

INTEGRATION OF STREAM FLOW DURATION WITH HYDRAULIC GEOMETRY IN THE SOUTHERN PIEDMONT

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Abstract. Stream hydrology is often described based on five fundamental properties of a river's flow regime: magnitude, frequency, duration, timing, and rate of change. Flow duration curves provide a powerful tool for integrating magnitude, frequency, and duration. Though flow duration curves have been well established at regional scales, the correspondence between in-stream flow duration and the duration of flood events onto adjacent floodplains has not been adequately explored especially at subwatershed and stream reach scales. By combining flow duration curves with channel geometry, site-specific stage duration curves and flood duration can be created. Herein, flow duration curves are used in conjunction with channel hydraulic geometry to estimate flood duration of southern Piedmont floodplains.

BACKGROUND

Floodplains have long been recognized as ecologically important zones at the interface of aquatic and terrestrial ecosystems. A critical driving force in these ecosystems is the flow regime of the neighboring river (Junk et al. 1989), which consists of the magnitude, frequency, timing, duration, and rate-of-change of river discharge (Poff et al. 1997). Significant understanding of floodplain function can be obtained through an adequate comprehension and quantification of a river's flood regime.

Flood magnitude, frequency, and duration may be, at least in part, quantified using flow duration curves (FDCs). These curves illustrate the percent of time a discharge was equaled or exceeded, i.e., exceedence probability, for a range of discharges. These curves have a long history in river management (e.g., Searcy 1959) and a variety of potential uses (Vogel and Fennessey 1995).

Channel shape and geometry interact with flow regime to determine flooding regime. Bankfull depth is the depth of water that fills the channel to the top of banks, i.e., the point of incipient flooding (Watson et al. 1999). Generally, the top of levee where incipient flooding of the adjacent land surface is not provided on the USGS field measurement form 9-207 (personal communication with A.J. Getvald, USGS, Atlanta, Georgia, 2012). Hydraulic geometry curves are often developed to quantify the relationship between river size (assessed as drainage area) and a variety of bankfull parameters such as depth, width,

cross-sectional area, and discharge. Typically, these curves are developed for a specific hydrophysiographic region such as the Appalachian Piedmont (Doll et al. 2002, McCandless and Everett 2002).

Though flow duration curves have been developed for several regions of the United States including Georgia, the correspondence between flow duration and the duration of flood events onto adjacent land surfaces including active and abandoned floodplains (terraces) has not been adequately explored at regional scales. The objective of this paper is to assess changes in flood duration with channel size at a regional scale. To do so, we couple channel geometry data (via regional hydraulic geometry curves) with flow regime variables (via flow duration curves).

STUDY SITE

The Piedmont physiographic province extends from Maryland southwesterly to middle Alabama and is generally bound by the Appalachian mountains to the northwest and the Coast Plain to the southeast. Specifically, the study area was located in the Southern Outer Piedmont of Georgia (hereafter referred to as, the southern Piedmont) (Griffith et al., 2001). Southern Piedmont elevations range from 152 to 457 meters (500 to 1500 feet) above mean sea level. The Savannah, Apalachicola, Altamaha and Ogeechee Drainage Basins are included, in part, in the southern Piedmont. The streams flowing through the Winder and Washington Slope areas drain to the Atlantic Ocean while the Gulf of Mexico receives water flowing through the Greenville Slope area. Much of the original topsoil has eroded away due to poor agricultural practices during the turn of the twentieth century, exposing red clay subsoils (argillic horizon) (Trimble 1969, Burke 1990). Prevalent geologic formations in the area are metamorphic in origin consisting of mafic gneisses, especially hornblende gneisses with intercalated amphibolites and biotite gneisses (Bennison 1975). The mean annual rainfall is 112 to 142 cm (44 to 56 inches). Mean annual temperature ranges between 15 and 18°C (59 to 64°F), and mid-winter minimum temperature falls between 0 to 2°C (32 and 36°F). The frost-free season is 210 to 240 days (Robertson 1968). Geomorphologically, the southern Piedmont consists of foothills and broad interstream areas (Perkins 1977). Cressler et al. (1983) described the stream network

in the southern Piedmont area southeast of the Chattahoochee River as a superimposed dendritic drainage pattern.

METHODS

We studied seven sites in the Southern Piedmont across a wide range of drainage areas and channel sizes (Table 1). All sites are at current or historic streamflow gages with five sites monitoring daily discharge data and two only peak discharge data (USGS 2012).

Based on previous studies (Trimble 1969, Burke 1990), many Piedmont stream channels are degraded and enlarged such that the stream has been decoupled from its historic floodplain. For this reason, bankfull and channel-full stages are defined as follows (Pruitt et al. 1999). Bankfull stage corresponds to the elevation that on the long-term does the most channel work such as channel maintenance, moving sediment, forming or removing bars, forming or changing bends and meanders (Dunne and Leopold 1978). In addition, it is the stage that corresponds with the effective discharge. In general, in the southeast the bankfull stage is represented by the top of the point bar or the active floodplain which is equivalent to a recurrence interval of 1 to 2 years. Channelfull corresponds to the stage and discharge required to flood the terrace or the historic (abandoned) floodplain.

Identification of bankfull indicators in this investigation included the following steps (See Pruitt 2001 for a more detailed methodology): 1) The stream upstream and downstream at seven Piedmont USGS gage stations was inspected to identify a representative “natural” channel profile in cross section and planform at an adequate distance from the bridge to reduce “bridge-effect”; 2) Bankfull indicators were identified and marked at several locations longitudinally along the representative reach; 3) Using a Topcon™ (Model 303D) and traditional engineering survey techniques, a cross section was surveyed across the valley flat which traversed one set (left and right banks) of the bankfull indicators identified above; and 4) Bankfull features were tied to the gage record by surveying the water surface elevation from the cross section to the bridge and vicinity of the USGS gage and/or staff plate. Also, a parallel line was developed by surveying the additional bankfull indicators and channelfull stage indicators between the cross section and the bridge. The water surface and the parallel line created from the bankfull and channelfull indicators were surveyed to the USGS gage datum at the bridge to determine the stage and discharge that coincided with the surface water elevation, bankfull, and channelfull.

Employing classic hydrologic methodology (Dunne and Leopold 1978), probability analysis was calculated using USGS peak discharge data for each station (hereafter, referred to as at-station data). Discharge, recurrence interval, and probability of exceedence were estimated by

regression analysis from peak discharge data for each at-station data set based on the stages that represented bankfull and channel full. Mean depth at bankfull, channel full, and standard recurrence intervals were estimated from discharge regressed against mean depth derived from the USGS Summary of Discharge Measurement Data (9-207 forms). Hydraulic geometry (width and cross sectional area) was also regressed against discharge.

Table 1: USGS gaging stations used in this study.

USGS Gage and daily data period	DA (mi ²)	Q _{BKF} (cfs)	Q _{CHF} (cfs)	P _{BKF}	P _{CHF}
Oconee River near Penfield Gage: 02218300 1978-2011	940	8711	8711	8.86*10 ⁻³	8.86*10 ⁻³
Ogeechee River near Jewel Gage: 02200000	242	4149	7467	n/a	n/a
Apalachee River near Bostwick Gage: 02219000 1978-2011	176	2862	2862	3.46*10 ⁻³	3.46*10 ⁻³
Beaverdam Creek at Elberton Gage: 02188600 1987-1995	72	1037	1782	3.04*10 ⁻³	1.21*10 ⁻³
Hudson River at Homer Gage: 02191200 1960-1978	60.9	507	3639	1.87*10 ⁻²	1.44*10 ⁻⁴
South Fork Ogeechee River nr Crawfordville Gage: 02199700 No daily data	31.3	809	1542	n/a	n/a
North Fork Broad near Toccoa Gage: 02189500 1959-1968	18.3	443	1108	0	0

Flow duration curves were constructed for the five USGS gages where daily discharge measurements were available (USGS 2012). Notably, FDCs can vary significantly depending upon the data resolution and period of record (Vogel and Fennessey 1994, McKay and Fischenich in press). Our analysis used daily-averaged discharge and the entire record for each gage, regardless of different time periods. FDCs were used to estimate the probability of exceeding both bankfull and channel-full discharge over the observed period of record (Table 1).

We then normalized FDCs at each gage by drainage area and computed a regional FDC as the average exceedence probability over the five gages for a given value of normalized discharge (discharge / drainage area in units of cfs/mi²). This regional FDC was applied in conjunction

with the regional hydraulic geometry curve to develop a regional bankfull exceedence curve.

A suite of numerical routines was developed to conduct all analyses using the R statistical software package (version 2.15.0, R Development Core Team 2007). All algorithms and code are available upon request to the authors.

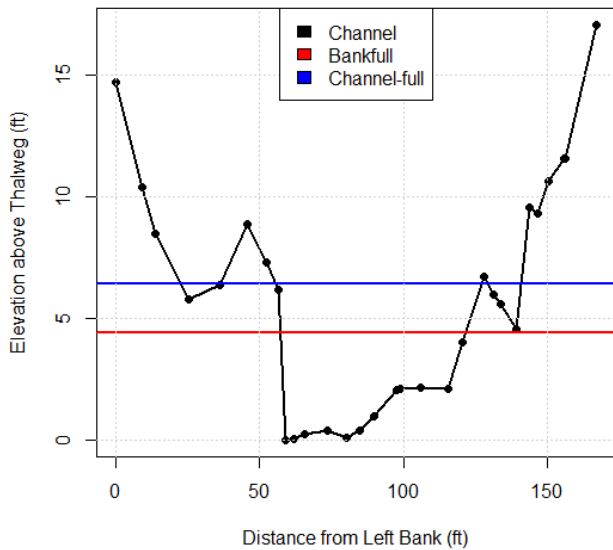


Figure 1: Sample cross-section defining channel shape parameters (data from Beaverdam Creek at Elberton).

RESULTS

Although regional hydraulic geometry curves typically include relationships with bankfull depth, width, area, and discharge, only the bankfull discharge curve is presented here (Figure 2; Other curves may be found in Pruitt 2001). This hydraulic geometry curve fits observed data quite well ($R^2 = 0.905$). Doll et al. (2002) and McCandless and Everett (2002) present alternative hydraulic geometry curves for the Appalachian Piedmont, which are also shown in Figure 2. The relationship presented here matches the general trend of their curves, but does provide distinguishably different estimates of bankfull discharge. These differences could be attributable to larger data sets in the other studies as well as fundamental differences in hydraulic geometry in the Mid-Atlantic and Southern Piedmont.

The regional flow duration curve (Figure 3) closely matches four of the five gage specific FDCs. However, the curve poorly matches data from the North Fork of the Broad River. Notably, this gage relies on data from a different period of record, and thus, the poor fit may be attributable to larger differences in climate over this period.

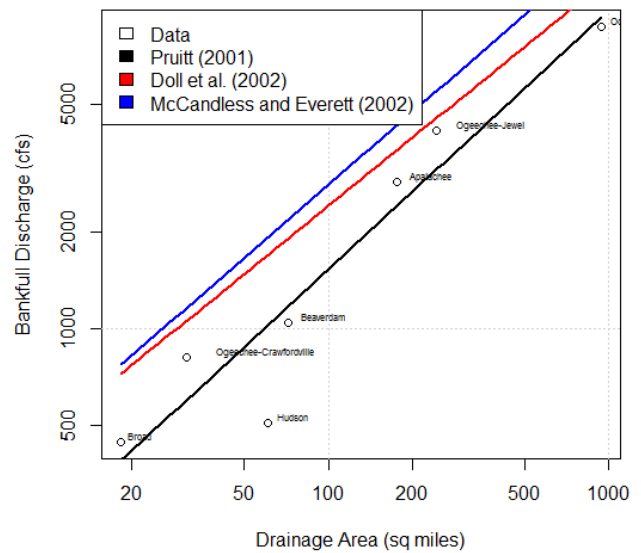


Figure 2: Regional hydraulic geometry curves from Pruitt 2001 ($Q_{bf} = 36.7 DA^{0.81}$, $R^2 = 0.905$), Doll et al. 2002 ($Q_{bf} = 91.6 DA^{0.71}$), and McCandless and Everett 2002 ($Q_{bf} = 84.6 DA^{0.76}$).

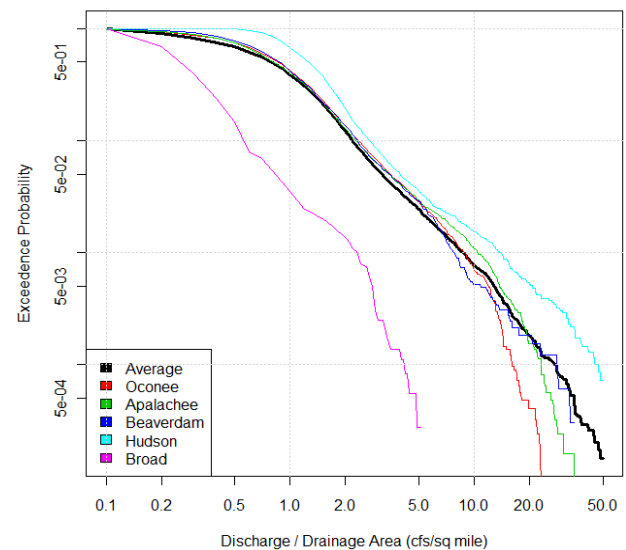


Figure 3: Regional flow duration curve.

Bankfull exceedence probabilities were observed at each of the five gaging stations with daily data and estimated from the regional bankfull exceedence curve (Figure 4). Because the regional curve was developed using these stations, this analysis does not validate the model against independent data, but does verify its usefulness. The regional approach qualitatively matches the general trends in the data with the exception of one gage station (Hudson Creek at Homer). This discrepancy could be due to problems with the regional exceedence model, insufficient period of gage record, inaccurate identification of bankfull, or a variety of other issues.

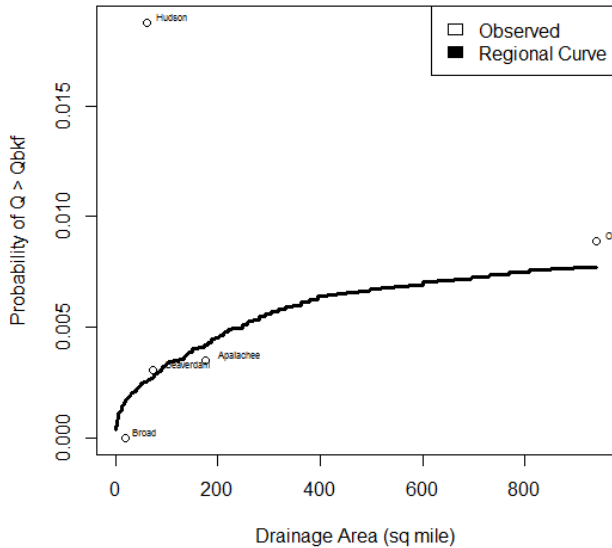


Figure 4: Regional bankfull exceedence curve.

DISCUSSION

Although this preliminary analysis relies on a small sample size, the methods we present are transferrable to other sites (i.e., larger data sets) and regions (e.g., coastal plain). We have used geometry and gage data from the same sites, but these data could be collected independently. For instance, a hydraulic geometry curve may be specified at ungaged sites throughout a region. This curve could be couple with a regional FDC developed at gaged sites to develop a regional exceedence curve.

Significant outliers emerge even from our limited data set (e.g., Hudson Creek in Figure 4). Uncertainty is a common (and not unexpected) problem in large regional analyses. For instance, Yu et al. (2002) highlight multiple techniques to examine uncertainty in regional FDCs. Future analyses should address the compounding uncertainties associated with combining imperfect predictions of hydraulic geometry with imperfect predictions of flow duration.

In riverine systems, estimation of flood frequency and duration is critical in federal wetland jurisdiction and assessing wetland functions. In 1978, Dunne and Leopold suggested the use of the dimensionless rating curve to map areas subject to flooding. For a treatise and application of dimensionless rating curves, see Pruitt (2001).

CONCLUSIONS

There are many potential applications of flood duration probabilities, including but not limited to:

- **Flow targets:** Instream or environmental flows are currently a point of significant discussion and contention in Georgia. Floodplain access and duration

often have many accompanying ecological benefits (e.g., spawning access for fishes, biogeochemical processing, riparian seed dispersal). The methods presented here provide an objective technique for identifying these thresholds across a range of watershed sizes (drainage areas).

- **Channel evolution:** Many Piedmont streams are undergoing significant changes in channel shape owing to the long-term effects of poor agricultural practices during the mid-1800s and early 1900s as well as modern urban development. The distinction presented here between bankfull and channel-full geometry and accompanying effects of flood duration may provide a useful metric for quantifying the impacts of channel evolution on floodplain access.
 - **Flood risk management:** The risk of flooding in urban settings is predominantly concerned with flood frequency, i.e., What is the potential or probability of an area being flooded in a given year? In contrast, in agricultural or silvicultural land uses, flood frequency may not adversely affect the growth, development and reproduction of crops and tree plantations if the duration of the flood event is relatively short.
 - **Riverine wetlands:** Wetland hydroperiod includes both flood frequency and flood duration components. Wetlands are defined as, “Those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions” (CE Federal Register 1982 and EPA Federal Register 1980).
- Future research should include: application to larger flood probability and the advantages and disadvantages to using annual peak data, partial records, and average daily data (as used here) to calculate exceedence probability.

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NOTATION

BKF	Bankfull
CHF	Channel-full
D	Depth
DA	Drainage area
FDC	Flow duration curve

REFERENCES

- Bennison, A.P. 1975. Geological highway map of the southeastern region. The American Association of Petroleum Geologists. Map No. 9.
- Burke, M.A. 1990. Historic evolution of channel morphology and riverine wetland hydrologic functions in the piedmont of Georgia. Masters Thesis. University of Georgia. Athens, Georgia.
- CE Federal Register. 1982. "Title 33: Navigation and Navigable Waters: Chapter 2. Regulatory Programs of the Corps of Engineers," U.S. Government Printing Office, Washington, DC. 47(138), 31,810.
- Cressler, C.W., C.J. Thurmond and W.G. Hester. 1983. Ground water in the greater Atlanta region, Georgia. Georgia Geological Survey Information Circular 63.
- Doll B.A., Wise-Frederick D.E., Buckner C.M., Wilkerson S.D., Harman W.A., Smith R.E., and Spooner J. 2002. Hydraulic geometry relationships for urban streams throughout the Piedmont of North Carolina. Journal of the American Water Resources Association, Vol. 38 (3): 641-651.
- Dunne, T. and L.B. Leopold. 1978. Water in Environmental Planning. W.H. Freeman, San Francisco USA.
- EPA Federal Register. 1980. "40CFR Part 230: Section 404(b)(1) Guidelines for Specification of Disposal Sites for Dredged or Fill Material," U.S. Government Printing Office, Washington, DC, 45(249), 85, 352-82, 353.
- Griffith, G.E., Omernik, J.M., Comstock, J.A., Lawrence, and Foster, T. 2001. Ecoregions of Georgia. Corvallis, Oregon, U.S. Environmental Protection Agency (map scale 1:1,500,000).
- Junk W.J., Bayley P.B., and Sparks R.E. 1989. The flood-pulse concept for river-floodplain systems." Proceedings of the International Large River Symposium, Vol. 106: 110-127.
- McCandless T.L. and Everett R.A. 2002. Maryland stream survey: Bankfull discharge and channel characteristics of streams in the Piedmont hydrologic region. CBFO-S02-01. Chesapeake Bay Field Office, U.S. Fish & Wildlife Service.
- McKay S.K. and Fischenich J.C. *In review*. Development and application of flow duration curves for stream restoration. U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.
- Perkins, H.F. and M.E. Shaffer. 1977. Soil associations and land use potential of Georgia soils. In Cooperation with the United States Department of Agriculture, Soil Conservation Service. Georgia Agricultural Experiment Station, University of Georgia, College of Agriculture, Athens, GA, USA.
- Poff N.L., Allan J.D., Bain M.B., Karr J.R., Prestegard K.L., Richter B.D., Sparks R.E., and Stromberg J.C. 1997. The natural flow regime. *Bioscience*, 47, 769-784.
- Pruitt, B.A., W.L. Nutter, and W.B. Ainslie. 1999. Estimating flood frequency in gaged and ungaged watersheds. In Proceedings of the 1999 Georgia Water Resources Conference, held March 30-31, 1999, at The University of Georgia, Kathryn J. Hatcher, Editor, Institute of Ecology, The University of Georgia, Athens, Georgia.
- Pruitt B.A. 2001. Hydrologic and soil conditions across hydrogeomorphic settings. PhD Dissertation. University of Georgia.
- R Development Core Team. 2007. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. www.R-project.org.
- Robertson, S.M. 1968. Soil survey of Clarke and Oconee Counties, Georgia. United States Department of Agriculture, Soil Conservation Service, in cooperation with the University of Georgia, College of Agriculture, Agricultural Experiment Station, Athens, GA, USA.
- Searcy J.K. 1959. Flow-duration curves. In Manual of Hydrology. Water Supply Paper 1542-A, United States Geological Survey, Washington, D.C.
- Trimble, S.W. 1969. Culturally accelerated sedimentation on the middle Georgia piedmont. M.S. Thesis, University of Georgia, Athens, GA, USA.
- United States Geological Survey (USGS). 2012. River gage data. National Water Information System. www.waterdata.usgs.gov/usa/nwis/.
- Vogel R.M. and Fennessey N.M. 1994. Flow duration curves I: New interpretation and confidence intervals. *Journal of Water Resources Planning and Management*, 120 (4): 485-504.
- Vogel R.M. and Fennessey N.M. 1995. Flow duration curves II: A review of applications in water resources planning. *Water Resources Bulletin*, 31 (6): 1029-1039.
- Watson C.C., Biedenarn D.S., and Scott S.H. 1999. Channel rehabilitation: Process, design, and implementation. U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.
- Wharton, C.H. 1978. The natural environments of Georgia. Published jointly by: Geologic and Water Resources Division and Resource Planning Section, Office of Planning and Research, Georgia Department of Natural Resources, Atlanta, GA, USA.
- Yu P.S., Yang T.C., and Wang Y.C. 2002. Uncertainty analysis of regional flow duration curves. *Journal of Water Resources Planning and Management*, 128 (6): 424-430.