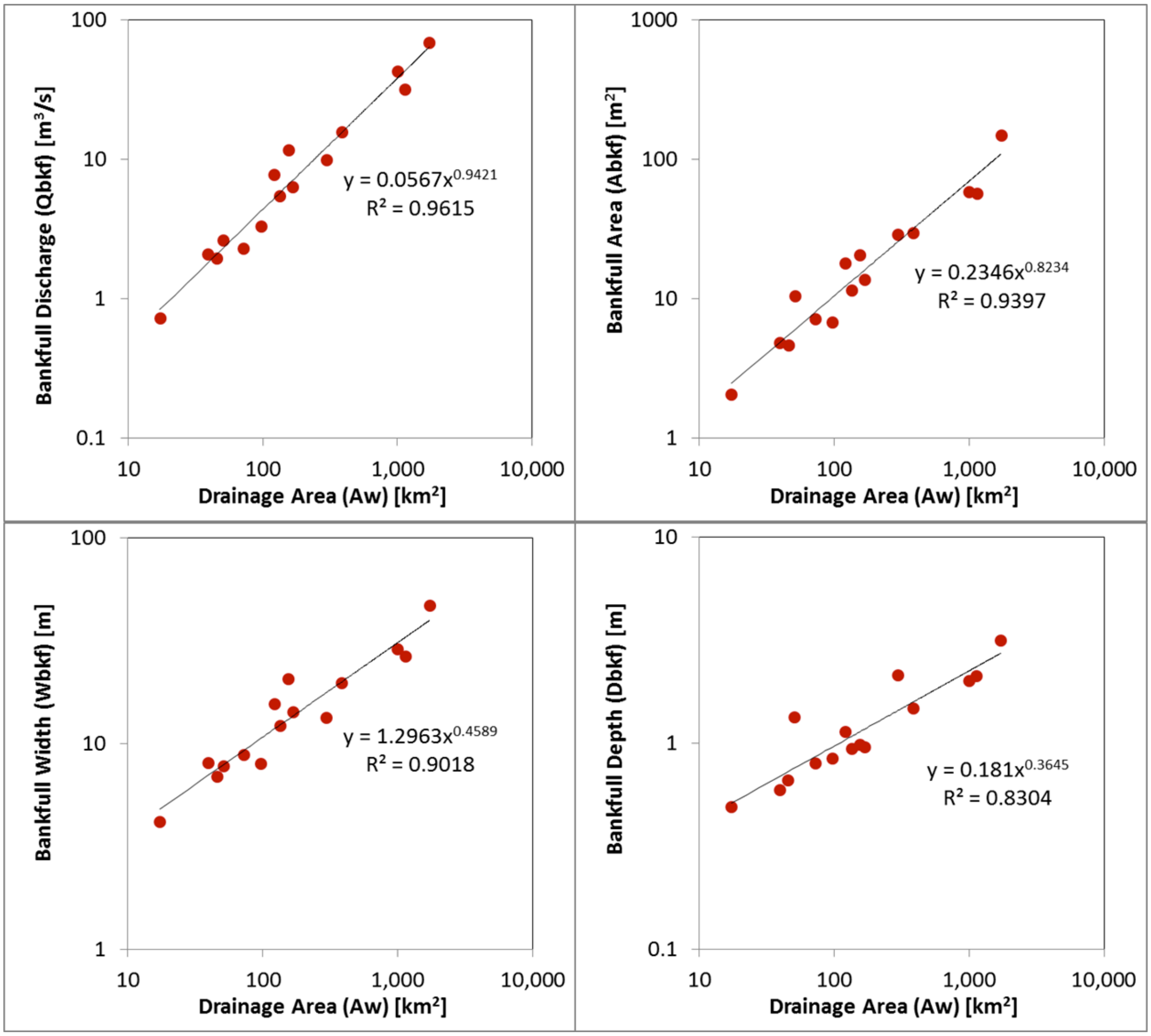

Figure 2: Hydraulic geometry curves for the middle Pee Dee river basin relating drainage area to bankfull dimensions

bankfull dimensions were significantly related. The relationships that described hydraulic geometry had coefficients of determination that fell within the range reported in the literature, 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) with the highest coefficients of determination typically being those that compared bankfull area and flow rate to watershed area (Sweet and Geratz, 2003; Doll et al., 2002), and the lowest consistently those that compared 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 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 region. These relationships 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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