U.S. Fish & Wildlife Service

Maryland Stream Survey:

Bankfull Discharge and Channel Characteristics of Streams in the Piedmont Hydrologic Region

CBFO-S02-01

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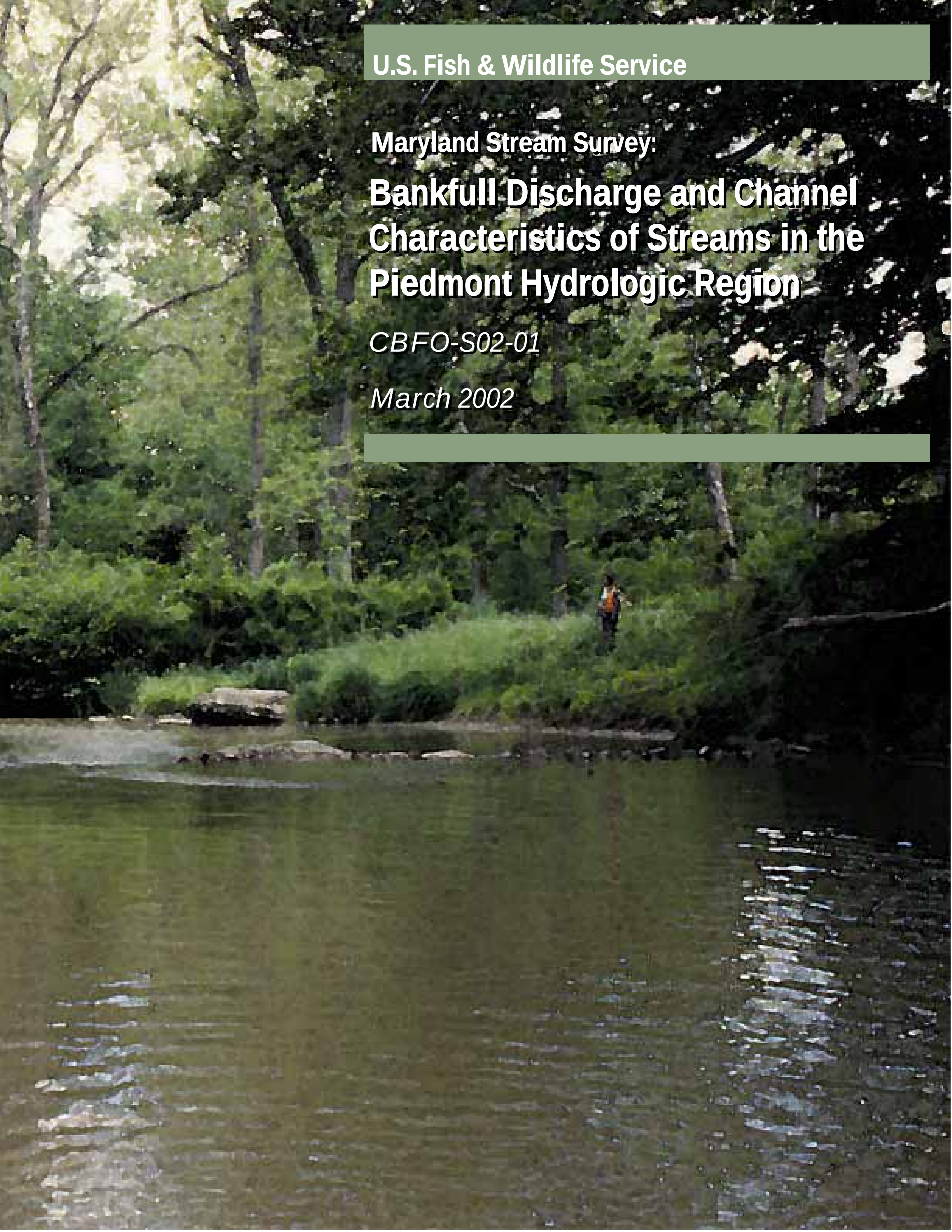

MARYLAND STREAM SURVEY: BANKFULL DISCHARGE AND CHANNEL CHARACTERISTICS OF STREAMS IN THE PIEDMONT HYDROLOGIC REGION

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Prepared in cooperation with:

Maryland State Highway Administration and

U.S. Geological Survey

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Executive Summary

Increasingly, engineers and environmental managers are attempting to design in accordance with the natural tendencies of rivers in flood protection, channel stabilization, stream crossing, channel realignment, and watershed management projects. There is also a great interest in restoring the physical, biological, and aesthetic characteristics of previously degraded rivers. For both these endeavors, designers need basic information to evaluate and predict the dimension, pattern, and profile of natural rivers.

Empirical relationships between dimensions of bankfull channel geometry (i. e., width, depth, cross-sectional area) and water discharge or drainage area have long been found useful as a first step towards preliminary design and evaluation of river channels. An increasing number of river design approaches require or recommend the use of such relationships. As with all empirical relationships, the applicability of the derived predictive equations is limited to rivers similar to those providing the data. Thus, empirical relationships for channel geometry are for specific hydro-physiographic regions with relatively homogeneous climate, geology, and vegetation.

The U.S. Department of Interior, Fish and Wildlife Service (Service) and the Maryland State Highway Administration (SHA) in conjunction with the U.S. Geological Survey (USGS) are developing regional channel geometry relationships for major hydro-physiographic regions in Maryland. The first phase of the survey involves detailed channel geometry surveys at stream gages operated by the USGS in the Piedmont hydro-physiographic region of Maryland. Later phases of the survey will address the Coastal Plain (eastern and western), Ridge and Valley, and Appalachian Plateau provinces. Channel surveys and gage flow records are used to establish discharge magnitudes, recurrence intervals, cross-section, channel pattern, and longitudinal profile dimensions corresponding to the bankfull stage. Preliminary data reveal significant relationships between drainage area and bankfull channel dimensions and discharge.

The Service and SHA have obtained the cooperation of the state and federal agencies involved in the review of highway projects through the formal Partnering Agreement and formation of a Maryland Stream Survey Advisory Panel. It is important that all interested agencies agree to the approach and objectives of the survey. The agencies agreed that, upon review and acceptance by the Advisory Panel, the information would provide a useful tool for evaluating the effects of proposed projects in channel, wetlands, and flood plains.

<ins>OBJECTIVES</ins>

The Service and SHA developed objectives agreeable to all parties. These objectives include:

- determine and analyze the hydraulic and planform characteristics of Maryland streams,
- determine the degree to which the Rosgen Classification System can explain and account for the amount of variability in the data, and
- develop regional channel geometry relationships to facilitate and improve the accuracy of future studies that evaluate and classify stream channels.

EXPECTED RESULTS AND PRODUCTS

A database of stream characteristics will serve as a source of information on basic channel characteristics at the time of the surveys, for anyone involved with work affecting Maryland

streams. The analyses from the stream surveys will provide regional channel geometry relationships useful for watershed management, emergency watershed protection, and other stream restoration and protection efforts.

For the first phase of the project, the Service will produce a document incorporating the following:
1) *Maryland Stream Ssurvey: Bankfull discharge and channel characteristics of streams in the Piedmont hydrologic region;*
2) *Appendix A: Site characteristics for selected USGS gage stations in the Piedmont hydrologic region;* and
3) *Appendix B: Protocols for field surveys at gage stations.*

Phase II will result in additional reports on the sites characteristics of streams in the Appalachian, Ridge and Valley, and Coastal Plain hydro-physiographic provinces along with the examination of relationships of bankfull discharge and drainage area and channel dimensions and drainage area.

PHASE I – PIEDMONT HYDRO-PHYSIOGRAPHIC REGION

In this Pilot Study, we conducted surveys of 25 gaged stream reaches in the Piedmont hydro-physiographic province of Maryland to test for relationships between:
a) drainage area and bankfull discharge;
b) drainage area and bankfull channel dimensions;
c) planform and riffle-pool attributes;
d) bankfull discharge and channel cross-section dimensions; and
e) relative roughness and flow resistance.

We also classified each reach according to the Rosgen classification system of natural rivers (Rosgen, 1994, 1996a), and examined the utility of such classification for explaining the observed variability in the above relationships.

Because of concerns raised by the Advisory Panel regarding the issue of whether the gage survey sites represented reference reaches, the information related to channel size and planform, riffle-pool attributes, and other discussions on channel geometry have been deleted from the report.

FINDINGS

Bankfull Discharge

Bankfull discharge is significantly related to drainage area, with about 93% of the variability in discharge explained by drainage area (Figure 1). Examination of Figure 1 reveals that the data for four locations located in the northeastern Piedmont region plot relatively high.

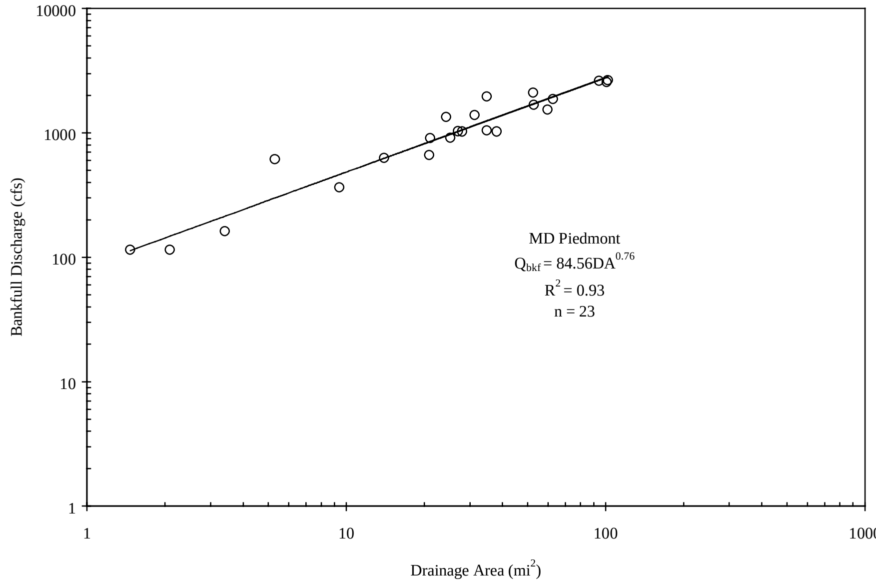

Figure 1. Bankfull discharge as a function of drainage area for Maryland Piedmont survey sites.

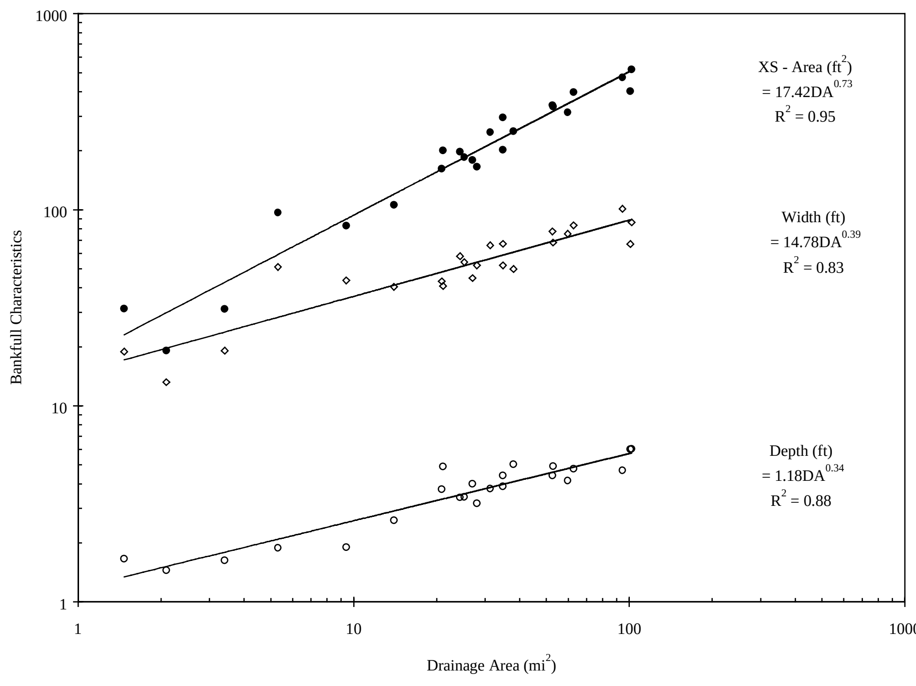

Figure 2. Bankfull channel dimensions as a function of drainage area for Maryland Piedmont survey sites.

<u>Bankfull Indicators</u>

Physical features of streams indicate certain discharge events, mostly notably the bankfull discharge. Bankfull indicators include geomorphic features developed by the channel as well as distribution limits for vegetation. We found several indicators of bankfull stage in the Piedmont streams, and observed that the floodplain break was the dominant indicator associated with the bankfull discharge.

Bankfull Discharge Recurrence Interval
The recurrence intervals for the bankfull discharge associated with the dominant indicators range from 1.26 – 1.75 years, and average 1.5 years.

Cross-section Relationships by Drainage Area
Width, mean depth, and cross-sectional area are all significantly related to drainage area and bankfull discharge (Figure 2). Of the three parameters, cross-sectional area has the greatest percent of the variability in size explained by drainage area, followed by depth and width, as indicated by the regression coefficients of determination (R^2).

Resistance Relationships
There is a negative but significant relationship between relative roughness (R/D_{84}), and resistance expressed as Manning's "n".

Rosgen Classification
In that all the reaches we surveyed classified to a specific stream type, the results of this study support the applicability of the Rosgen classification system to Piedmont channels. However, a limited number of stream types were observed at the gage stations in the Piedmont – most of the channels classified as C type streams, and of these C4 (gravel) – type channels were predominant.

CONCLUSIONS

- The relationships presented here serve to provide preliminary design parameters for streams with a similar range of characteristics. The results of this work should guide practitioners in the expected bankfull channel dimensions at ungaged streams.

- Maryland Piedmont channels can be classified using the Rosgen stream classification system, however the limited number of independent observations of different stream types at this point in the work prevents us from examining the use of the classification in helping explain some of the observed variability in stream characteristics.

- The northeastern Piedmont may constitute a discrete region with respect to the relationship between drainage area and bankfull discharge. However, more surveys are necessary for a proper statistical analysis.

- There is a well-defined relationship between drainage area and bankfull discharge in the main Piedmont region.

- There are well-defined relationships for Maryland Piedmont streams between drainage area and bankfull channel dimensions, and these relationships compare favorably to those documented by previous workers elsewhere in the Piedmont of the eastern U.S. and nearby regions. The most conservative relationship with drainage area is for cross-sectional area.

- Variability in the average flow resistance in Maryland Piedmont streams as represented by the Manning "n" is fairly well explained by variability in relative roughness, expressed as R/D_{84}.

APPLICATIONS

Use of Regression Relationships for Design Purposes

Several caveats exist for these relationships, and argue strongly against their use for detailed design specifications.

- Relationships are representative of a restricted range of basin and reach characteristics (e.g. drainage area, geology, land use, etc.) and must be used with caution when applying to streams across the Piedmont.

- Often the gage and study reaches are not the same reaches. Rather to maintain the study reach selection parameters, it is often located upstream of the gage.

- While we do not consider any of the reaches represented here to be in a state of rapid adjustment, we have no information about the relative rates of lateral or down-valley meander migration.

- Relationships are not necessarily representative of "reference reach conditions". We suspect that many reaches in proximity to gages at road crossings were altered at some time in the past by channelization or realignment. These relationships provide no information about ecological parameters, and may not represent "good" habitat conditions. In fact, the low amounts of large woody debris in the surveyed channels are likely an indication of relatively poor habitat conditions.

- The range of stream types represented by the data is low, consisting of one to three in most stream types, with only C4 stream types well represented.

- The reaches represented here seem to broadly correspond to the category termed "transport" reaches, in that there are not many well-developed depositional features such as point bars. Imposition of the channel characteristics represented by these relationships on streams in the "source" and "response" categories would likely be problematic.

Given these caveats, the relationships documented here can provide preliminary design parameters for streams with a similar range of drainage area, sediment, slope, and entrenchment conditions. Channel designers need to identify discrete project goals and objectives, with respect to both physical and biological desired conditions, and determine the appropriate design parameters for achieving those conditions. In most cases the best design guidance for finer scale aspects of channel design will come from carefully selected reference reaches that closely match the controlling conditions at the project reach, and exhibit those characteristics specifically identified as design objectives. The results of this study may best serve as guidance to the expected range of bankfull channel dimensions at ungaged reaches.

RECOMMENDATIONS FOR ADDITIONAL WORK

- Once the gage calibration surveys represented by Phases I and II are in-hand, the information can be used to facilitate identification of bankfull channels at ungaged reference reaches selected for particular purposes including biological quality, sediment transport, over-bank discharge frequency, and diversity of fluvial features. This information will provide a foundation for future development of a reference reach design database for Maryland streams.

- Additional sites should be surveyed in the northeastern Piedmont. Although additional active gage sites are not available, discontinued stations with updated stage-discharge relationships would provide useful information regarding the magnitudes of bankfull discharge and channel dimensions.

- Additional observations of stream reaches, and reaches with less bedrock control and perhaps a greater range of bank material composition than was present in this set of study sites, will be necessary to test the ability of Rosgen's system to usefully partition channel types.

ACKNOWLEDGEMENTS

This report is a result of a cooperative effort between U.S. Fish and Wildlife Service, the Maryland State Highway Administration, and the Maryland-Delaware-D.C. District of the U.S. Geological Survey.

Many people contributed to the effort represented by this report, however any errors are strictly the responsibilities of the authors. This survey and report would not be possible without the dedication to improve stream management efforts by the SHA Division of Bridge Design, in particular Andrzej J. Kosicki, Dr. Richard Woo, Len Podell, and Stan Davis. We would like to thank field personnel who contributed innumerable hours slogging through the Maryland Piedmont rivers particularly Chris Eng, Mark Secrist, Andy Priest, Sean Uber, Howard Weissberg, Richard Starr, Jeremy Mondock, Ben Soleimani and Alex Smolyak. Chris Eng and Mark Secrist, in particular, contributed greatly to the development of survey information, processing field data, and produced all plan view maps. Many people contributed to development of the field protocols including reviews by Dave Rosgen, field testing and writing by Richard Starr, and graphics assistance by Laurie Hewitt. A special thank you to Sherry Johnson and Patty McCawley for their patience and expertise in word processing assistance and to Ed Doheny, USGS, who provided expert advise and assistance in all phases of the work. The Environmental Protection Agency, U.S. Fish and Wildlife Service, Federal Highway Administration, SHA, and USGS provided funding for this work.

Advisory Panel

The Service and SHA have obtained the cooperation of the state and federal agencies involved in the review of highway projects through a formal Partnering Agreement and formation of a Maryland Stream Survey Advisory Panel. It is important that all interested agencies agree to the approach and objectives of the survey. The agencies agreed that, upon review and acceptance by the Advisory Panel, the information would provide a useful tool for evaluating the effects of proposed projects in channel, wetlands, and flood plains.

Maryland Department of the Environment, Water Management Administration
Maryland Department of Natural Resources, Chesapeake and Coastal Watershed Service
Maryland State Highway Administration
Natural Resources Conservation Service
U.S. Army Corps of Engineers, Regulatory Branch
U.S. Federal Highway Administration, Maryland Division
U.S. Fish and Wildlife Service
U.S. Forest Service

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SYMBOLS AND ABBREVIATIONS

Symbol	Definition
A_{xs}	Cross-sectional area
d	Mean bankfull depth
D_{50}	Median particle size
D_{84}	Particle size at which 84% of sample is smaller
DA	Drainage area
"f"	Darcy-Weisbach friction factor
g	Gravitational acceleration
MP	Main Piedmont region
MWR	Meander width ratio
"n"	Manning's roughness coefficient
NEP	Northeast Piedmont region
p	Probability
Q	Discharge
R	Hydraulic radius
Rc	Bend radius
RI	Riffle interval
s	Second
S	Slope
SC	Silt-clay
W	Bankfull width
ρ_s	Density of sediment
ρ_w	Density of water
τ_{cr}	Critical shear stress
τ_o	Boundary shear stress

INTRODUCTION

*Bankfull discharge is not necessarily of constant frequency or the most effective flow. Channel form is the product not of a single formative discharge but of a range of discharges, which may include bankfull, and of the temporal sequence of flow events. However, the bankfull channel is the one reference level, which can reasonably be defined, and it remains intuitively appealing to attach morphologic significance to bankfull flow (*Knighton, 1984).

The U.S. Fish and Wildlife Service and Maryland State Highway Administration (SHA) signed a cooperative agreement to develop regional relationships of bankfull cross-section dimensions versus drainage areas for some of the physiographic provinces within Maryland. The short-term goal of this agreement is to develop appropriate relationships of stream characteristics on a statewide basis. The long-term goal is to provide the SHA with the information needed to develop hydraulic designs of culverts and small bridges that maintain as much as possible the natural bankfull channel dimensions. Maintenance of natural channel conditions should minimize disturbances to existing stable stream channels and their associated flood plains and wetlands, and help alleviate unstable conditions caused by crossing structures. The Pilot Study reported here has two primary objectives: development of field and office protocols for stream surveys and documentation of preliminary evidence that regional relationships exist.

Relationships between discharge and channel cross-section dimensions, termed "downstream hydraulic geometry", have been recognized for some time (Inglis, 1949; Blench, 1957; Leopold & Maddock, 1953; Wolman, 1955; Nixon, 1959; Hey & Thorne, 1986). For obvious reasons, drainage area is identified as a consistent and convenient surrogate for discharge in the development of such relationships (Leopold and others, 1964). Similarly, several workers (Leopold & Wolman, 1960; Hey, 1983; Williams, 1986), have identified functional relationships between channel size (usually expressed as width) and planform patterns, channel boundary materials and channel shape (Schumm, 1960), and bed roughness and flow resistance (Limerinos, 1970; Hey, 1979). Because of the number and complexity of determining variables actually underlying these relationships, it is widely recognized that such relationships hold only within relatively homogeneous regions or for specified ranges of state variables (Leopold & Maddock, 1953; Leopold et al, 1964). Regional characteristics of interrelated variables such as precipitation, soils, and vegetation strongly influence the specific quantitative nature of down-stream hydraulic geometry, planform, and resistance relationships.

The value of a quantitative understanding of hydraulic geometry relationships for water resource planning and management has long been recognized (Dunne & Leopold, 1978). For river engineering purposes, particularly in the field of river restoration, regional channel geometry relationships are widely viewed as an important tool for both assessment and design procedures (U.S. Army Corps of Engineers, 1994; Rosgen, 1994, 1996a; Brookes & Shields, 1996; Thorne et al., 1997). A number of more-or-less regional relationships between discharge or drainage area and channel dimension have been developed for a variety of geographic areas in the Eastern United States (Wolman, 1955; Brush, 1961; Kilpatrick & Barnes, 1964; Leopold et al., 1964). Unfortunately, a lack of consistency among these authors in selection of formative, or dominant, discharge, and definition of the bankfull channel makes comparison among these relationships difficult. In addition, the most accessible set of regional relationships between drainage area and channel geometry for the Eastern U. S., that published by Leopold and his coworkers (Leopold, Wolman, & Miller; Dunne & Leopold; Leopold, 1994), lacks any expression of the range of expected variability. For both assessment of stream channel condition and design of channels that approximate “natural” states, an understanding of the range of natural variability between drainage area and channel dimensions is as important as knowledge about central tendencies.

Engineers, geologists, and geomorphologists have long resorted to classification schemes as a means of imposing order on the inherently variable physical nature of rivers. While early attempts focused on fairly coarse (Leopold and Wolman, 1957) or more finely distinguished (Brice, 1960) characterizations of planform, later systems have become more comprehensive and process-based by incorporating cross-section, longitudinal profile, or channel material characteristics (Schumm et al., 1984, Simon, 1989; Montgomery and Buffington, 1993; Whiting and Bradley, 1993; Rosgen, 1994, 1996a). One of the great attractions of these process-based approaches to classification is that, beyond their use for mere organization of information, some suggest they have predictive value. Engineers and resource managers want and need conceptual tools for predicting the nature, direction, and rate of river adjustment processes. Not surprisingly, a great deal of discussion revolves around the merits and drawbacks of specific systems.

Rosgen (1996a) developed his system to address specific, applied objectives related to conditions and processes: to predict behavior from appearance, to develop specific hydraulic and sediment relationships for given stream types and states, to provide a mechanism for extrapolation of site-specific data to streams of similar type, and to provide a consistent frame of reference to aid communication about river morphology and condition among various disciplines. While Rosgen’s system has many adherents, particularly within resource management agencies, others question both the general applicability of the system throughout the U. S., and its ability to meaningfully represent basic fluvial processes (Miller and Ritter, 1996). In partial response to these criticisms, Rosgen (1996a,b) has explicitly reiterated the need for regional refinement and calibration of the basic system.

In this Pilot Study, we conducted surveys of 25 gaged stream reaches in the Piedmont hydro-physiographic province of Maryland to test for relationships between:

1) drainage area and bankfull discharge,
2) drainage area and bankfull channel dimensions,
3) channel size and planform and riffle-pool attributes,
4) bankfull discharge and channel cross-section dimensions; and
5) relative roughness and flow resistance.

We also classified each reach according to the Rosgen classification system of natural rivers and examined the utility of such classification for explaining the observed variability in the above relationships.

Because of concerns raised by the Advisory Panel regarding the issue of whether the gage survey sites represented reference reaches, the information related to channel size and planform, riffle-pool attributes, and other discussions on channel geometry have been deleted from the report.

METHODS

Selection of Gage Sites

We selected twenty-one sites (Figure 1) for survey from the network of active gage sites operated by the Maryland-Delaware-D.C. District of the USGS in the Piedmont hydro-physiographic region in Maryland. As most of the active stations have drainage areas greater than 10 mi^2, we selected four additional stations from among the inactive gages, previously operated by the USGS. At these four inactive sites, the USGS collected contemporary discharge measurements and prepared revised stage-discharge ratings. Table I lists the name, station number and drainage area for sites included in the analyses. Appendix A, *Site Characteristics for Selected USGS Gage Stations in the Piedmont Physiographic Province*, provides a complete description of each site.

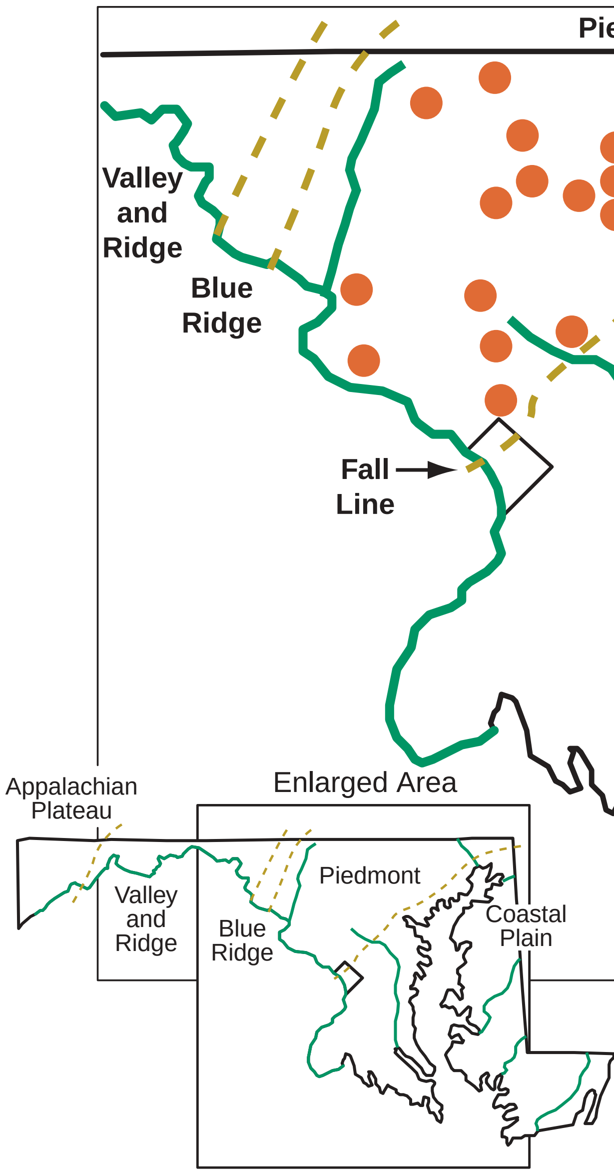

Figure 1. Survey site locations in the Maryland Piedmont hydro-physiographic province.

Table I. USGS Gage Stations in Maryland Piedmont Survey		
USGS Gage Site (all in MD)	USGS Station #	Drainage Area (mi^2)
Baisman Run @ Broadmoor	1583580	1.47
Basin Run @ Liberty Grove	1579000	5.31
Beaver Run near Finksburg	1586210	14.00
Beaverdam Run @ Cockeysville	1583600	20.90
Bennett Creek @ Park Mills	1643500	62.80
Big Elk Creek @ Elk Mills	1495000	52.60
Big Pipe Creek @ Bruceville	1639500	102.00
Cranberry Branch near Westminster	1585500	3.40
Deer Creek @ Rocks	1580000	94.40
Hawlings River near Sandy Spring	1591700	27.00
Jones Falls @ Sorrento	1589440	25.20
Little Falls @ Blue Mount	1582000	52.90
Little Patuxent River @ Guilford	1593500	38.00
Long Green Creek @ Glen Arm	1584050	9.40
Morgan Run @ Louisville	1586610	28.00
Northeast Creek @ Leslie	1496000	24.30
NW Br Anacostia River near Colesville	1650500	21.10
Patuxent River near Unity	1591000	34.80
Piney Creek @ Taneytown	1639140	31.30
Seneca Creek @ Dawsonville	1645000	101.00
Slade Run near Glyndon	1583000	2.09
Western Run @ Western Run	1583500	59.80
Winters Run near Benson	1581700	34.80

The criteria for inclusion of all sites included the following:

- Intact staff gage or recoverable benchmarks referenced to staff gage elevations.
- Unarmored channel near the gage, capable of adjusting to the flow regime. Natural bedrock vertical and horizontal controls were acceptable.
- Sufficient length (10-20 bankfull widths) of channel for a longitudinal profile survey through the gage location.
- An acceptable study reach (ideally at least 20 bankfull widths) near the gage that had not been obviously channelized or otherwise altered in the recent past. In some cases, there was evidence of historic channel manipulations, but the age of vegetation on the banks indicated that several decades had elapsed since the work was completed. Some study reaches also had constructed revetments (boulder or gabion) along short stretches of bank, but in all such cases, the opposite bank was natural and able to adjust to the flow regime.
- Ten years of record, to permit adequate estimation of flood frequency distributions.

At 13 sites, gage reaches and study reaches are not contiguous. This is usually due to significant stretches of artificial channel control (rock, gabion, or concrete revetment), influence on the channel from the bridge crossing (usually backwater, scour, or channelization), or an insufficient length of channel with homogenous characteristics. For these sites, we selected separate study reaches with sufficient length (as above) of homogenous channel upstream or downstream of the gage reach.

We have eliminated two sites, Cattail Creek near Glenwood, Maryland (USGS Station #1591400) and Piney Run at Dover, Maryland (USGS Station # 1583100) from the final analysis. Cattail Creek plots well outside the 95% confidence limits for the remaining data, and on this basis we consider it an anomalous outlier and exclude it from further analyses. Piney Run's rating table has been unstable compared to earlier records and since reinstatement of the gage by the USGS. Recently, the USGS has identified a significant channel modification downstream of the gage, which may be causing a backwater at the gage.

One important consideration of stability in the Piedmont is the duration of land use changes. Jacobson and Coleman (1986) suggest that the stratigraphic record show evidence of channels deepening. They and others (Costa 1975, Trimble 1974, and Wolman 1967) suggest that the hydrology and sediment supply of the Piedmont watersheds have varied over the last 250 years based on the history of land use, with peaks in agriculture from 1900 to 1910. These land uses have clearly impacted the Piedmont channels. Our task was to determine, on-site, whether to use a stream reach for the survey, and that the present bankfull conditions are representative of a stable, dynamic channel. It was not to determine the rate of change of channel morphology in the present day.

The gaged sites do not necessarily represent reference reach sites and some of the streams may represent transition stream types. The relationships provide no information about chemical or ecological parameters, and do not necessarily represent "good" habitat conditions. In fact, the low amounts of large woody debris in the surveyed channels are likely an indication of relatively poor habitat conditions. From our experience in the Piedmont physiographic region, not only at gaged sites but also at other sites as well, many streams represent borderline or transition reaches. This may very well be a result of recent alteration but most certainly is a result of past land use practices, in particular agriculture and the resultant floodplain fills.

Preliminary Analysis of Gage Records

The USGS provided records of station descriptions and analyses, level notes, log-Pearson type-III flood frequency distributions (annual maximum series), and stage-discharge relationships for each of the selected gage stations. Flood frequency distributions, provided as exceedance probabilities calculated according to *Guidelines for Determining Flood Flow Frequency* (Interagency Advisory Committee, 1982), were transformed via inversion into recurrence intervals, and plotted on log-Pearson type-III probability paper. The SHA provided land use and cover characteristics, including an estimate of the percent imperviousness, from 1994 Landsat and Spot images using the computer program *GIS-Hydro* (Ragan, 1991).

Field Surveys

Below, we provide brief summaries of study procedures; detailed descriptions of specific survey methods are in Appendix B *Protocols for Field Surveys at Gage Stations*.

Bankfull Channel: Definition and Indicators

The concept of the "bankfull" channel has been problematic. At the simplest level, the term is used to describe the point of "incipient flooding": that elevation at a cross-section at which a rising water level just begins to flow out of the channel and over the floodplain (Wolman and Leopold, 1957). Much discussion has revolved around the degree to which this morphologic bankfull flow corresponds to the more process-based dominant and effective flows. While some studies have reported close agreement between these various discharges (Andrews, 1980, Leopold, 1992), other workers have reported contrasting results (Pickup & Warner, 1976). A wide variety of approaches to measuring or estimating the relevant variables involved makes objective comparisons among the various studies difficult (see excellent summaries in Knighton, 1984 and Richards, 1982).

Not least of these problems is that of defining and identifying the limits of the bankfull channel. While "the elevation at which a rising water level just begins to inundate the floodplain" is conceptually appealing, in practice the identification of such a point is fraught with difficulty. There is wide agreement that the floodplain of interest is that which is actively building and is maintained by the river under current conditions of discharge (both water and sediment), as opposed to portions of the valley flat that are not altered by river flows. There seems equally wide agreement that the interface between channel and floodplain can be difficult to distinguish in reaches that lack the well-developed depositional bars where new floodplain surfaces occur. Even with a prominent floodplain, the point of incipient flooding can become subjective. Local characteristics of over-bank flow patterns, deposition, and vegetation interact to produce a floodplain surface that is anything but flat, particularly at a scale encompassing tenths of a foot. At this scale, the floodplain surface adjacent to the active river channel is a heterogeneous mosaic of humps and depressions. At more geologically confined reaches, and in reaches that have undergone considerable incision, a well-developed floodplain may not even be present. There is thus a need to carefully define and describe those attributes, or indicators, used to delineate the bankfull channel in any specific reach.

An often-expressed assumption is that the channel is adjusted to the range of flows that just fill its banks (Knighton, 1984). A fine-scale ability to delineate the transition from actively maintained channel to non-channel is then critical if one wishes to identify the dimensions of self-maintained rivers. A discrete transition from a relatively vertical channel bank to a relatively flat floodplain is the best indicator of bankfull elevation. As noted above, the floodplain-channel interface is often variable, or a floodplain is irregularly present or even absent. Under such circumstances, other indicators of a channel maintaining stage (or narrow range of stages) are required. Because the primary mechanisms of channel maintenance are erosion and deposition, the most indicative characteristics should also be representative of such processes. For channels that are not changing in dimension, point bar (and therefore floodplain) building requires balancing erosion. The process discontinuity produced by a transition from in-bank to over-bank flow can result in a change in the relative erosive abilities of flows working on the channel banks, such that erosion scars may be found on higher banks (i.e., where the channel impinges on a terrace) at elevations coincident with those of channel-floodplain transitions. These erosion indicators manifest on a vertical surface as wear lines, or are acute or obtuse changes from vertical in bank slope. Lateral depositional features other than point bars are often observed, with elevations coincident with the point bar-floodplain transition. These lateral depositional areas may be relatively long (many channel widths), or short features developed where the channel has become locally widened.

Additional, non-morphological, characteristics of bankfull elevation have been used, such as discontinuities in the distribution and composition of vegetation (Woodyer, 1968; Nunnally, 1967), and the vertical distribution of fines in the bank materials (Nunnally, 1967). However, subsequent studies have suggested that these characteristics are too variable for use as primary indicators, and should instead support or refine bankfull delineations based on morphologic criteria (Williams, 1978; Richards, 1982).

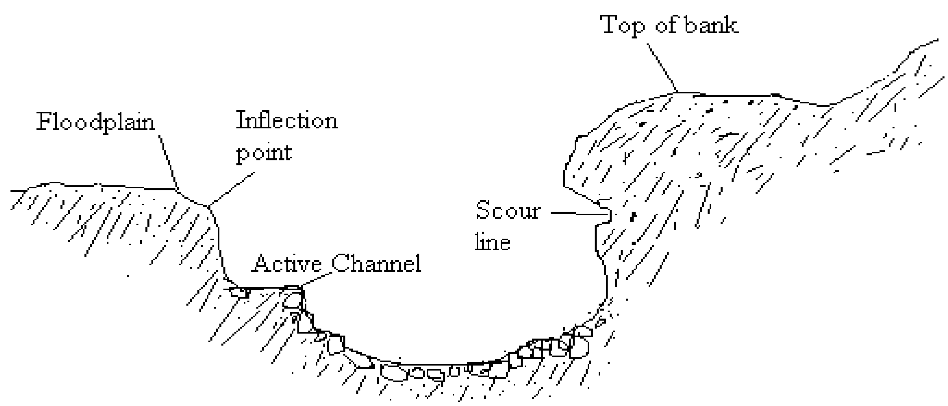

Figure 2. Typical bankfull indicators.

We used the following indicators to identify potential bankfull elevations (Figure 2):

> *Floodplain break:* a discrete transition from near vertical to near horizontal; used on straight reaches or on bends lacking point bars. In some cases, (where the stream in not entrenched or incised) the floodplain break may also be the top of bank.
>
> *Inflection point*: where the transition from near vertical bank to near horizontal floodplain is not relatively discrete, but instead occurs over a transitional zone often composed of one or more obtuse slope breaks over a vertical distance of several tenths of a foot, the inflection point is the lowest identifiable break in slope.
>
> *Scour line*: a wear mark on a vertical bank, or a discrete break in slope (acute or obtuse) of the channel bank, distinguished from an inflection point by being further down from the top of bank.
>
> *Depositional bench*: the flat surface, or highest elevation, of a lateral depositional surface other than a point bar. This may also be referred to as the active channel.
>
> *Point bar*: the transition point from inclining point bar surface to horizontal floodplain surface.

Prior to field surveys, we conducted reconnaissance investigations to identify and flag bankfull indicators (described above) at each site. For the 13 sites with noncontiguous gage and study reaches, we performed separate surveys in each reach, using both a laser level and tape or a survey total station, as follows.

Gage Reaches

We surveyed longitudinal profiles, referenced to gage datum and including the gage location, for bankfull indicators, bed and water surface elevations. We used these profiles to estimate the gage datum elevations for each particular series of indicators. We also surveyed a cross-section, at a riffle or a run in close proximity to the gage. We examined vertical profiles from each survey for evidence of a relatively linear trend parallel to the line of water surface elevations. We considered linear groups of points with similar relative elevations above water surface to indicate potential bankfull elevations.

Study Reach Surveys

We conducted surveys at study reaches to quantify average reach slope, the proportional distribution of channel units, a visually representative cross-section at a riffle or run, particle size distributions for reach channel materials, particle size distributions at the cross-section location, bank materials at the cross-section location, and planform characteristics. We used three different survey approaches: at 13 reaches we used a laser level to measure average stream slope and a riffle cross-section; at five reaches, we used a laser level to survey a detailed longitudinal profile defining individual channel-unit facets (pools, riffles, runs) and a riffle cross-section; and at five reaches, we used a survey total station instrument to map the longitudinal profile, planform, and several cross-sections through riffles and pools.

We quantified reach particle size distributions for the channel boundary materials as one of the criteria for Rosgen classification, using Rosgen's (1996a) modification of the Wolman pebble count method. We determined a particle size distribution for the cross-section riffle in each reach in a similar manner by sampling ten transects spaced at equal intervals along the riffle. We assigned sand and smaller particles to a size range by comparing sampled grains with standard size fractions glued on a "sand gauge". We collected bulk samples from each bank at the riffle cross-section locations to determine particle size distributions for bank materials. In the laboratory, we combined and air-dried the samples, removed macroscopic organic litter such as leaves and twigs, mechanically shook the sediments through a series of standard sieves, and weighed the separated size fractions. While we did collect bank samples at each cross-section, the bank sample was only used to characterize the composition of the banks and was in no way used to weight the reach average pebble distribution.

In each study reach, we surveyed one visually representative riffle or run to determine cross-section dimensions and flood prone widths. Rosgen has defined the flood prone width as the distance across the valley at an elevation above the thalweg equal to twice the maximum bankfull depth. We located the flood prone elevations on each side of the stream with a laser level and either measured the distance with a tape, estimated the distance with a topographic map (where the distance was the approximate width of the floodplain), or included flood prone elevation points in a total station survey.

We used a total station instrument to quantify the planform characteristics of each reach by surveying sufficient points at the bankfull elevation, water surface, thalweg, and tops of banks to map the meander pattern of the channel. Our measure of sinuosity is the "total" sinuosity as defined by Mueller (1968), and as such incorporates components of sinuosity due to both geologically constrained (topographic) and alluvial (hydraulic) meandering.

Data Analysis

For laser-level surveys, we used the calculation and graphing capabilities of the software program *Excel* (Microsoft Corp., Redmond, WA) to determine cross-section and slope parameters, and plot detailed longitudinal profiles. We used the software program *Terra Model* (Spectra Precision Software, Inc., Atlanta, GA), to produce planform, longitudinal and cross-section plots from the total station surveys. We measured planform parameters, such as bend radii and meander lengths, using analytical geometry capabilities of the software. We exported the cross-section data from *Terra Model* to customized *Excel* spreadsheets designed to automatically calculate the hydraulic parameters width, mean depth, cross-sectional area, and hydraulic radius.

We classified each of the reaches according to the Rosgen system, using the delineative criteria of entrenchment ratio, width/depth ratio, sinuosity, water surface slope, and median particle size. Because the variability in these parameters among streams is continuous while the stream classification is composed of discrete types, some ambiguity can occur at the interface between types. To classify streams under such circumstances, we compared the observed values of each of the parameters with the frequency distributions presented by Rosgen (1996b) for each stream type.

We performed calculations for statistical analyses using either *Excel*, or *Minitab* (Adobe Systems, Inc., State College, PA). We used the Anderson - Darling test to examine data for departures from the normal distribution; an F-test to examine for variances for homogeneity; t-tests to compare regression slopes and intercepts (Zar, 1999). For all tests, we used an a-priorie $\forall = 0.05$ unless otherwise noted.

RESULTS AND DISCUSSION

Summary of General Site Characteristics

Summaries of surveyed characteristics for each study reach are in Appendix A. The 23 study reaches used in the analysis are distributed throughout the Piedmont region of Maryland (Figure 1), and are located in 10 major river basins and 7 counties (Table II). Drainage basin sizes range from 1.47 mi^2 – 102 mi^2, and Shreve (1967) magnitudes vary between 2 - 189. Although we attempted to use sites with low degrees of basin development, the percent imperviousness of the watersheds draining to the study reaches ranges from 2 - 21%. Seventeen of the 23 sites have less than 12% imperviousness.

Table II. Summary of site location and basin characteristics for study reaches at USGS gage stations in the Maryland Piedmont.

River Basin	No. Sites	County	No. Sites	Drainage Area (mi^2)	No. Sites	Percent Impervious	No. Sites	Shreve Mag.	No. Sites
Anacostia	1	Baltimore	7	<10	5	0-3	4	0-20	6
Bush	1	Carroll	5	10-20	1	3-6	8	20-40	4
Elk	1	Cecil	3	20-30	6	6-9	5	40-60	3
Gunpowder	6	Frederick	1	30-40	4	9-12	0	60-80	4
Monocacy	3	Harford	2	40-50	0	12-15	2	80-100	2
Northeast	1	Howard	1	50-60	3	15-18	1	100-120	0
Patapsco	4	Montgomery	4	60-70	1	18-21	2	120-140	2
Patuxent	3			70-80	0	21-24	1	140-160	0
Seneca	1			80-90	0			160-180	1
Susquehanna	2			90-102	3			180-200	1

We suspect that many of the gage reaches at road crossings were altered at some time in the past by channelization or realignment. While most gages themselves are located at bridges, the actual study reach and cross-section measurement locations were located away from the influence of these structures. Few channels have escaped manipulation or anthropogenic influence over the past 350 years in not only Maryland but also the entire mid-Atlantic. However, channel recovery does occur, and there are many examples of stable channels throughout the mid-Atlantic. We do not have information regarding rate of degradation from channelization or rate of recovery. This requires further examination with more intensive sampling at known disturbance sites. While we often see degradation at bridges due to channel confinement and increased velocities through the bridge, quite often it is a localized effect and does not proceed far up- or downstream. We have seen instances of exposed footings but an otherwise stable channel away from the bridge site. While we do not consider any of the represented survey sites in a state of rapid adjustment, we have no information about the relative rates of lateral or down-valley meander migration.

Rosgen Stream Types

The 23 reaches partition into three Rosgen Level II stream types (Table III). There are nineteen C-type, three E-type, and one B-type channels. The bed material varies in the reaches with two boulder/bedrock channels, eight gravel channels, nine gravel/bedrock channels, two sand channels, and two sand/bedrock channels. Sixty-eight percent of the sites had non-uniform reach-average pebble count distributions. In the case of a bimodal or skewed distribution, Rosgen (1996) recommends using the dominant size class sampled, rather than the percent cumulative of the channel material size group, for classification. Rosgen also states that the D_{50} of the riffle size distribution often mirrors the dominant particle size of the reach.

Figure 3 shows the Piedmont stream type delineative values or, where possible, averages and ranges, plotted with Rosgen's average values and ranges for similar stream types (Figure 3). The Piedmont E streams have lower entrenchment and greater width/depth values than the average values reported by Rosgen although the Piedmont E streams are well within the range of Rosgen's data set. The C streams, on the other hand, have higher entrenchment but lower width/depth values than same stream types in Rosgen's data set, with the Piedmont C5 streams outside the range of Rosgen's data set (1996a) for entrenchment and width/depth (Figure 3).

Across all stream types, the Piedmont channels have lower sinuosities than reported by Rosgen (Figure 3). All stream types in the Piedmont have slopes within the ranges reported by Rosgen (Figure 3). Piedmont C5 channels have higher average slopes compared with Rosgen's data set for the same stream type, while the average slope for Piedmont C4 channels is quite close to that reported by Rosgen. Not unexpectedly for the limited number of samples per stream type, and the restricted geographic range, the ranges of observed slopes in Piedmont channels is markedly less than the ranges reported by Rosgen with the exception of C4 streams (the largest representative stream type surveyed) (Figure 3).

Table III. Maryland Piedmont survey sites - Rosgen stream classifications.

USGS Gage Site	Entrenchment Ratio	Width / Depth Ratio	Sinuosity	Water Surface Slope	Meander Width Ratio	D50 (mm)	Particle	Rosgen Stream Type
Baisman Run @ Broadmoor	24.23	11.39	1.29	0.0160	4.44	9.47	medium gravel	C4
Basin Run @ Liberty Grove	7.04	27.04	1.40	0.0059	1.88	10.31	medium gravel	C4
Beaver Run near Finksburg	3.13	15.49	1.06	0.0050	2.15	36.63	very coarse gravel	C4/1
Beaverdam Run @ Cockeysville	10.73	11.52	1.13	0.0008	2.20	0.63	coarse sand	C5/1c-
Bennett Creek @ Park Mills	3.26	17.41	1.11	0.0019	1.94	16.95	coarse gravel	C4/1
Big Elk Creek @ Elk Mills	5.25	17.57	1.04	0.0014	2.71	17.97	coarse gravel	C4/1
Big Pipe Creek @ Bruceville	3.69	14.32	1.45	0.0013	7.25	20.20	coarse gravel	C4/1
Cranberry Branch near Westminster	17.79	11.72	1.60	0.0061	4.19	6.68	fine gravel	C4
Deer Creek @ Rocks	1.61	21.54	1.22	0.0021	4.95	19.04	coarse gravel	B4/1c
Hawlings River near Sandy Spring	14.17	11.20	1.19	0.0022	2.28	0.36	medium sand	C5
Jones Falls @ Sorrento	3.63	15.74	1.13	0.0016	1.93	7.70	fine gravel	C4
Little Falls @ Blue Mount	4.61	13.79	1.09	0.0019	3.00	18.73	coarse gravel	C4
Little Patuxent River @ Guilford	9.60	9.88	1.37	0.0005	5.34	0.71	coarse sand	E5
Long Green Creek @ Glen Arm	4.22	22.95	1.04	0.0165	1.06	132.81	large cobble	C2/1*
Morgan Run @ Louisville	3.42	16.35	1.18	0.0052	6.04	32.00	very coarse gravel	C4/1
Northeast Creek @ Leslie	3.12	17.01	1.11	0.0120	7.41	106.94	small cobble	C2/1*
NW Br Anacostia River near Colesville	14.71	8.32	1.06	0.0017	1.93	1.13	very coarse sand	E5/1
Patuxent River near Unity	8.23	13.37	1.26	0.0021	5.96	14.00	medium gravel	C4
Piney Creek @ Taneytown	9.12	17.41	1.47	0.0025	5.08	14.54	medium gravel	C4/1
Seneca Creek @ Dawsonville	12.02	11.11	1.05	0.0014	1.48	2.83	very fine gravel	C4
Slade Run near Glyndon	33.76	9.11	1.07	0.0120	1.89	10.69	medium gravel	E4
Western Run @ Western Run	21.10	18.13	1.47	0.0024	7.96	4.28	fine gravel	C4/1
Winters Run near Benson	3.73	15.19	1.14	0.0052	3.54	26.42	coarse gravel	C4/1

* Bimodal distribution, largest number of observations is in boulder size class.

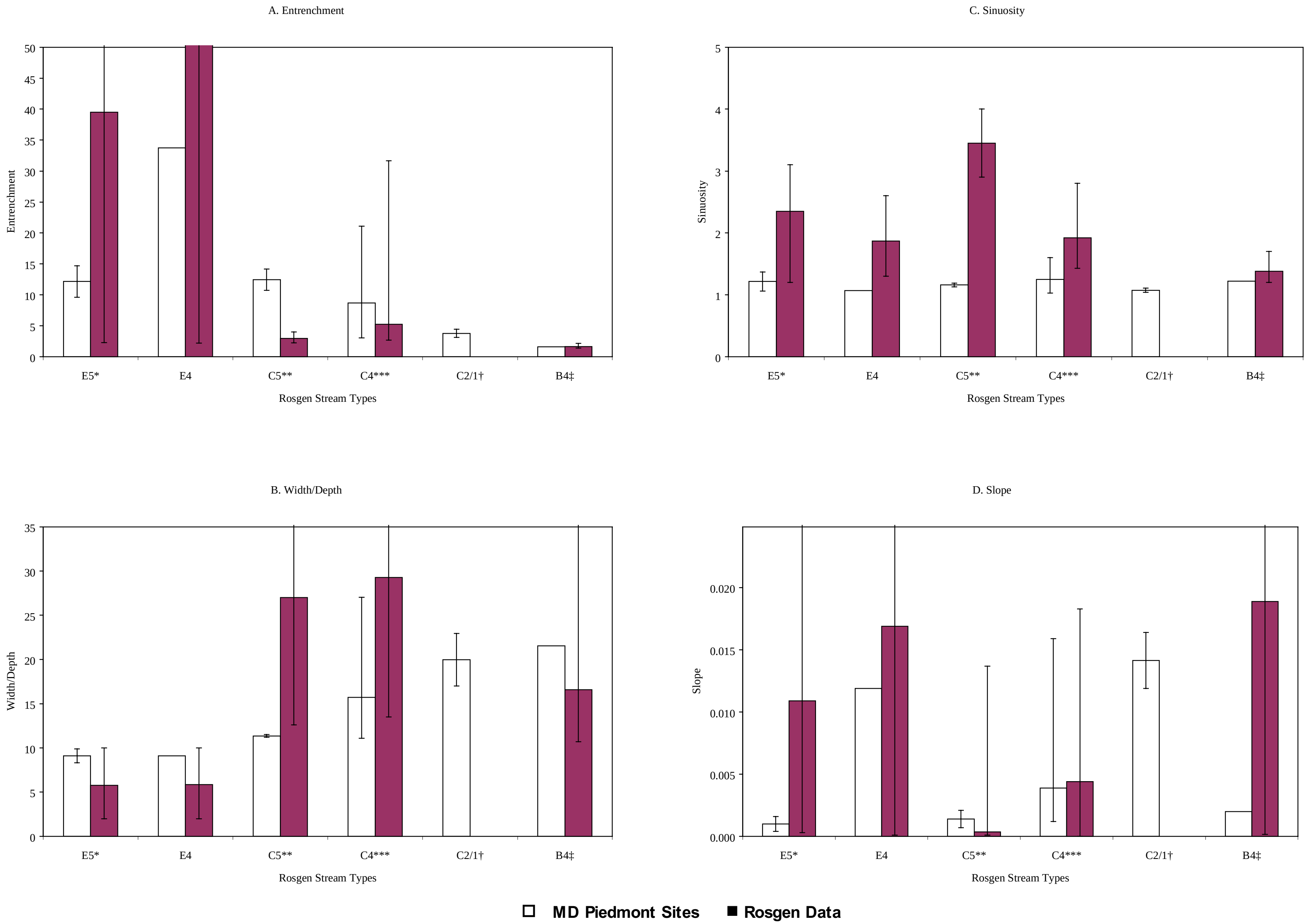

Figure 3. Maryland Piedmont surveys compared with Rosgen Classification criteria (Rosgen 1996).

* Maryland Piedmont sites include E5 and E5/1. ** Maryland Piedmont sites include C5 and C5/1c. *** Maryland Piedmont sites include C4/1.
† No Rosgen C2/1 data available. ‡ Maryland Piedmont site is a B4/1.

Discussion

In that all the reaches we surveyed classified to a specific stream type, the results of this study support the applicability of the Rosgen classification system to Maryland Piedmont channels. However, a limited number of stream types were observed at the gage stations in the Piedmont – most of the channels classified as C type streams, and of these C4 (gravel) – type channels were predominant. For the Maryland Piedmont streams surveyed, there are insufficient numbers of different stream types to allow examination of regional relationships partitioned by major Rosgen stream types. The low degree of variability in width/depth ratios across all streams results in a high number of channels falling in the region of overlap between the major stream types. The USGS gage station survey sites do not necessarily represent "stable, reference reach sites" and some of the surveyed streams may represent transition stream types. From our experience in the Piedmont physiographic region, not only at gaged sites but also at other sites as well, many streams represent borderline or transition reaches. In some cases, this may very well be a result of recent alteration but most certainly is a result of past land use practices, in particular agriculture and the resultant floodplain fills.

To classify some streams, it was necessary to compare the site data with the distribution of criterion values reported by Rosgen (1996a) for specific stream types, rather than with the broad delineative criteria, because the streams did not fit neatly into the broad categories. Several factors contributed to this problem. First, the width/depth for the Piedmont streams surveyed tends to be low, probably due to the cohesive bank materials and stabilizing influence of riparian vegetation. Thus, 10 of the 23 sites had width/depth ratios in the range 10-14, making the distinction between C and E stream types more complicated. Second, sinuosities of the streams are also low, and this in turn influences the secondary criterion of meander width ratio.

For example, survey results from Hawlings River and Little Patuxent River overlapped at the cut-off values in the broad level delineations. Table IV lists the broad delineative criteria values for C and E stream types (with the applicable "adjusted" value shown in parentheses) and the observed range of parameter values for C5 and E5 stream types reported by Rosgen for his 450 reach data set (Rosgen 1996a). The following describes the process by which we assigned stream types for Hawlings River and Little Patuxent River.

We initially classified Hawlings River as an E5 but changed it to a C5 following review by Rosgen (written commun., 1999). The measured median particle size distribution dictates that the numeric component of the stream type will be a "5" or sand. The survey reach has an entrenchment of 14.2, meeting the broad criteria for both C and E stream types. The width/depth ratio is 11.2 fitting the E-stream type broad delineative criteria but on the borderline with C-stream types (although within the variability ± 2.0). The sinuosity is 1.19, which fits the broad delineative criteria for the C-stream type. The slope is 0.0022, fitting both the broad E-and C-stream type criteria. The confinement at Hawlings River is 2.2, well below both the C and E averages, but near the range of C (4 – 20). Hawlings River is a pool/riffle/run stream with some mid-channel and point bar depositional features. Because the survey data more closely meets the broad criteria of C stream types, the stream type classification is a C5.

Little Patuxent River also has a measured median particle size distribution of sand designating the numeric component of "5". The entrenchment of 9.6 meets the broad criteria for both E and C stream types. However, it is well outside the range for C5 stream types and in the range of E5 stream types. The width/depth ratio is 9.9, fitting the E-stream type broad delineative criteria and on the borderline with C-stream types (although within the variability ± 2.0). The width/depth ratio at Little Patuxent River falls below the ranges for C5 but within the E5 stream types. The sinuosity is 1.37 (the fifth highest measured), which fits the broad range of the C-stream type delineative criteria of >1.2 ± 0.2 units but also fits into the E category >1.5 ± 0.2 units. The slope is 0.0005, fitting the broad E criteria and the Cc- criteria. The confinement at Little Patuxent River is 5.04 below both the E- and C-stream type averages, but in the range of C (4 – 20). Little Patuxent River is a pool/riffle/run stream with poorly defined point bar depositional features. While the stream is on the borderline between C and E, this channel is more typical of an E5 stream type than a C5, based on the range and average data.

Table IV. Classification by comparison with Rosgen delineative criteria ranges. Comparison of ranges of delineative criteria values observed by Rosgen (1996a) and delineative criteria cut-offs for major stream types. Parenthetical values in the criteria cut-off columns are the criteria limits after the adjustment allowed by Rosgen.

	C5		E5	
Criteria	**Rosgen Range**	**C Criteria Cut-off**	**E Criteria Cut-off**	**Rosgen Range**
Entrenchment (flood prone width/bankfull width)	2.25 - 4.0	>2.2 (2.0)	>2.2 (2.0)	2.27 - 200
Width/Depth	12.6 - 46.0	>12 (10)	<12 (14)	2.0 - 10.0
Sinuosity	2.9 - 4.0	>1.2 (1.0)	>1.5 (1.3)	1.2 - 3.1
Slope	.0002 - .0138	<.02	<.02	.0004 - .049

With the exception of Northeast Creek at Leslie with its boulder/cobble banks, all of the Piedmont study reaches have banks made up of sand. At some study reaches, there are broad low depositional features within the bankfull channel with a fine deposition on top. The bankfull to bankfull reach-average pebble count used to classify the stream reach materials may result in sand classifications for some streams in the Maryland Piedmont due to the sand composition of the banks and sidebars within the bankfull channel. However, classifying the streams, as sand bed streams would be misleading since the riffle compositions are obviously gravel. Thirty-two percent of the study sites have a uniform reach-averaged particle size distribution, while for the remaining non-uniform sites (68% or 17 sites), it was necessary to classify using the largest number of observations.

Overall, the Maryland Piedmont C4 and C5 channels were comparable to the range of delineative parameter values reported by Rosgen from North America and New Zealand. The departures, such as high entrenchment values in C5 channels compared with Rosgen's observed ranges are undoubtedly due to comparing data from markedly different geographic ranges. Of the five delineative criteria for the Piedmont sites, sinuosity was the parameter that least conformed to Rosgen's classifications, being uniformly low in all observed stream types. This is not as problematic as it might seem, as Rosgen has stated that sinuosity is of secondary importance in determining major stream type, compared to entrenchment, width/depth, and slope. To avoid undue confusion, the range of sinuosities expected for each stream type in the Piedmont may need to be refined. However, to adequately test this hypothesis, further observations will be needed, particularly for reaches less influenced by bedrock than the gaged streams surveyed in this study.

Rosgen (1994, 1996a) has published average and range values for dimensionless meander belt widths (BW/W_{bkf}), which he calls meander width ratios (MWR), by major stream type categories. The average MWR values for E and C type channels in the Maryland Piedmont are strikingly lower than those presented by Rosgen (Figure 4). The difference is particularly large for E-type streams, where the average Piedmont MWR is almost one tenth of that reported by Rosgen, and for which there is no overlap in the ranges of MWR. The MWR for Piedmont C-type streams is approximately one third of that reported by Rosgen. Although there is some overlap between Piedmont and Rosgen MWR data for C-type streams, all Piedmont MWR observations are lower than the average reported by Rosgen. These lower confinement ratios appear to correspond to the rather low sinuosities observed in the Piedmont streams, perhaps due to past land uses as stated above. However, the existence of bedrock outcrops in the Piedmont (found at nearly 60% of the study reaches) may be the dominant confinement factor at the study reaches. The question also arises as to the length of channel used in measuring planform characteristics such as sinuosity. Although Rosgen (1996) indicates a study reach length of 20 to 40 bankfull-widths, this may be too short to examine planform characteristics such as sinuosity. We found that some parameters of the classification (entrenchment, width/depth, etc.) often changes beyond the study reach, suggesting that measurements of planform characteristics from aerial photographs may include different stream types. A comparison of the study reach sinuosity to the channel sinuosity taken from aerial photographs over a longer reach would be helpful in examining relationships between reach and overall channel pattern.

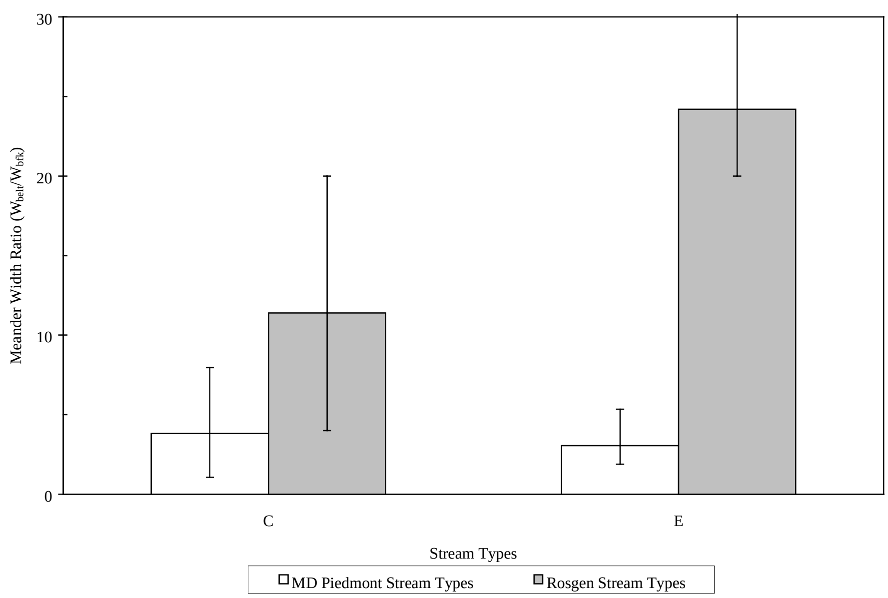

Figure 4. Maryland Piedmont survey sites meander width ratios compared to Rosgen stream types (1996).

Stream channels and drainage networks are highly dynamic, self-adjusting, systems, wherein morphologic changes occur through continuous, rather than discrete processes. Classification systems, by their very nature are composed of discrete entities, and are thus artificial constructs that, to varying degrees, ignore or minimize the importance of natural variability. This said, classification systems can be powerful tools for organizing voluminous and variable information, and perhaps even assist in identifying the meaningful outliers that can be used to test assumptions and dogma. Rosgen's (1994, 1996a) classification system for natural rivers is based on quantitative delineative criteria that characterize the physical attributes underlying hydraulic and sediment transport conditions in rivers. Rosgen developed the classification system to, in part: help predict a river's behavior from its appearance; provide a mechanism to extrapolate site-specific data to stream reaches having similar characteristics; and provide a consistent frame of reference to aid communication of stream morphology and condition among workers from a variety of disciplines.

Central to the success of Rosgen's system in attaining the stated goals is the degree to which the delineative criteria for specific stream types actually fit the observed natural variation in river morphology. While Rosgen developed his system from a database of 450 rivers throughout the U.S., Canada, and New Zealand, it is new enough to require independent validation of its applicability, and refinement of the expected ranges of variability within the delineative criteria for stream types, for specific regions. Rosgen (1996a, page 3-7) has acknowledged the need for refinement of the system, using the analogy of the USDA Soil Classification system, which is essentially under continual refinement and revision. Indeed, Rosgen revised the delineative ranges of sinuosity for four of the major stream types (C, D, DA, & F) between publication of the basic system (Rosgen, 1994) and subsequent release of an expanded treatment in book form (Rosgen, 1996a). A major aid to the further evaluation of the generality of Rosgen's system would be the publication of the original 450 site data set.

Bankfull Discharge

Indicators

Bankfull, as a linear collection of geomorphic indicators running relatively parallel to the trend in water surface elevation, is distinct at all sites. At most sites, the top of bank/floodplain break is a primary indicator, with other indicators, depending on site-specific characteristics of the channels, present at the corresponding height above water surface. For instance, while the primary indicator along a reach might be the floodplain break, at locations where the channel is impinged on a terrace or hill-slope, a scour line (usually not continuous) composed of wear marks, undercuts, or obtuse slope breaks may be evident at the same elevation relative to water surface. At such points along a reach, the top of bank occurs at a higher elevation than the floodplain break. In some locations, local bank-top topography is uneven due to non-continuous but natural flood levee deposits, tree throws, or scour from over-bank flows. Because of this, simply plotting elevations for top of bank results in a nonlinear collection of points. At locations with a high bank where the channel has widened in the past, there might also be a depositional bench, the top of which also corresponds to the floodplain and scour elevations. At sites with well-developed point bars, the top of the point bar might also occur at the same relative elevation above the water surface as the floodplain break. However, there are many instances, particularly in channels with low width/depth ratios, where the tops of point bars are well below the elevation of the floodplain break.

We consistently observed the six distinct geomorphic indicators of bankfull stage described under Methods during the field surveys (Figure 5). At 83% of the sites, the elevation of the floodplain break indicates, at some points along the reach, the bankfull stage. At 61% of the sites, the inflection point indicates bankfull stage, and at between 30 and 40% of the sites the top-of-bench, a scour line, or a slope break indicates bankfull stage. Top of point bar indicates bankfull stage at less than 10% of sites.

At 13 of the sites, there also occurs a relatively linear set of geomorphic indicators well down inside the channel. This is often observed as a narrow bench, supporting annual vegetation or even very young individuals of perennial species, or a scour line below which little or no annual vegetation grows. This lower series of indicators, which we refer to as the "active channel", first described by Osterkamp and others (1982), later in Northern Virginia (Osterkamp et.al. 1984) and in the southern Piedmont by Kolberg (1989), is usually much more discontinuous than the higher floodplain or top of bank series. We also found that the *lower indicator* was inconsistent in the Piedmont survey. Where it was found, it did not provide a contiguous set of indicators in the majority of sites. The selection of the actual bankfull indicators is a result of a consistent set of indicators surveyed throughout the Maryland Piedmont physiographic region.

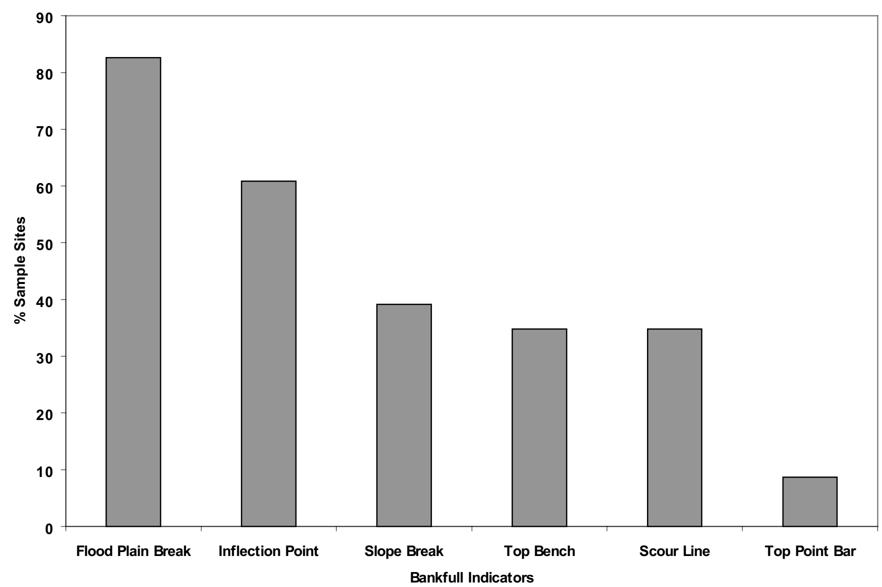

Figure 5. Percent of sites exhibiting geomorphic indicators of bankfull stage.

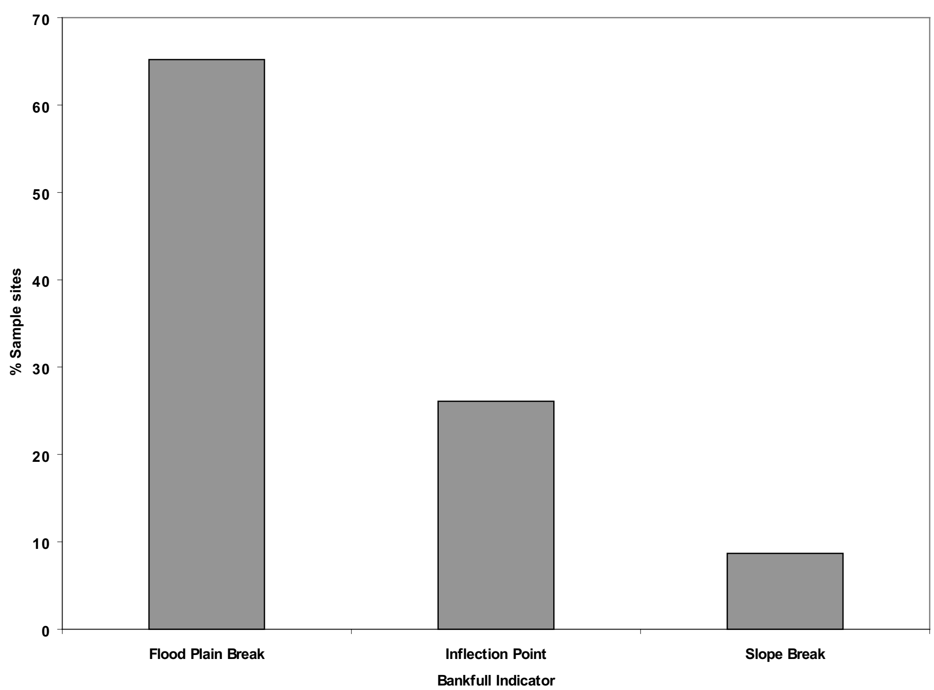

Figure 6. Percent of sites exhibiting primary bankfull indicators.

Discussion

A number of indicators for bankfull stage have been cited by many workers. These indicators include: the valley flat, the active floodplain, the low bench, the middle bench, the most prominent bench, tops of bars, the lower limit of perennial vegetation, the upper limit of sand in banks, the minimum width/depth ratio, the first maximum of the Riley bench index, a slope break in a plot of cross-sectional area vs. width, the 1.5 year recurrence interval discharge, the 1.58 year recurrence interval discharge, and the 2.33 year recurrence interval discharge. Williams (1978) compared the results of 16 published methods for estimating bankfull discharge applied to 28 different gaged sites in the western U. S., and documented a wide variability and lack of consistency in the magnitudes of the estimates, suggesting these indicators are not all related to the same flow, or narrow range of flows, within a reach. Williams also reiterated the problem of identifying some of the features, particularly the “active” floodplain, and the high degree of variability in others, such as vegetation and sediment size distribution. Williams concluded that investigators should specify the bankfull indicators used, and the way in which a corresponding discharge is determined for a chosen indicator. Our results strongly suggest that one indicator at all points along a reach does not mark the bankfull stage. Rather, while the floodplain break is the primary indicator, there exist additional secondary indicators such as scour marks and breaks in slope that occur at the same relative elevation.

Our observations also support those of previous workers who determined that vegetative patterns are best used to support a bankfull determination made based on geomorphic evidence. In the channels we surveyed, we often found large trees, particularly sycamores (*Platanus occidentialis*), growing well below the bankfull stage. In some cases, this was clearly due to slumping of the tree’s root mass following erosion of supporting bank materials. While smaller individuals, presumably not more than one or two years, did seem to have a lower distributional limit near the geomorphic bankfull elevation, there was noticeably greater variation than for the geomorphic indicators.

Bankfull Discharge

By Drainage Area

Bankfull discharge is significantly related to drainage area, with about 93% of the variability in discharge explained by drainage area (Table V, Figure 7). Examination of Figure 7 reveals that four locations in the northeastern Piedmont region (Basin Run, Big Elk Creek, Northeast Creek, and Winters Run) plot relatively high, indicating a greater bankfull discharge per drainage area. However, Deer Creek, also in the northeastern Piedmont, plots on the trendline.

Table V. Bankfull discharge vs. drainage area. Bankfull discharge (cfs) regressed against drainage area (mi^2) for study reaches at USGS gage stations in the Maryland Piedmont. Calculated test statistics (F, se, t), degrees of freedom (df), significance (p), and coefficient of determination (R^2) for least-squares linear regression, and t-tests for differences between slopes and intercepts. NS = no significant difference at ∝ = 0.05. All = data from all sample sites, NEP = data from northeastern Piedmont, MP = data from main Piedmont excluding NEP.

		Regression					Slope			Intercept		
Group	N	Equation	R^2	Se (%)	F	p	df	t	p	df	t	p
All	23	$Q_{bkf} = 84.56DA^{0.76}$	0.93	11	277	<.001						
NEP	5	$Q_{bkf} = 266.26DA^{0.52}$	0.98	4.5	117	<.001	19	4.04	.05	20	5.06	<.05
MP	17	$Q_{bkf} = 71.74DA^{0.78}$	0.98	5.8	882	<.001						

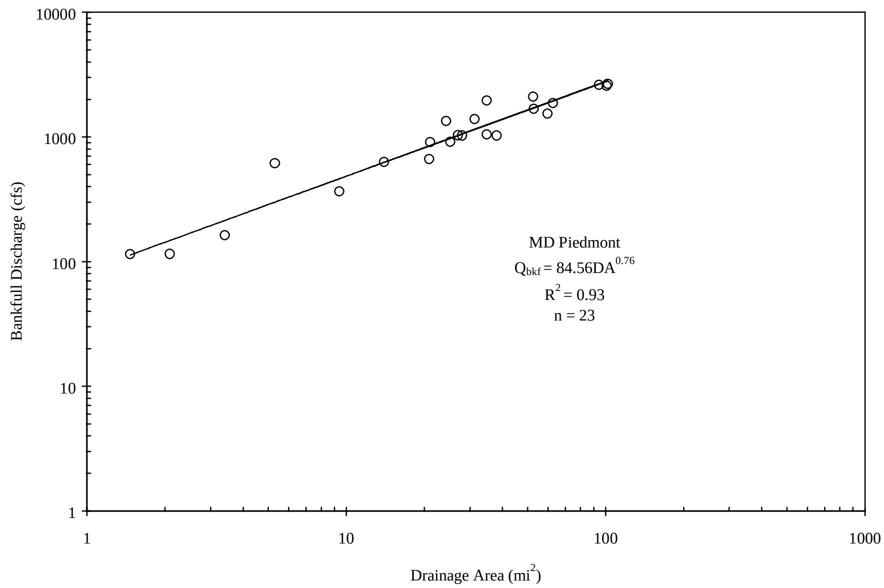

Figure 7. Bankfull discharge as a function of drainage area for Maryland Piedmont survey sites.

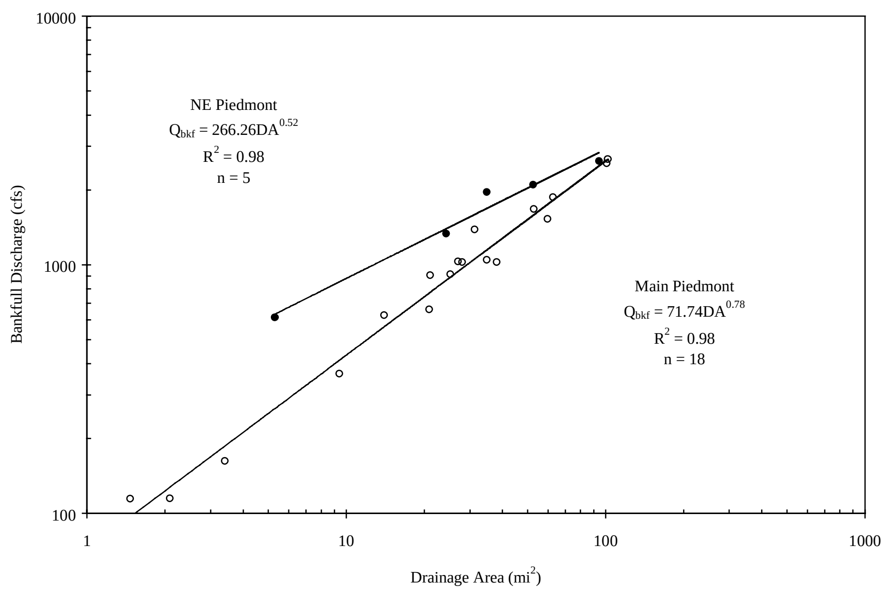

Figure 8. Bankfull discharge as a function of drainage area for Maryland Piedmont survey sites partitioned by northeastern Piedmont.

Partitioning the sites into groups composed of northeastern and main Piedmont sites results in significant relationships for both (Figure 8, Table V). The explanatory ability of the regression relationship for both the northeastern Piedmont and main Piedmont is improved somewhat over that of the full 23 sites. Comparison of the two regressions reveals they are significantly different, suggesting that streams in the northeastern Piedmont have a greater bankfull discharge per unit drainage area than streams in the remainder of Maryland's Piedmont region. The relative change in discharge with a change in drainage area is different in the two regions as suggested by the differing slopes.

Discussion

The relationship between drainage area and bankfull discharge estimated for the Maryland Piedmont survey (Figure 7) compares well with those described from previous studies in the East (Table VI). In particular, those equations developed for Maryland and Pennsylvania (this study; Leopold and others, 1964; and Wolman & Leopold, 1957) describe relationships between drainage area and discharge that produce very close estimates. For 10 mi^2, these three equations predict discharges within a range of 147 cfs, representing approximately a 30% error, while for 100 mi^2, the range is 161 cfs and the error approximately 6%.

Table VI. Comparison of bankfull discharge to drainage area relationships from the Maryland Piedmont and other nearby regions. The relationships are all expressed as power functions of the form $Q_{bkf} = aDA^b$, where Qbkf is bankfull discharge in cubic feet per second and DA is drainage area in square miles. R^2 is the regression coefficient of determination, n = number of observations.

Source	**a**	**b**	**n**	**R^2**	**Geographic Area**
This Study	84.56	0.76	23	0.93	Maryland Piedmont
This Study	71.74	0.78	18	0.98	Main Maryland Piedmont
This Study	266.26	0.52	5	0.98	NE Maryland Piedmont
Leopold et al., 1964	61	0.82	8	?	SE PA Piedmont
Wolman & Leopold, 1957	43.8	0.89	18	0.64	SC, NC, Maryland, PA, NY, CT
Brush, 1961	55	0.86	7	0.86	Central PA Valley & Ridge
Kilpatrick & Barnes, 1964	285	0.50	34	0.63	NC & SC, GA, AL Piedmont

The relationships for the NE Piedmont of Maryland and the Southern Piedmont between North Carolina and Alabama are strikingly different from the others. For the NE Piedmont, the greater bankfull discharge per drainage area may be partially due to a combination of greater runoff and bankfull recurrence intervals for that region. Two-year recurrence interval discharges from the USGS log-Pearson flood frequency distribution, which provide a measure of runoff magnitude independent of this survey, are greater in the NE Piedmont (Figure 9), compared to the rest of the region. Recurrence intervals, while not statistically greater in the northeast, nevertheless are mostly at the higher end of the range.

The high discharges estimated for the Piedmont in the southeastern states may be a consequence of both higher precipitation, and the definition of bankfull. Kilpatrick and Barnes (1964) defined bankfull as the elevation of the “primary”, or widest, bench on the valley flat. In their study, of the data from sites where multiple benches were identified, the recurrence intervals for bankfull discharges corresponding to the primary benches ranged from 1.1 – 14.0 years, suggesting that infrequently flooded terraces may have been mistaken for active floodplains. Piedmont valleys experienced significant aggradation during early colonial era land clearing and pre-soil conservation agricultural practices (Trimble, 1974; Costa, 1975; Jacobsen & Coleman, 1986). Subsequent incision following decreases in sediment production has produced incised channels in many parts of the Piedmont with poorly defined active floodplains at lower relative elevations than the abandoned floodplains, or terraces, comprising most of the valley flats.

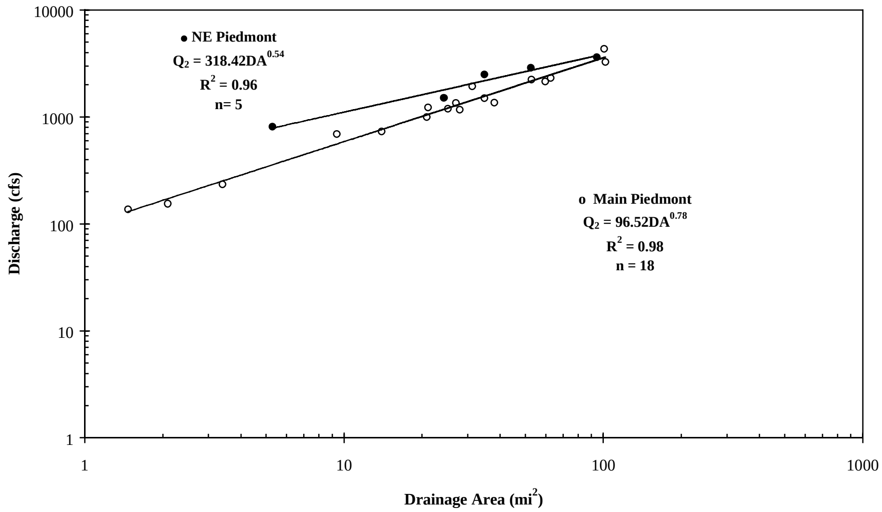

Figure 9. Two-year recurrence interval discharge as a function of drainage area, partitioned by northeastern Piedmont and the main Piedmont survey sites.

While the statistical analysis indicates that the bankfull discharge and drainage area relationship may be different for the northeastern Piedmont, our confidence in the results is low due to the low power associated with a small sample size for that sub-region. Although, the independent review of discharge strictly associated with the flood frequency data does support our observations, review of the northeastern Piedmont data set shows that the smallest site, Basin Run at Liberty Grove (an inactive site), has a large influence on the regression. Removing this site would result in a different trend line for the northeastern Piedmont. We think that additional survey work should be conducted in the northeastern Piedmont to not only examine the interaction of drainage area and bankfull discharge but also bankfull channel dimensions and drainage area. For this reason, we adopt a conservative approach below, and do not partition the various relationships by sub-region.

Although additional active gage sites were not available at the time of the survey in the northeast Piedmont, it would be interesting to plot channel dimensions for ungaged sites with the data of this study to see if the additional observations support the trend toward greater discharge. A second, process-based expectation is that the greater bankfull discharge per unit drainage area in the northeastern Piedmont would result in larger channels. However, to some extent it appears that larger discharges are accommodated by increased velocities in the northeastern Piedmont (Figure 10). Comparison of the average velocities (calculated using the continuity equation) at each site indicates that the northeastern Piedmont reaches tend to have velocities at the high end of the range observed for the 23 sites, with 3 of the 5 sites having higher reach average water surface slopes (Figure 11).

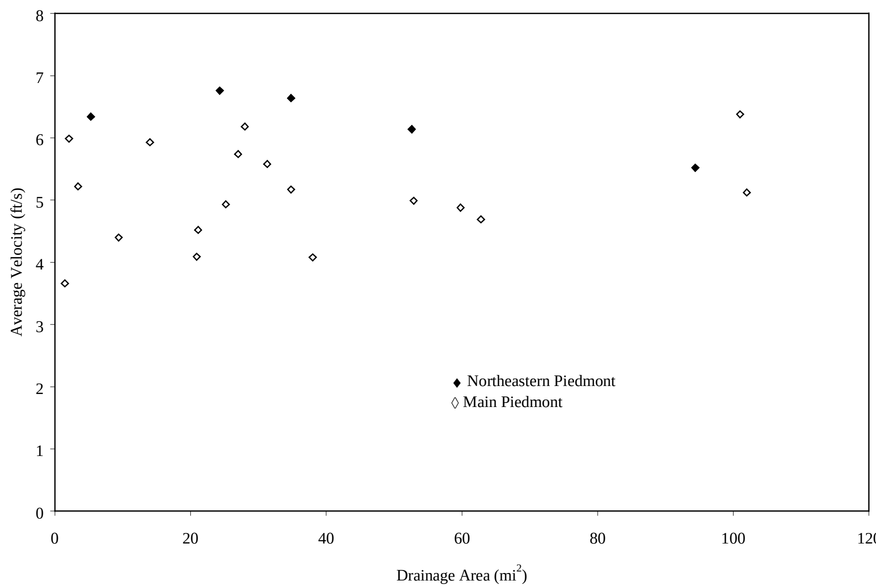

Figure 10. Average bankfull velocity for Piedmont survey sites.

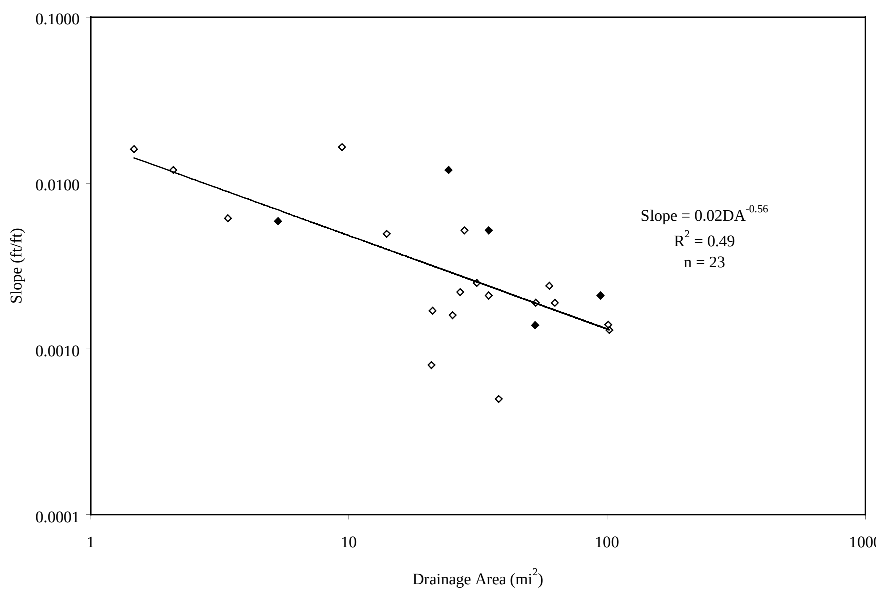

Figure 11. Reach average water surface slope as a function of drainage area (northeastern Piedmont sites shown as solid triangles).

<u>Bankfull Discharge</u>

Recurrence Interval

Recurrence intervals for field-estimated bankfull discharges, calculated from the annual maximum discharge series following the *Guidelines for Determining Flood Flow Frequency* (Interagency Advisory Committee, 1982), range from 1.26 – 1.75 years, and average 1.5 years (Figure 12). For several sites, the log-Pearson flood frequency did not match the period of record for the gage station. For example, at Seneca Creek and Jones Falls, we used later portions of the period of record for the flood frequency distribution to avoid problems associated with significant changes in development. For both sites we examined the record of peak flows above base for obvious changes in magnitude of flows, and selected a cut-off date that excluded markedly lower flows and any obvious transition period. The log-Pearson period of analysis for each site is found in Appendix A.

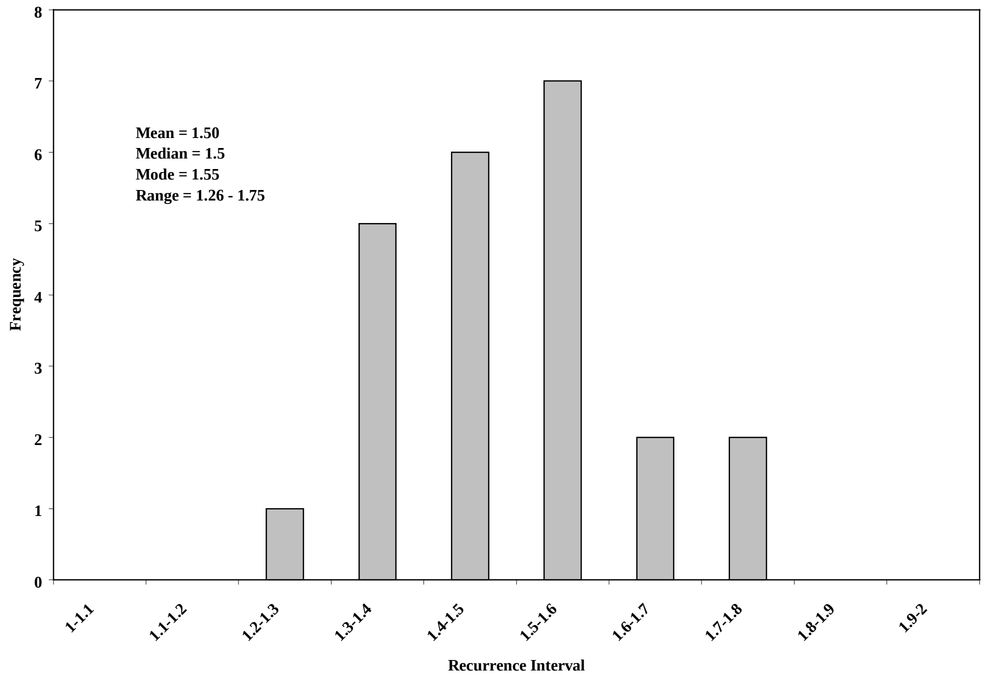

Figure 12. Frequency of recurrence interval for field-estimated bankfull discharge.

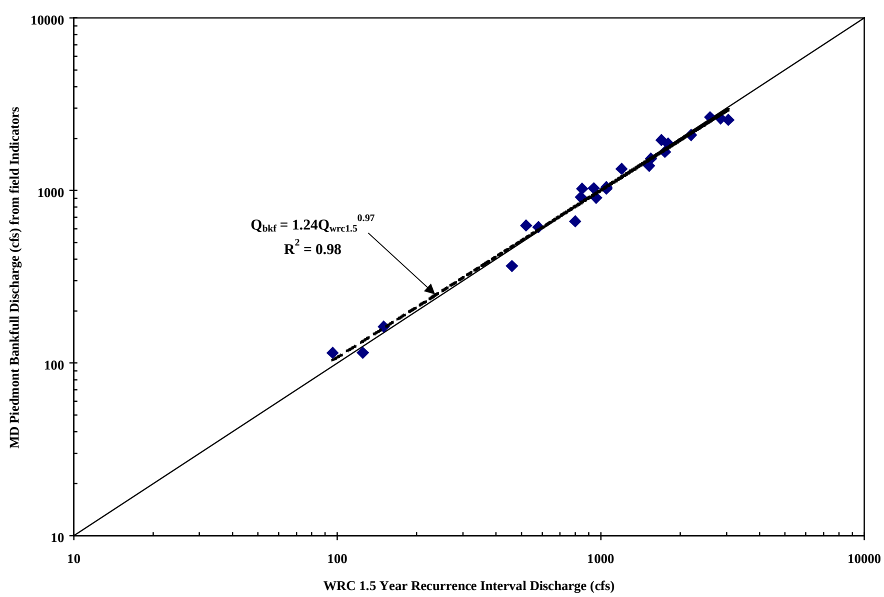

Figure 13. Comparison of field-estimated bankfull discharges from Maryland Piedmont survey sites with the WRC 1.5 recurrence intervals.

Comparison of the field-estimated bankfull discharges with the WRC 1.5-year recurrence intervals shows very close correspondence and a close fit to a 1:1 relationship (Figure 13). The average ratios of bankfull discharge to the WRC 1.5 and 2-year recurrence interval discharges are 1.01 (sd = 0.12) and 0.75 (sd = 0.08), respectively. Comparison of the regression relationships by drainage area for the field-estimated bankfull and WRC estimated 1.5-year recurrence interval discharges (Figure 14) reveals no difference in either the intercepts (t = -0.855, v = 42, p > 0.05) or slopes (t = -0.193, v = 43, p > 0.05). This indicates that the overall relationships between drainage area and the field estimated bankfull and 1.5-year recurrence interval discharges are essentially the same.

At 12 of the 13 sites where we observed a lower series of channel indicators, we extended the surveyed series through the gage to estimate a discharge. This lower series of geomorphic indicators is associated with a discharge close to the 1-year recurrence interval. The average recurrence interval is 1.07 years, with a standard deviation of 0.084, and a range of less than 1.005 to 1.2. A proportional frequency distribution shows that at half the sites, the recurrence interval of the low indicator is less than 1.01 years (Figure 15).

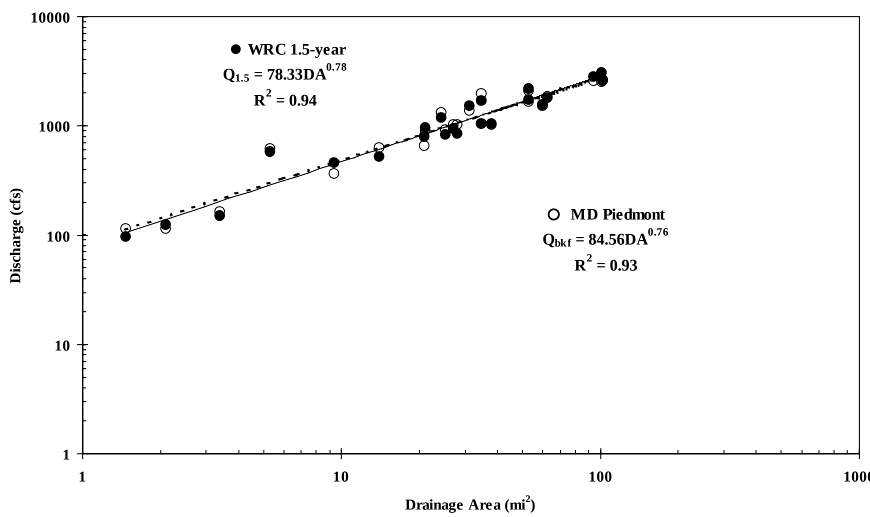

Figure 14. Drainage area versus discharge: Maryland Piedmont field-determined bankfull and WRC 1.5-year recurrence interval.

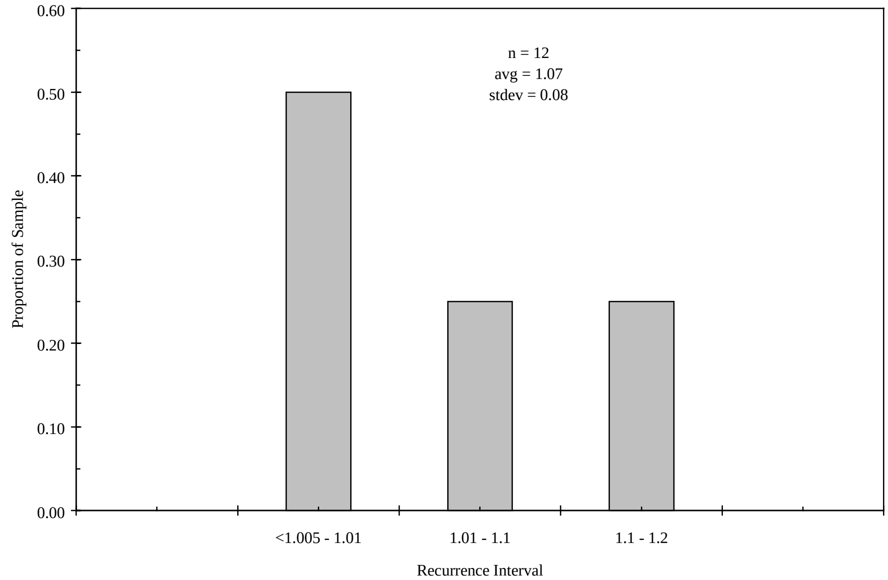

Figure 15. Recurrence intervals for field-observed active channel or inner berm.

Discussion

The recurrence intervals for discharges corresponding to the field-identified bankfull stages agreed well with previous work that has demonstrated a central tendency of 1.5 years on the annual maximum series. Wolman and Leopold (1957) reported bankfull recurrence intervals between 1 - 2 years for 37 reaches in the U.S. and India, and that at the "better studied" sites it was closer to 1 year. Although the range of bankfull recurrence interval estimate was from 1.01 to 200 years, Wolman and Leopold (1957) indicated that many of the sites with longer recurrence intervals occurred in steep, mountainous terrain with difficult to distinguish floodplains. For the 26 sites at which they considered the floodplain evident, the average recurrence interval was 1.59 years, with a range of 1.01 to 5 years. A frequency distribution of the recurrence intervals at these 26 sites indicates that at 54% of the sites the floodplain recurrence interval was between 1.01 and 1.2 years, between 1.2 and 1.6 years at 31%, and over 2 years at 15%. Interestingly, 8 of their 26 distinguishable floodplain sites were in the Piedmont physiographic region of Maryland and Pennsylvania. At these Piedmont sites, the average recurrence interval was 1.55 years, with a range of 1.07 to 2.7 years.

In addition to testing the correspondence of various bankfull indicators, Williams (1978) also examined the frequency distribution of bankfull discharge recurrence intervals for a compiled data set of 36 sites. Although the data came from several different workers, at all 36 sites bankfull was equated with the "active floodplain". The mode of the frequency distribution was approximately 1.5 years, with a range of 1.01 – 32 years. Similar to the data set of Wolman and Leopold, Williams reported data for several sites in the Eastern U.S. (Pennsylvania 3, West Virginia 2, Kentucky 2, and Tennessee 1). At these 8 sites, bankfull, which was equated to the elevation of the valley flat, averaged 28.4 years. However, all of the sites had recurrence intervals less than 2 years except for two sites with intervals of 3.4 and 200 years, respectively. Omitting the 200-year site, the average dropped to 1.56, with a range of 1.02 to 3.4 years.

Two other studies have examined bankfull discharge and recurrence intervals in the eastern U.S., and deserve comment. Kilpatrick and Barnes (1964) surveyed 34 sites in the Piedmont region of North Carolina, South Carolina, Georgia, and Alabama, using the most prominent bench as the indicator for bankfull. At four sites, it was not possible to distinguish between two bench levels regarding prominence. Using the higher of the two benches at these four sites, the average recurrence interval for the 34 sites was 3.68 years with a range of 1.01 – 14 years. Using the lower bench at the four sites, the average for the 34 sites was 3.4 years, with a range of 13.7 years. At 19 of the sites, multiple cross-sections were surveyed in a reach, permitting the detection of several benches. Five sites had two benches, eight sites had three benches, and five sites had four benches. Several aspects of the study make comparison with the others summarized above difficult. First, none of the benches were identified as active floodplain; second, the number of distinct benches at several sites suggests that incision and floodplain abandonment may have occurred; and third, significant changes in channel slope were present in many of the reaches.

Brush (1961) examined relationships between drainage area and bankfull discharge at 119 reaches on 16 streams in central Pennsylvania. None of the reaches was gaged, but at five gage sites in the vicinity, Brush surveyed the bankfull (not defined specifically, but assumed to equal top of bank) channel and determined that the recurrence intervals ranged from 1.9 to 10 years on the partial duration series. By plotting specific recurrence interval discharges against drainage area for the five stations, and comparing the resulting iso-frequency lines to the plotted bankfull discharges by drainage area, Brush determined that the mean annual flood (recurrence interval = 2.33 years) line best fit the measured bankfull points. On this basis, he concluded that bankfull discharge at the 119 stations was equivalent to the mean annual discharge. This approach to determining bankfull discharge is significantly different from the present study or the others summarized, in which longitudinal profiles were surveyed through active gaging stations. Also, as in the Kilpatrick and Barnes study, there was no evaluation of whether the top of bank was likely the active floodplain, or even if the top of bank elevations paralleled water surface, as would be expected for a channel maintaining flow.

Thus, the previous studies (Wolman & Leopold, 1957; Williams, 1978) that involved methods and geographic locations similar to that used in the present study reported recurrence intervals very similar to those we estimated in the Maryland Piedmont. At this point in time, and with the available information, it is difficult to address the greater ranges of bankfull recurrence intervals reported in the earlier studies. It is apparent; however, those differing definitions of bankfull and methods of estimation may likely contribute greatly to these discrepancies.

Comparison of Gage and Study Reaches

At 20 sites, the gage and study reaches are located some distance apart, raising the possibility that bankfull dimensions at the study reaches are not indicative of the discharges measured at the gages. To test the hypothesis that the bankfull channels we measured at the study reaches are not likely associated with the bankfull discharges we estimated at the gage reach, we compared the cross-sectional areas for each. In all cases, the indicators we used to delineate the bankfull channel in the gage reach were the same as the study reach. Our assumption is that, with no major tributaries in between, the range of discharges that forms and maintains the channel at the gage is also responsible for channel dimensions in the nearby study reach. Channel cross-sectional area near the gage is plotted against cross-sectional area in the study reaches in Figure

16, along with the line representing a 1:1 correspondence for comparison. A paired t-test detects no difference in the mean cross-sectional areas of the two reaches (Gage cross-section mean = 237 ± 34; Study reach cross section mean = 230 ± 34; t = 1.4, df = 19). Thus, we conclude that the bankfull channels identified in the study reaches are likely the result of the same range of discharges forming and maintaining the bankfull channels in the gage reaches.

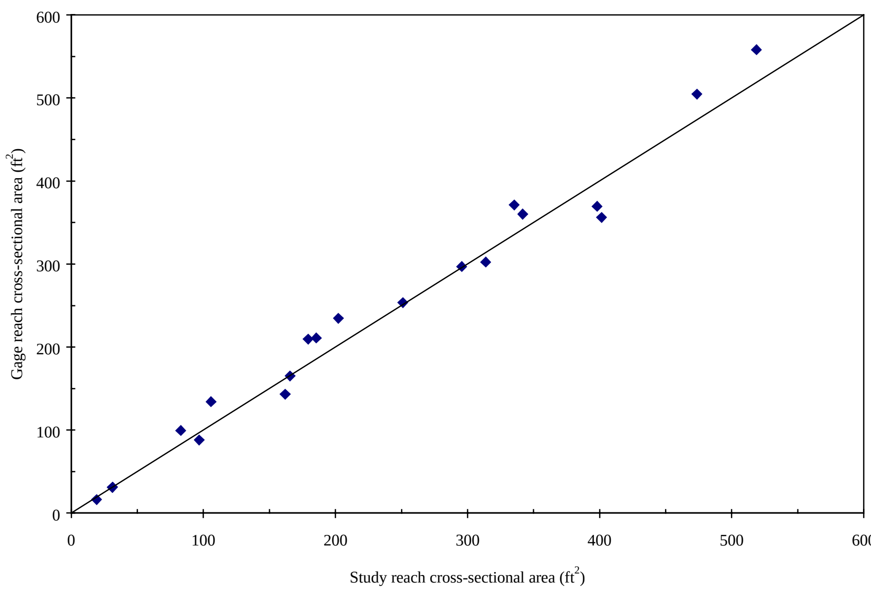

Figure 16. Comparison of gage reach and study reach cross-sectional area.

Cross-section Relationships

We used data from the cross-section surveys to test for predictive relationships between the independent variables of drainage area and bankfull discharge and the dependent variables of width, mean depth, and cross-sectional area. We also tested for relationships between bank material composition and channel shape, and between relative roughness (R/D84) and flow resistance (Manning's "n").

By Drainage Area

We used data from the cross-section surveys to test for predictive relationships for width, mean depth, and cross-sectional area. Width, mean depth, and cross-sectional area are all significantly related to drainage area (Figure 17, Table VII). Of the three parameters, cross-sectional area has the greatest percent of the variability in size explained by drainage area, followed by mean depth and width, as indicated by the regression coefficients of determination (R^2 values).

Table VII. Cross-section dimensions vs. drainage area. Bankfull width (ft), mean depth (ft), and cross-sectional area (ft^2) regressed against drainage area (mi^2) for study reaches at USGS gage stations in the Maryland Piedmont. Calculated test statistics (F, se), significance (p), and coefficient of determination (R^2) for least-squares linear regression.

N	Regression Equation	R^2	Se (%)	F	p
23	Cross-sectional Area = $17.42DA^{0.73}$	0.95	9.1	368.7	<.001
23	Width = $14.78DA^{0.39}$	0.83	9.1	104.3	<.001
23	Depth = $1.18DA^{0.34}$	0.86	6.5	160.7	<.001

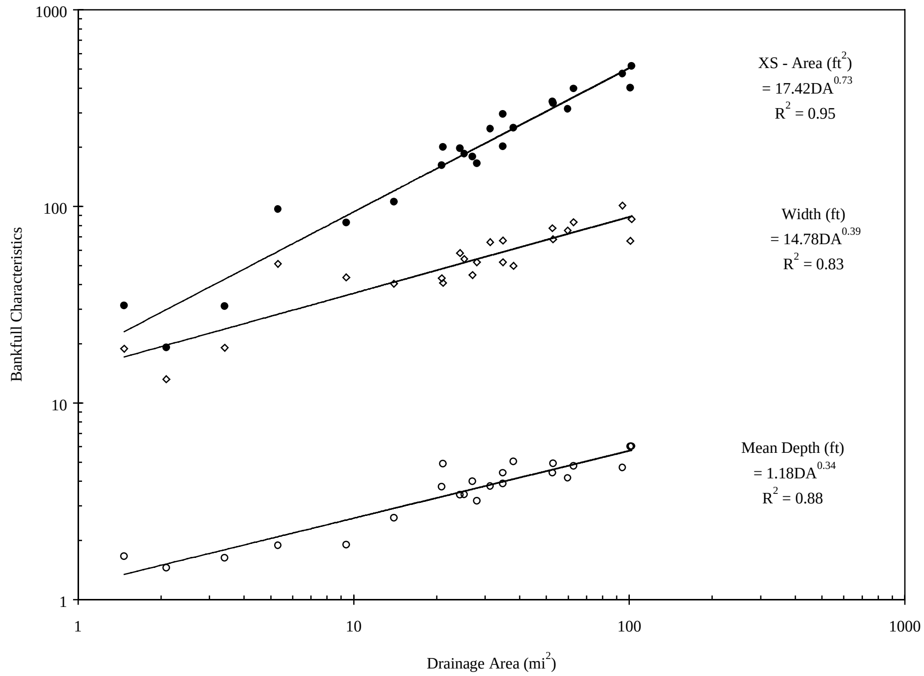

Figure 17. Bankfull channel dimensions as a function of drainage area for Maryland Piedmont survey sites (n = 23).

Discussion

The results of this study document significant relationships between all three cross-section parameters (area, width, and depth) and drainage area in streams of the Maryland Piedmont. Cross-sectional area is the parameter for which drainage area explains most of the observed variability, followed in order by depth and width.

Currently, the graphical relationships between drainage area and bankfull channel dimensions in southeastern Pennsylvania, published by Leopold and his co-workers (Leopold et al., 1964; Dunne & Leopold, 1978), are used by many environmental scientists and engineers for predicting bankfull dimensions at ungaged stream reaches in the Piedmont region of Virginia, Maryland, and Pennsylvania. Unfortunately, neither of these two references provide either equations or data for the relationships. We have estimated the equations for the published regression lines by graphically identifying points along the lines that coincide with intersections of iso-values of drainage area and dimensions. These estimated equations, expressed as power functions are $A = 20.5DA^{0.71}$, $W = 14.3DA^{0.39}$, and $D = 1.4DA^{0.3}$. As with the relationships between drainage area and bankfull discharge reviewed above, comparison of these equations with the power functions summarized in Figure 17 reveals an extremely close correspondence between the southeastern Pennsylvania regression relationships and those developed in this study for the Maryland Piedmont.

By Bankfull Discharge

Width, mean depth, and cross-sectional area in the Piedmont streams are all significantly related to bankfull discharge (Figure 18). Comparison of the coefficients of determination (R^2) show that, as with drainage area, discharge best explains the variability in cross-sectional area, followed in order by width and depth (Table VIII).

Table VIII. Cross-section dimensions vs. bankfull discharge. Bankfull width (ft), mean depth (ft), and cross-sectional area (ft^2) regressed against bankfull discharge (cfs) for study reaches at USGS gage stations in the Maryland Piedmont. Calculated test statistics (F, se), significance (p), and coefficient of determination (R^2) for least-squares linear regression.

N	Regression Equation	R^2	Se (%)	F	p
23	Cross-sectional Area = $0.28Q_{bkf}^{0.94}$	0.97	6.8	629.1	<.001
23	Width = $1.46Q_{bkf}^{0.52}$	0.92	6.5	228	<.001
23	Depth = $0.19Q_{bkf}^{0.42}$	0.83	7.9	102.5	<.001

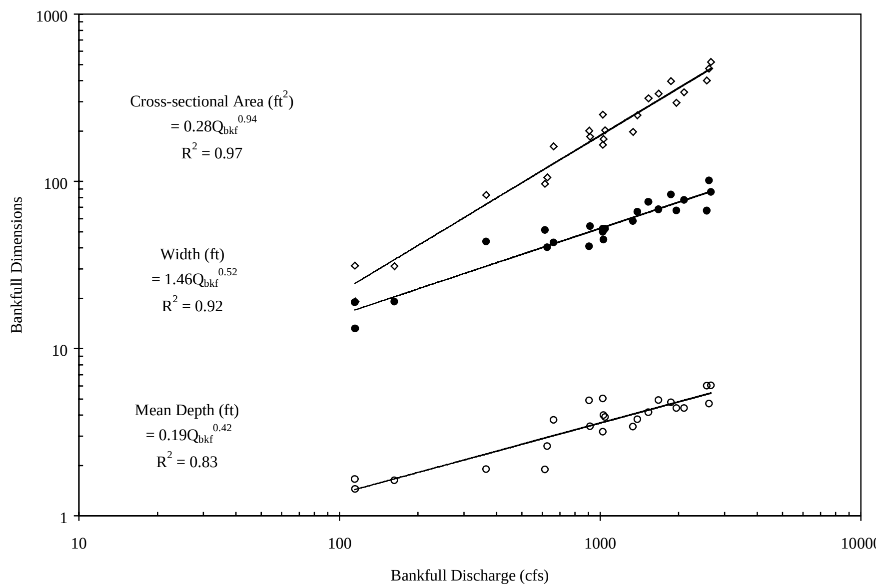

Figure 18. Bankfull channel dimensions as a function of bankfull discharge for Maryland Piedmont surveys sites (n = 23).

Discussion

The power function equations determined in this study compare favorably with the equations developed by other workers (Table IX). This is particularly true for the exponents (b), which describe the slope of the regression line, and indicate the degree of change in a dimensional parameter for every unit of change in bankfull discharge. As for the relationships observed between cross-section dimensions and drainage area, the exponents for cross-sectional area vary the least among the studies, again indicating that cross-sectional area, which represents a dynamic balance between width and depth, is a more conservative parameter than either width or depth alone. Neither Leopold & Maddock (1953) nor Wolman (1955) provided coefficients for the relationships determined in their studies. The equations of this study and that of Nixon

(1959) have dimensional units in feet, while that of Hey and Thorne (1986) is for metric units. One may compare the slope functions expressed by the dimensionless exponents directly, however the coefficients, which represent the y intercepts, must be converted for comparison. The converted (to feet) coefficient ranges provided by Hey and Thorne for width (7.12-13.06) and depth (0.52-0.65) suggest their study streams have greater width/depth ratios than those of this study and that of Nixon.

Table IX. Comparison of relationships between bankfull discharge and channel dimensions. Coefficients and exponents of power functions describing relationships between bankfull discharge and channel dimensions from selected channel geometry studies. Power functions have the form $W = aQ_{bkf}^{b}$, $D = cQ_{bkf}^{f}$ and $A = gQ_{bkf}^{h}$. Superscripts: for Study, 1 = units in feet, 2 = metric; for Area, * = determined by regression analysis, + = determined from mathematical relationship of hydraulic geometry equations wherein h=b+f. Hey & Thorne provide separate equations for different bank vegetation conditions, hence the range of coefficients.

	Width (W)		Depth (D)		Area (A)	
Study	a	b	c	f	g	h
This Study[1]	1.46	0.52	0.19	0.42	0.28	0.94
Leopold & Maddock, 1953-2[1]		0.50		0.40		0.90^{+}
Hey & Thorne, 1978[2]	2.17-3.98	0.52	0.16-0.20	0.39		0.91^{+}
Nixon, 1959[1]	1.65	0.50	0.55	0.33	0.9	0.83
Wolman, 1955[1]		0.42		0.45		0.87^{+}

Cross-section shape

There is not a significant relationship (Table XI) between channel shape, as described by the width/depth (W/d) ratio, and the percentage of bank materials composed of silt and clay, indicating that other factors play a stronger controlling role in the channel shape. The sample size for the analysis of w/d ratios as a function of silt-clay content is 22, rather than 23 sites, because Northeast Creek has cobble and boulder banks with only a thin mantle of finer sediment and is not included in the analysis.

Table XI. Channel shape (width/depth) vs. stream bank silt-clay content. Bankfull width/depth ratio of classification cross-section regressed against % silt-clay in bank sediments for study reaches at USGS gage stations in Maryland Piedmont. Calculated test statistics (F, se), significance (p), and coefficient of determination (R^2) for least-squares linear regression.

N	Regression Equation	R^2	Se (%)	F	p
22	W/D = -0.17(%Silt-Clay) + 18.52	0.13	446	2.96	NS

Discussion

Schumm (1960) reported a significant and negative relationship between bank silt-clay content and width/depth ratio for 69 streams in the mid-west using a weighted mean percent silt-clay content for the channel perimeter as a whole, based on bulk samples of both bed and bank materials. We did not collect bulk samples of bed materials, precluding a strict comparison with Schumm's findings. Bank silt-clay content ranges from about 5% to 45% by dry weight among the 23 Piedmont sites sampled. A plot (Figure 19) of the Piedmont data with Schumm's data for 19 sites with a comparable range of bank silt-clay content shows an almost complete separation of the two data sets. For any silt-clay content in this range, Piedmont streams have average lower width/depth ratios.

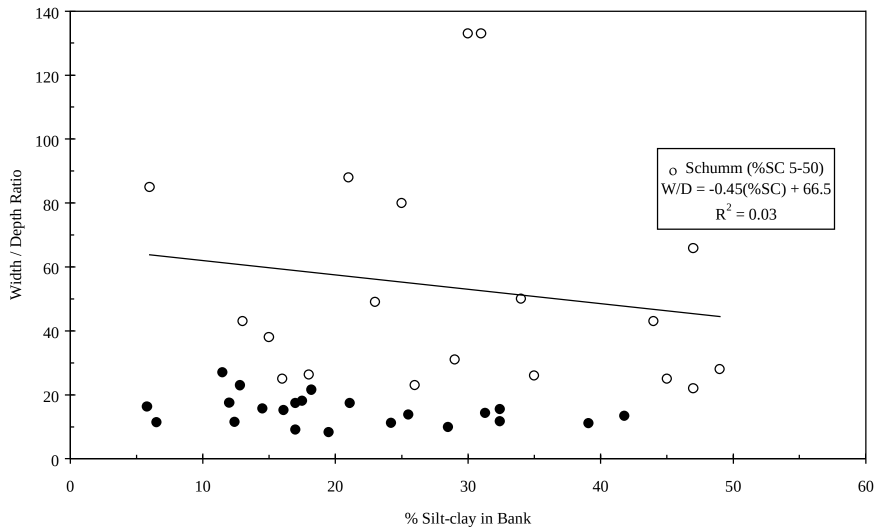

Figure 19. Channel form (width/depth) as a function of bank silt-clay content. Maryland Piedmont data (shown as solid dots) compared with Schumm (1960).

Resistance Relationships

There is a significant relationship between relative roughness (R/D_{84}), and resistance expressed as Manning's "n", with about 75% of the variability in n values explained by the relative roughness of the bed material (Table XII, Figure 20). However, the derivation of both the dependent and independent variable includes the hydraulic radius.

Table XII. Flow resistance as a function of relative roughness. Average flow resistance expressed as Manning's "n", regressed against relative roughness, or R/D_{84}. Calculated test statistics (F, se), significance (p), and coefficient of determination (R^2) for least-squares linear regression.

N	Regression Equation	R^2	Se (%)	F	p
23	"n" = $0.062(R/D_{84})^{-0.20}$	0.75	0.7	44.4	<.001

Discussion

Comparison of the Maryland Piedmont data with the data of Limerinos (1970) from California (Figure 21) and with Hey's (1979) data from Britain (Figure 22) indicates a close correspondence in both cases. For ease of comparison, we have converted the Maryland "n" values to match Limerinos and Hey who express resistance as $n/R^{1/6}$ and as Darcy-Weisbach "f", respectively. To make the comparisons as meaningful as possible, only those sites that fell within the ranges reported by Limerinos and Hey for R, slope, D_{84}, and R/D_{84} were used in the regression analysis; the remaining sites that fell outside these ranges are shown for comparison.

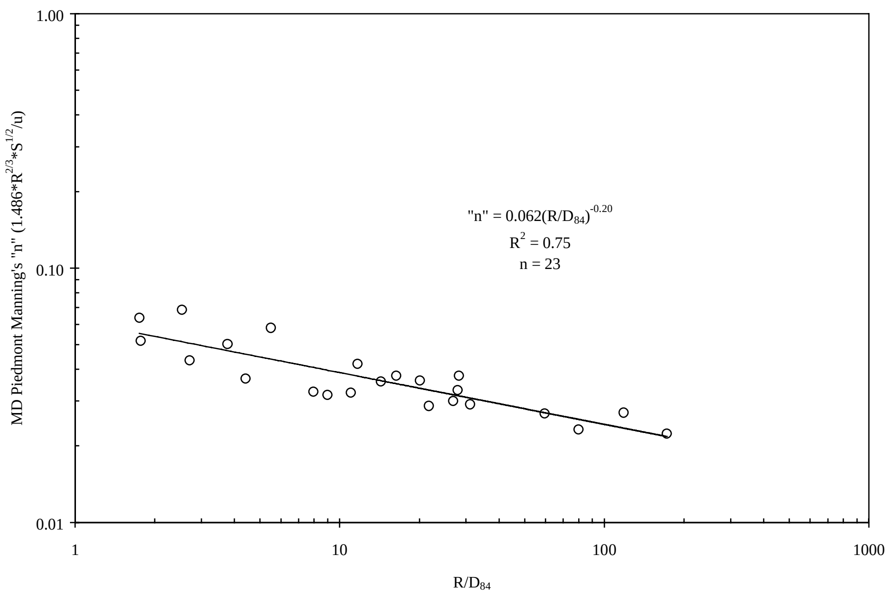

Figure 20. Manning's "n" as a function of relative roughness (R/D_{84}) for Maryland Piedmont survey sites.

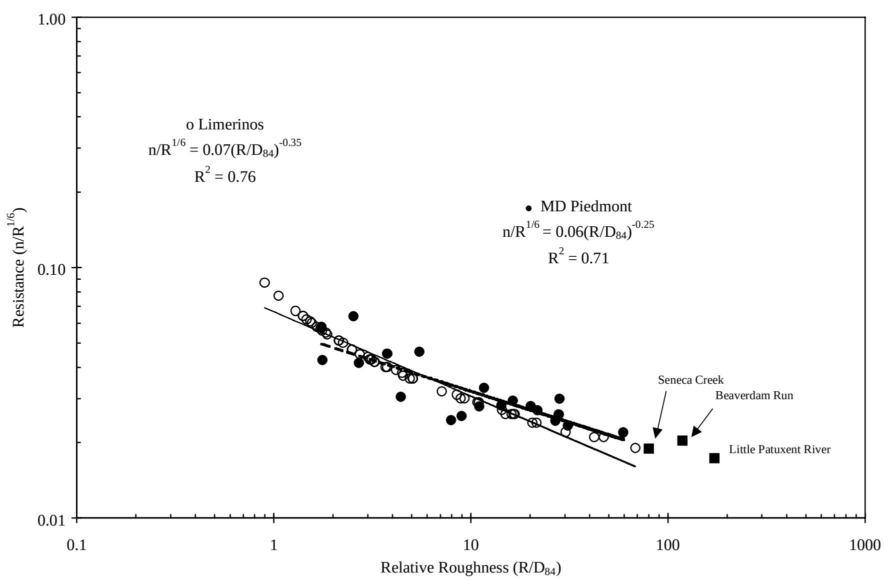

Figure 21. Manning's "n" as a function of relative roughness (R/D_{84}). Maryland Piedmont survey sites compared with Limerinos (1970). Maryland Piedmont samples outside range of Limerinos are labeled and not included in regression analysis.

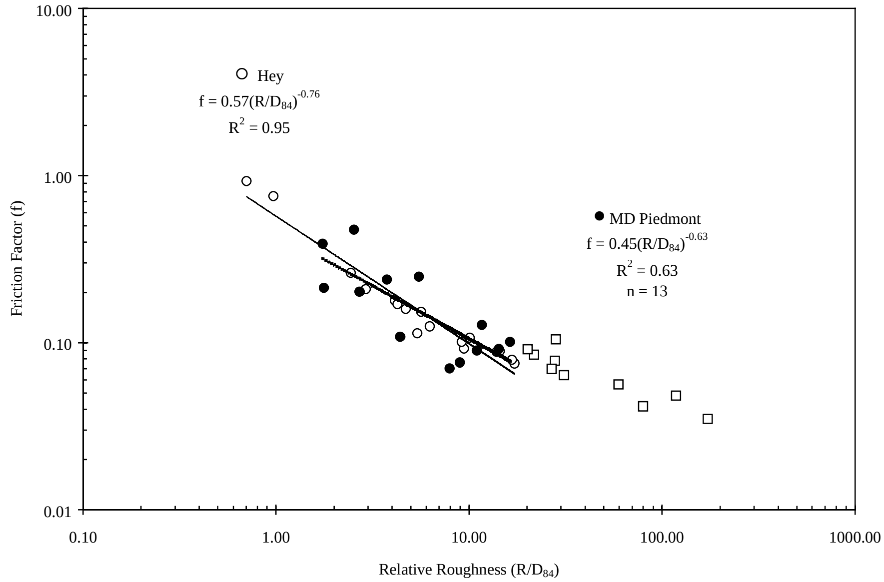

Figure 22. Friction factor as a function of relative roughness. Maryland Piedmont survey sites compared with Hey (1979). Square symbols represent Maryland Piedmont samples outside of Hey's data range and are not included in regression analysis.

Resistance by Stream Type

Rosgen (1994, 1996a) has published a summary of average "n" values by stream type. Because Rosgen did not publish the data, we have estimated the average values from his published figure, and plotted them in descending values of Manning's "n" for comparison with the Maryland Piedmont data for individual stream types and the average and range for groups of stream types (Figure 23). The single Piedmont observation for B4 (0.033) plots near the Rosgen average for this stream type, while the single E4 (0.043) plots slightly above the average values presented by Rosgen for E3/E4 stream types. While Rosgen does not provide values for C type streams with boulder and bedrock bed material, the Maryland Piedmont average (in parentheses, ± 1 sd) (0.058 ± 0.008) plot between B2 and B3 Rosgen stream types. The Piedmont averages for E5 (0.029 ± 0.009) stream types are very close to the average of E5/E6 stream types, C5 (0.026 ± 0.004) and C4 (0.038 ± 0.01) observations indicate a fair amount of variability, and significant divergence from the averages provided by Rosgen. A Mann – Whitney test detected a significant difference (p = 0.02) in "n" values among the C5 and C4 stream types in the Maryland Piedmont.

Rosgen has reported that most of the C4 streams in his data set were larger than the streams we surveyed in the Maryland Piedmont. In our surveyed streams, the combined mean depth for C4 stream types is 3.8 ft with an average "n" value of 0.038 (range 0.027 - 0.069). For C5 stream types the combined mean depth is 4.3 ft with an average "n" value of 0.025 (range 0.022 - 0.029). Upon review of the draft Maryland Piedmont report, Rosgen suggests that until more data are collected, an adjustment of the Manning's "n" values by stream type is warranted for C4 and C5 stream types in the Maryland Piedmont (written commun., 1999). For C4 and C5 streams with average depths less than 4 feet, use 0.038 for C4 and 0.025 for C5 streams. The influence of in-channel riparian vegetation and woody debris can obviously have a large effect on the predicted roughness value.

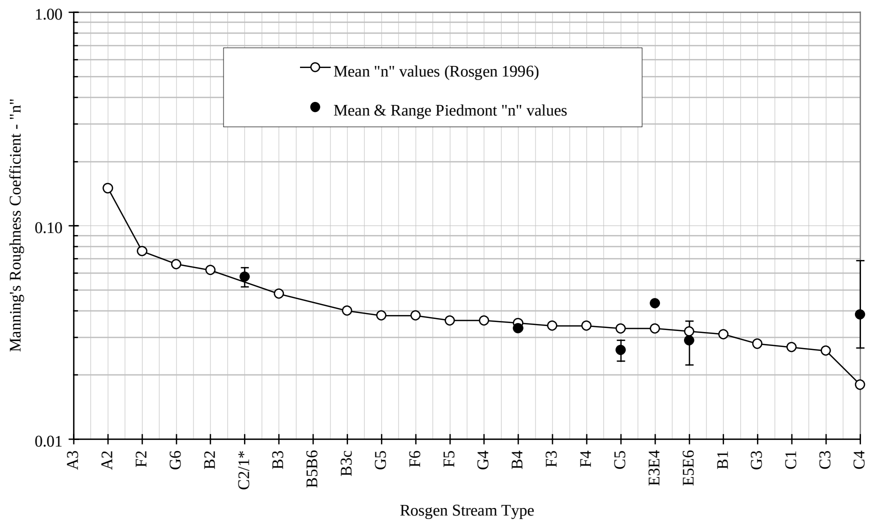

Figure 23. Comparison of Maryland Piedmont survey sites Manning's "n" values with average "n" values by Rosgen stream type (adapted from Rosgen 1996).

Shear Stress

For 23 sites, the calculated average boundary shear stress ($\tau_o = p_w gRS$) at the bankfull stage exceeds the estimated critical shear stress (τ_{cr}) for the D_{50} of the riffle bed material (Figure 24). We selected a value of 0.03 for the Shield's dimensionless parameter in the abscissa based on review of the literature and discussions with several experienced workers (G. Parker and W. Emmett, pers. comm.). Subsequently, we have been made aware of publications that suggest different, larger values would be more appropriate for the Shield's parameter (Buffington and Montgomery (1997) Wilcock (2001)). Nevertheless, in the absence of both empirical data required for estimating the Shield's parameter, and a clear rationale for selecting a specific value, we have elected to retain our original approach. The point of the exercise is simply to develop a coarse estimate of the degree to which the bed materials are likely to be subject to movement at or near the estimated bankfull stage. With these caveats, the comparison suggests that, for those sites plotting above the line of agreement, bed materials are likely mobile at or near the bankfull stage.

Discussion

Most of the study sites had calculated τ_o greater than the estimated τ_{cr} for the D_{50} of the bed material. The low site plotting closest to the line, Big Pipe Creek, appears altered upstream of the gage by channelization. The low τ_o for the observed particle size distribution may be an indication of an incipient shift in sediment transport dynamics at this site. The site plotting with the greatest τ_{cr} is Northeast Creek, has one of the steepest gradients of the 23 sites, 1.7%, and large bed material. The median particle diameter, or D_{50}, is 0.3 feet, while the D_{84} and D_{95} are 1 and 1.7 feet, respectively. Carling (1988) has shown that steep channels with large and armored bed material are susceptible to general mobilization of bed clasts only at flows that significantly exceed bankfull.

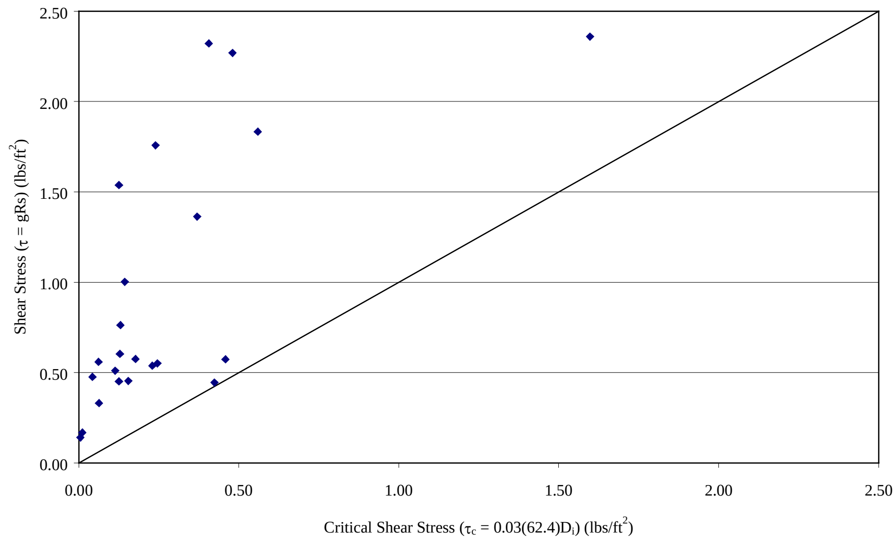

Figure 24. Comparison of estimated average boundary shear stress and calculated critical shear stress.

CONCLUSIONS

- Maryland Piedmont channels can be classified using the Rosgen stream classification system, however, the limited number of independent observations of different stream types at this point in the work prevents us from examining the use of the classification in helping explain some of the observed variability in stream characteristics.

- The northeastern Piedmont may constitute a discrete region with respect to the relationship between drainage area and bankfull discharge. However, more surveys are necessary for a proper statistical analysis.

- There is a well-defined relationship between drainage area and bankfull discharge in the main Piedmont region.

- There are well-defined relationships for Maryland Piedmont streams between drainage area and bankfull channel dimensions, and these relationships compare favorably to those documented by previous workers elsewhere in the Piedmont of the eastern U.S. and nearby regions. The most conservative relationship with drainage area is for cross-sectional area.

- Width/depth ratios are not significantly related to silt-clay content of banks. In general, for a given silt-clay content Piedmont streams have much lower width/depth ratios than the mid-west streams studied by Schumm (1960).

- Variability in the average flow resistance in Maryland Piedmont streams as represented by the Manning “n” is fairly well explained by variability in relative roughness, expressed as R/D_{84}.

APPLICATIONS

Use of Regression Relationships for Design Purposes

Several caveats exist for these relationships, and argue strongly against their use for detailed design specifications.

- Relationships are representative of a restricted range of basin and reach characteristics (e.g. drainage area, geology, land use, etc.) and must be used with caution when applying to streams across the Piedmont.

- Often the gage and study reaches are not the same reaches. Rather to maintain the study reach selection parameters, it is often located upstream of the gage.

- While we do not consider any of the reaches represented here to be in a state of rapid adjustment, we have no information about the relative rates of lateral or down-valley meander migration.

- Relationships are not necessarily representative of "reference reach conditions". We suspect that many reaches in proximity to gages at road crossings were altered at some time in the past by channelization or realignment. These relationships provide no information about ecological parameters, and may not represent "good" habitat conditions. In fact, the low amounts of large woody debris in the surveyed channels are likely an indication of relatively poor habitat conditions.

- Many of these reaches have significant bedrock controls such that general extrapolation of meander and profile patterns to situations lacking such bedrock influence may not be appropriate.

- The range of stream types represented by the data is low, with one to three streams observed in most stream types (B4, C5, C2, E5, and E4), and only C4 stream types well represented with fifteen observations. Several common stream types, such as A2 and B3, often found in geologically confined transitional reaches, are not represented.

- The reaches represented here seem to broadly correspond to the category termed "transport" reaches, in that well developed depositional features such as point bars are not well represented. Imposition of the channel characteristics represented by these relationships on streams in the "source" and "response" categories would likely be problematic.

Given these caveats, the relationships documented here can provide preliminary design parameters for streams with a similar range of discharge, sediment, slope, and entrenchment conditions. However, channel designers need to identify discrete project goals and objectives, with respect to both physical and biological desired conditions, and determine the appropriate design parameters for achieving those conditions. In most cases the best guidance for finer scale aspects of channel design will come from carefully selected reference reaches that closely match the controlling conditions at the project reach, and exhibit those characteristics specifically identified as design objectives. The results of this study may best serve as a guide to the expected range of dimensions for bankfull channels at ungaged reaches.

Recommendations for Phase II

For Phase II of the Maryland Stream Survey, we recommend modifications to channel surveys as follows:

- Surveys will be confined, as much as possible, to a single reach containing the gage, to avoid problems of extrapolation.

- Surveys will consist of longitudinal profiles and cross-sections, and not include meander geometry. This will narrow the focus of the study to relationships between drainage area and bankfull discharge and drainage area and bankfull cross-section. These relationships are intended for primary use as guides to preliminary identification of bankfull channel dimensions at ungaged reaches.

- Surveys will include stream classification, to broaden the base of information for the utility of the Rosgen classification system in partitioning the data.

Recommendations for Additional Surveys

- Once the gage calibration surveys represented by Phases I and II are in-hand, they can be used to facilitate the identification of bankfull channels at ungaged reference reaches selected for particular purposes including biological quality, sediment transport, over-bank discharge frequency, and diversity of fluvial features. This information will provide a foundation for future development of a reference reach database for Maryland streams.

- Surveys of additional sites in the northeastern Piedmont are needed. Although additional active gage sites are not available, discontinued stations with updated stage-discharge relationships would provide useful information regarding the magnitudes of bankfull discharge and channel dimensions.

- Additional observations of stream reaches, and reaches with less bedrock control and perhaps a greater range of bank material composition than was present in this set of study sites, will be necessary to test the ability of Rosgen's system to usefully partition channel types.

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