ABSTRACT

Title of dissertation: EFFECTS OF SCALE AND SPATIAL VARIABILITY ON HYDRAULIC GEOMETRY IN THE POTOMAC RIVER BASIN

Chung Hye Kim Read, Doctor of Philosophy, 2006

Dissertation directed by: Emeritus Associate Professor, Derek Thompson
Department of Geography

Scale issues in hydrology arise because different hydrological processes are dominant at different regional scales. Recent hydrological research suggests that the geographic scale (size) of watersheds may influence the behavior of hydraulic geometry exponents (b and f, but not m values) of stream channels. Hence, the working hypothesis of this study is that variations of hydraulic geometry exponents are not random, but that there are systematic changes as a function of geographic scale as well as of water basin and channel physical and environmental characteristics (predictor variables).

To support this analysis, 43 subbasins in the Potomac River Basin ranging in size from 0.38 square miles to 1,642 square miles and representing a broad spatial diversity of predictor variables within the watershed were selected for study. Research goals were to attempt, via empirical correlations, to discern relationships between a geographic scale factor and b, f, and m values, to investigate the roles of predictor variables on b, f, and m

values, and their statistical significance, and to identify the most influential predictor variables and the complexity of fluvial physical processes via stepwise multi-variable regressions.

Statistical evidence was found that there is a relationship between geographic scale and hydraulic geometry exponents. In every selected predictor variable case, investigation of the correlations between b, f, and m with a single selected predictor variable in a scale context resulted in a noticeable improvement over the correlations of the hydraulic exponents with each individual predictor variable alone. The research shows that, under higher discharges, the behavior of b, f, and m mainly result in higher m and f, with a slight increase in cross-sectional area (f with negative b) in a scale context.

EFFECTS OF SCALE AND SPATIAL VARIABILITYON HYDRAULIC GEOMETRY IN THE POTOMAC RIVER BASIN

by

Chung Hye Kim Read

Dissertation submitted to the Faculty of the Graduate School of the University of Maryland, College Park in partial fulfillment of the requirements for the degree of Doctor of Philosophy
2006

Advisory Committee:

Emeritus Associate Professor Derek Thompson, Chairman/Advisor
Professor Ralph Dubayah
Professor Glenn E. Moglen
Professor Karen L. Prestegaard
Professor John R. Townshend

ACKNOWLEDGEMENTS

Completion of this research work would not have been possible without the active support over several years by my advisor, Dr. Derek Thompson. Although he is an excellent teacher and advisor, I am not the best student. I cannot thank him enough for his patience, encouragement, guidance and support.

I also wish to thank my committee members at The University of Maryland who assisted me on an array of technical issues as they arose. Dr. John Townshend for helping me conceive of and shape this research. Dr. Ralph Dubayah for helping me master SPlus to prepare data for numerous analyses. Dr. Glenn Moglen for helping me to develop a more mathematical approach to the geographic scale problem. Dr. Karen Prestegaard for helping me focus on data validity and fluvial geomorphology.

Special acknowledgement and thanks go to a number of offices and individuals of the U.S. Geological Survey who provided much of the baseline data, without which, this study would not have been possible. The USGS National Mapping Division provided all the DEM data; Water Resources Division offices in Baltimore and LaVale, Maryland and Richmond and Charlottesville, Virginia provided published and unpublished field notes of discharge measurements data. Mr. John Brakebill, Water Resources Division, Baltimore office provided GIS data. Dr. David Wolock, at Lawrence, Kansas provided numerous suggestions on concepts of topographic index calculations.

Also, thanks for hydrographic survey information are due to Mr. Ronny Lawson of the Virginia Department of Environmental Quality at Charlottesville.

I also am particularly grateful to my professional colleagues, Mr. Robert Hair and Mr. Michael Thomas, for their considerable hands-on statistical and geospatial support and for their suggestions on handling the gigantic volume of data.

My thanks, also, to my husband, Randy, for his unwavering support for my ambition to succeed. Finally, I want to dedicate this study to my Mother and Father who encouraged me that I could do anything if I set my mind to it.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION: Channel Properties and Hydraulic Geometry

1.1 Research Context

River channel research published over the last fifty years, since Horton's (1945) study of the relationships of stream length and stream number to stream order and Hack's (1957) work on the possible relations between the channel geometry and erosion processes, has focused on understanding the interactions between river mechanics and river morphology. Such research has produced a wealth of empirical information about the hydraulic geometries of different types of river channel systems and has developed a better understanding of stream flow and sediment transport processes in channels (Richards, 1982). The ultimate goal of much of the research in the second half of the twentieth century was to develop a physically based model to explain the morphological evolution of river systems over different space and time-scales.

The responses of channels to hydraulic dynamics like stream flow velocity and hydraulic geometry, channel width and depth, to changes of stream discharge are known to share certain characteristics which apply to many natural river cross-sections. These characteristics are important determinants of the shape of a channel at a cross-section and in the progressive changes in cross-section channel shapes downstream.

The term hydraulic geometry was introduced by Leopold and Maddock (1953) to describe the ways in which channel characteristics of width, depth, and velocity vary with stream discharge. In essence, hydraulic geometry is an empirical model expressing the changes in channel and hydraulic variables as simple power functions of discharge. The resulting hydraulic geometry equations have the form:

$$w = aQ^{b} \qquad (1)$$
$$d = cQ^{f} \qquad (2)$$
$$v = kQ^{m} \qquad (3)$$

where Q is the discharge in cubic feet per second; w is the channel width; d, the channel depth; v is the stream flow velocity; and a, c, k, b, f, and m are numerical constants. The numerical constants, a, c, and k are intercepts for width, depth, and velocity and increasing discharge relationships. Since this research is focused on the rates of change in width, depth, and velocity with changing discharge (not with time), b, f, and m constants are the subject of this research rather than a, c, and k. The intercepts are more dependent on local settings, but b, f, and m slope lines are more indicative of the trend and nature of channel interactions with various predictor variables. It follows that any spatial or temporal change in discharge must be accommodated by a suitable combination of changes in channel width and depth and stream flow velocity.

Since the aim of hydraulic geometry research is to describe and predict these changes, and because the exponents b, f, and m provide quantitative descriptions of rates of change, their variations can provide insight into relevant controlling conditions and maybe even the role of geographic scale. The quantitative description of how river width, depth, and velocity vary with changing discharge can be explained by, over time, at one site (at-a-station), or along and between rivers at a comparable discharge frequency (downstream hydrographic geometry).

At-a-station hydraulic geometry concerns the response of flow hydraulics at a channel cross-section to varying imposed flows. For a given imposed discharge, the problem is to determine how channel width, depth, and flow velocity vary with, respond to, or accommodate the changed stream discharge volume. Channel adjustments are reflected in the numeric values of the hydraulic exponents, b, f, and m. At any one time and place these variables are interrelated by the mass continuity equation:

$$Q = wdv \qquad (4)$$

Throughout this dissertation, the expression of the rates of changes in b, f, and m are with respect to discharge and not to time. That is, d (w, d, v)/dQ not d (w, d, v)/dt.

Examining at-a-station hydraulic geometry relationships as a function of drainage area characteristics is different than examining downstream hydraulic geometry relationships. At-a-station hydraulic geometry, which is the focus of this research, and downstream hydraulic geometry, differ in that at-a-station compares flows of vastly different frequencies while downstream hydraulic geometry analyzes variables at the same frequency of Q, even though the absolute values in cubic feet per second (cfs) units are different. The most meaningful discharge for any analysis of channel morphology is the one that forms or maintains the channel. The concept of downstream hydraulic geometry involves spatial variation in channel form and process at a constant frequency of flow. At-a-station hydraulic geometry involves temporal variation, but is spatially invariant (a fixed point on a channel).

Although hydraulic geometry deals specifically with only three parameters, many other morphologic and dynamic factors are considered implicitly because they influence these three elements of continuity. Thus, the equations of hydraulic geometry provide a simple summary of the complicated relations among stream channel and flow characteristics.

Subbasin morphology and hydrological processes are linked through the geomorphic development of a subbasin. Current morphology often acts as a dominant control on water flow paths and current hydrological processes, resulting in changes in landscapes. Therefore, studies of the relationships between morphology and hydrological processes can be a clue to understanding geomorphological changes in a subbasin.

Ferguson (1986) showed that the cross-sectional shape of a channel determines the rate of increase of stream width with depth, whereas the laws of flow resistance determine the rate of increase of mean velocity with depth. In turn, factors that affect channel geometry include vegetation (Hadley, 1961; Zimmerman et al., 1967), bank cohesiveness and sediment size (Schumm, 1960; Wolman and Brush, 1961; Knighton, 1974; Maizels, 1988), changes in suspended load (Leopold and Maddock, 1953; Wolman, 1955; Thornes, 1970), seasonal variation (Thornes, 1970), channel sinuosity (Knighton, 1975), channel roughness or flow resistance (Knighton, 1975), riffle spacing (Harvey, 1975; Prestegaard, 1983), the processes of scour and fill (Foley, 1978; Andrews, 1979), and stream size and order (Thornes, 1970; Miller and Onesti, 1977; Leopold, 1994). All of these stream parameters are candidates as covariates of the hydraulic exponents. However, many of these previous research efforts dealt with the correlations of candidate predictor variables to hydraulic geometry individually, not as collective variables to explain hydraulic geometry synergistically.

The fact that hydraulic geometry, specifically at-a-station hydraulic geometry, is notoriously unpredictable in a deterministic sense, but demonstrates clear regularity and a degree of predictability in an aggregate probabilistic sense is described by Leopold and Maddock (1953), Williams (1978), and Phillips (1990, 1991, 1995). Richards (1977) stated that "geographical patterns in the at-a-station exponent set may occur, but inter-regional differentiation is obscured by the more direct influence of bed and bank material."

Physical geographers and engineers have long been aware that landscapes are comprised of nested hierarchies of geomorphic systems and sub-systems at all scales. Sugden and Hamilton (1971), and O'Neill (1988) suggested that scale may be used as a framework for analysis because "by focusing on systems functioning at particular scales one can minimize 'background noise' emitted by systems at different scales." Kennedy (1977) proposed that establishing geomorphological theory necessitates developing an understanding of the rules linking process and form at different temporal and spatial scales.

An appreciation of scale effects was viewed as essential to overcome the disparities in spatial and temporal scales used in the different disciplines concerned with global environmental change by Roswall et al. (1988). The levels of certainty or rules deemed acceptable at one scale are not necessarily appropriate at another scale. This problem emphasizes the need to clearly define the spatial and temporal domains of geomorphic theory. Except for Penning-Rowsell and Townshend's (1978) study of the factors influencing stream channel slope, which found that a change in spatial scale caused a change in relative importance of different factors, and besides Leopold's (1994) comparison of b, f, and m values in three different river sizes, and Griffith's work (2003) on downstream hydraulic geometry and hydraulic scaling, few studies have shown the effects of spatial scale on fluvial geomorphology, specifically for at-a-station hydraulic geometry.

To understand a geomorphic system one does not have to consider every level of scale since, depending on the scale of the system and the objective of the investigation, certain levels will be dominant whereas others play a secondary role and can be ignored (de Boer, 1992). This statement raises questions such as: what are the significant levels of scale for the investigation of a specific problem; how can knowledge about the functioning of a geomorphic system at one scale be extrapolated to a system at a different scale; or can it be extrapolated to a system at a different scale at all.

Since the late 1980's, numerous stream channel research studies have revealed that hydrological processes and channel parameters exhibit considerable spatial variability, particularly with respect to scale, yet there have been no evaluations of spatial and temporal variability, that this author is aware of, as measured on at-a-station hydraulic geometry and considering the total spectrums of environmental parameters which may influence hydraulic geometry.

1.2 Research Objectives, Hypotheses, and Scope

This study investigates the role of watershed variables including geographic scale on the at-a-station hydraulic geometry exponents in selected subbasins of the Potomac River.

The main objectives are: a) to determine whether at-a-station hydraulic geometry changes significantly with watershed scale (which is manifested by the size differences of each subbasin area); and b) to determine whether watershed variables such as physiography, topography, lithology, geomorphology, landuse, channel pattern, channel shape, and bed and bank materials, affect the size and shape of stream channels and, thus, the at-a-station hydraulic geometry.

The working hypothesis for the first objective is that variations in each of the hydraulic geometry exponents are not random but that there are systematic changes as a function of watershed scale. In other words, there is a geographic scale impact on hydraulic geometry exponents such that b, f, and m in Amazon-size rivers are different from those of smaller rivers. This might explain why hydraulic geometry has different b, f, and m values where all other basin variables are the same or similar.

Even though width is the dominant variable in downstream hydraulic geometry and that there are interrelationships between at-a-station and downstream hydraulic geometry, the expected changes in the at-a-station hydraulic geometry as a function of scale is that channel width does not change much, depth increases rapidly, and flow velocity change rates will also increase.

A set of working hypotheses for the second objective is that particular watershed variables individually influence channel morphology by affecting stream discharge and sediment characteristics such as the size and amount of sediments delivered to the channels. Most researchers have assumed that watershed variables influence channel morphology by affecting the discharge and the sediment characteristics such as size and amount delivered to the channels. However, most previous work has not examined direct links between channel morphology and watershed variables. Given this, I am not postulating any different level of importance of the particular watershed variables to be used in this research.

In brief, previous research and literature that are relevant to this investigation, including hydraulic geometry in light of hydrogeomorphological and hydraulic engineering perspectives as well as in theoretical and empirical approaches are described in Chapter 2.

The expected correlations for b, f, and m with **watershed physiography** and **lithology** are that in the most easily eroded bank and bed physiography regions, increased rate of changes in width and depth of channels are expected resulting in higher values of b and f.

The expected correlations for b, f, and m with **watershed landuse** are that in agricultural areas the rate of changes in width and depth will increase higher and rate of change in flow velocity will be lower. It is also expected that b and f changes will be greater for agricultural areas than that of forest areas. The rationale is that, in agricultural areas, increased water discharge flows through plowed agricultural fields carrying more suspended and bed load material and has greater erosional impacts on channel beds and banks. On the other hand, in forest landuse areas, increased volumes of discharge occur after ground water saturation; therefore, the discharge would be more or less free of sedimentation compared to agricultural watersheds. That is, it is expected that watersheds in agricultural areas are more susceptible to erosion than those in forest areas. The expected changes in m would be the reverse because the increased bed or suspended load in stream discharge will reduce the flow velocity.

The expected correlations for b, f, and m with **channel pattern** are that in straight channels, b values are lower than those of f; in meandering channels, relatively higher rates of changes in width than those of depth. The rationale for these expectations is that straight channels are typically symmetrical and meandering channels are normally asymmetric in cross-section at the bends. Asymmetry provides for a relatively greater rate of increase in width, but f will probably still be greater than b. Braided channels are typically broad and shallow because of the unstable nature of their banks and the width-depth ratio commonly increases with increasing discharge.

Based on Rhodes' research (1977), the expected correlations between **channel shape**, which is categorized by visual inspection of each subbasin cross-section profile, and b, f, and m are rectangular channels which will have the lowest b values, parabolic channels which will have $b = f/2$, triangular channels which will have $b = f$, and braided channels which will have $b > f$.

The expected correlations for **channel asymmetry** and b, f, and m are that a positive, stronger relationship between b and asymmetry is expected compared to the correlationships of f and asymmetry or m and asymmetry. That is because when the thalweg of channel moves from the center of the channel, the width of the channel will inevitably change. And, since stream power is consumed in the widening of the channel, the m value must be reduced.

Based on Bathurst's research (1993), the expected correlations between **bed material** and b, f, and m are that the flow velocity increases as the bed material size increases such that, for sand-bed channels, $m < 0.40$; for gravel-bed channels, $m = 0.35$ to 0.45; and for boulder-bed channels, $m = 0.45$ to 0.55.

The expected correlations for **bank material** and b, f, and m are such that the value of the change in b will become larger in sequence from the least to the most resistant bank material: sand, gravel, cobble, and rock. In easily eroded channel banks, with the eroded bank material in the discharge, the rate of depth and flow velocity changes would be much less than b values. So that in easily eroded banks, such as sand banks, a relatively wide shallow channel develops, while in cemented bank materials (silt), the channel becomes deeper and narrower. As streams begin eroding their banks, their channel cross-sections become wide and shallow with consequent reductions of flow velocities.

Regarding topography (ln area/tanβ indices), expected correlations for topography and b, f, and m are such that b will be higher in areas of higher **topographic index** values which are reflective of wide floodplains and areas of increased runoff due to soil saturation. Steep valley areas reflect low topographic index values. In area of low topographic index values, the rates of change in depth and flow velocity will be less than the rate of change in width.

In order to undertake sufficient analysis for addressing the research questions, the thesis will, as a practical matter: (1) investigate rate of changes in width (b), rate of changes in depth (f) of channel, and rate of changes in velocity of channel flow (m) to changing discharge volumes; (2) determine correlations between scale and b, f, and m; (3) determine correlations between individual watershed controlling variables with b, f, and m and with the scale variable; and (4) investigate the total effects and role of watershed controls on at-a-station hydraulic geometry.

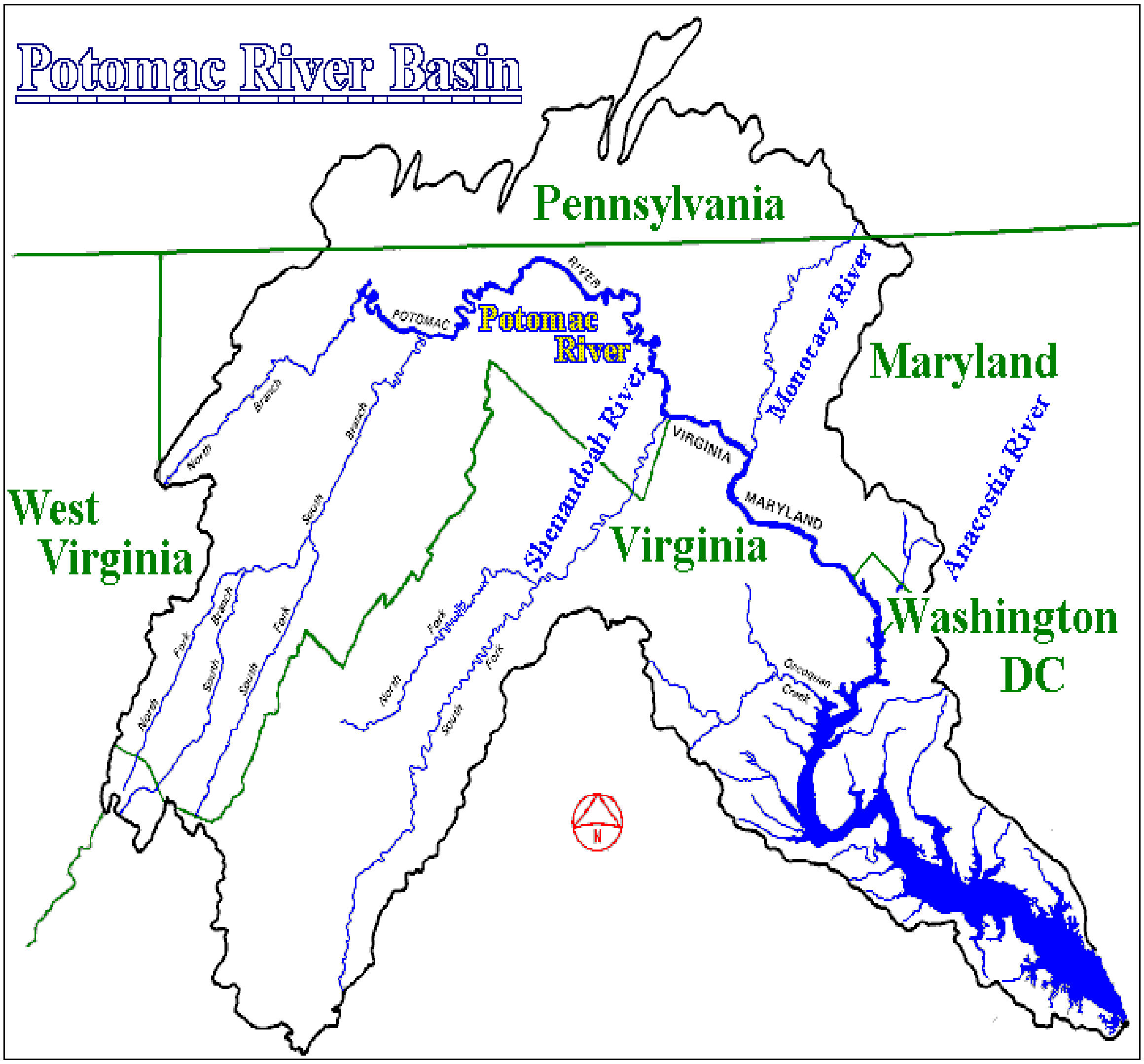


Figure 1.1 Study Area - Potomac River Basin
Source: US Geological Survey Water Resources Investigations Report 96-4034

1.3 Approaches for the Empirical Investigation

In order to accomplish the investigation, the Potomac River Basin was selected as the study area due to its ready access by the author, the variability of spatial watershed settings such as wide ranges of physiography, geology, lithology, etc., and the plethora of information on this area such as high resolution digital elevation data and hydrographic survey data.

The study area consists of 43 Potomac River subbasins sampled over a 10-year period, 1985-1995 as shown in Figure 1.1. The primary data are USGS Water Resource data and digital elevation model (DEM) data supplemented by numerous field surveys by the author. Using primary data, many derived measurements data such as drainage delineation, nested subbasins, topographic index, hydraulic geometry, channel asymmetry, channel pattern, channel shape were created by the author for this hydraulic geometry investigation and analyses. The study area is discussed in Chapter 3 and data (primary and derived) are discussed in detail in the Chapters 4 and 5.

The first part of the research was to identify Potomac River Basin stream channels most representative of the spectrum of subbasin sizes, the various Potomac River Basin physiographic settings, and the channel patterns and shapes as well as a hierarchy of channels feeding to bigger streams. The channels selected included those with a high number of hydrographic survey measurements at the same location along the channels in the Potomac River Basin. After study stream channels were identified, required primary data types and sources were identified and data were obtained from the USGS Water Resource Division Offices and Virginia Department of Environmental Quality in Baltimore and in La Vale, Maryland, and in Charlottesville and Richmond, Virginia. This data source is described in detail in Chapter 3. In some cases, the author accompanied USGS hydrographers on stream measurement surveys to acquire first hand familiarity with data collection methods and the survey sites. In addition, the author visited study sites and made numerous field observations to validate and verify channel bank and bed material information as well as environmental setting information and other reported channel characteristics.

For the preparation of data to perform the investigation and analyses, the hand-written survey measurement data, of USGS hydrographers' such as width, depth, and velocity data across a channel in segments, were digitized. The hydrographic surveys chosen for the study have, on average, width, depth, and velocity data in 30 segments across each channel cross-section per survey. Each of the 43 channels had an average of 30 surveys over the ten-year study period. The digitized data were then used to calculate channel pattern and shape and draw channel cross-section profiles. In addition, with the USGS's Maryland Index to Topographic and other Map Coverage, and that of Virginia, all topographic maps at 1:24,000 scale for the 43 subbasin areas and the DEMs (7 ½ minutes by 7 ½ minutes area by 30 meter post spacing data) which fall within these subbasins were identified and acquired from the USGS. The DEMs were merged using ARC/INFO™ and IMAGINE™ software for the preliminary drainage delineation and topographic index calculation. Due to the large scale of the topographic maps, not all needed DEMs were identified at first; more DEMs were identified and merged during the delineation of the subbasin boundaries. Preparation and processing of DEMs for subbasin boundary delineation are described in detail in Chapter 4. The delineation of drainage boundaries (subbasin boundaries) and calculation of subbasin sizes, hydraulic geometry, and topographic index, which is the key component of the topography-based TOPMODEL and defined as ($a / \tan \beta$) where a is the area draining through a point from upslope and $\tan \beta$ is the local slope angle, mid-point of the cross-section of channel width, width and depth ratio, and channel asymmetry and visualization of hydraulic geometry on an equilateral triangle (ternary diagram) are described in detail in Chapters 4 and 5.

To explain the hydraulic geometry in terms of hydraulic processes of b, f, and m, the temporal changes of the study area streamflow were used and these historical stream discharge volume data in histogram form came from downloading from the USGS's home page, Waterdata site, for each of the 43 gage stations for the study duration (1985-1995). Hardcopy descriptions of the 43 gage stations were also used to characterize each subbasin. The environmental settings, such as lithology and physiography, and needed primary and derived data are described in detail in Chapters 3 and 4.

To address the objectives, prior to the analyses, first the subbasin boundaries were delineated and stream flow directions identified. Also, the sizes of the subbasins were calculated and nested subbasins were identified for the relationships among these 43 subbasins. Secondly, hydraulic geometry exponents for width, depth, and velocity change rates with changing discharge volume were calculated using log regression. Thirdly, to amplify the nature of the width, depth, and velocity exponents, these values were plotted on a ternary diagram to present b, f, and m graphically and the location of the study area hydraulic geometry on the ternary diagram was divided into regions based on hydraulic principles and hydraulic geometry researchers' empirical data. Fifthly, to characterize the subbasins, channel cross-sections by profiles, mid-points of the channel widths, and channel asymmetry were generated.

A series of analyses intended to characterize b, f, and m (predicted variables), and show their relationships to predictor variables were conducted. The predictor variables for b, f, and m are continuous and categorical explanatory variables. Continuous explanatory variables used for the analyses are subbasin size (scale), channel asymmetry, topographic indices such as minimum, topographic index maximum, topographic index mean, and topographic index standard deviation, and various width to depth ratios such as the ratio of depth values associated with the widest width, depth value associated with the narrowest width. Categorical predictor variables are physiographical characteristics of the 43 individual subbasin areas, lithology of the 43 individual subbasin area, land use, channel pattern, channel shape, bank material, and bed material.

The following statistical analyses were performed (see Chapter 6) to investigate relationships between b, f, and m and the selected predictor variables:

(1) Descriptive statistics for b, f, and m and analysis of the b, f, and m values;

(2) Correlation between the geographical scale variable and b, f, and m, including hypotheses testing;

(3) Relationships between b, f, and m and the predictor variables such as phys1, litho1, landuse1, channel bed material, channel bank material, channel asymmetry, topographic index, channel pattern, and channel shape individually;

(4) Correlation between b, f, and m and each predictor variable in the scale context and the probability that correlations are statistically different from zero;

(5) Relationships between b, f, and m and predictor variables with interaction between geographical scale and predictor variables; and

(6) Linear regression analysis for which each predicted variable (b, f, and m) is regressed onto all predictor variables separately using stepwise regression.

Characteristics of the hydraulic geometry of each of the 43 subbasins and a subset of 23 well and moderately constrained subbasins are discussed in terms of hydraulic principles and empirical hydraulic geometry values. In conjunction with these statistical analyses, the roles of each of the predictor variables were investigated without and with scale context. Statistical analyses established the relationships between the rate of changes in channel width, channel depth, and stream flow velocity and predictor variables in the scale context. Also, statistical analyses identified the best predictor variables for estimation of the b, f, and m values.

CHAPTER 2

PREVIOUS STUDIES: How Important is Geographical Scale?

2.1 Introduction

This chapter provides a brief history of how at-a-station hydraulic geometry became one of the main research themes for understanding channel form and stream processes and describes previous research on at-a-station hydraulic geometry in general. These previous studies are cited to show: pioneering models developed to calculate the rate of changes in width (b), depth (f), and velocity (m) in accordance with the changing discharge; how to present and analyze the exponents of b, f, and m; what parameters were used to explain b, f, and m; as well as what other hydraulic processes might explain b, f, and m values in this study of Potomac River stream channels. At the end of each section, the author's approach and needed areas for further investigation are discussed.

In part because Roswall et al., (1988) stated that an appreciation of scale effect is essential to overcome the disparities in spatial and temporal scales used in different disciplines, the author initially considered investigating the geographical scale effects as a major predictor variable in hydraulic geometry. Even though stream hydraulic geometry, which deals with hydraulic geometry changes as a stream flows throughout the system, traversing many scales, can better investigate scale effects than at-a-station hydraulic geometry, the author hypothesized that there is a systematic geographical scale effect on at-a-station hydraulic geometry exponents. Hence, in this study, each predictor variable is investigated as a singularity and with the scale variable. This way the impacts of predictor variables of notoriously unpredictable at-a-station hydraulic geometry (Phillips, 1995), and Williams (1978)) are investigated with equal weight and with a geographical scale factor.

2.2 Automated Drainage Delineation

Watershed hydrological studies often begin with the generation and analysis of basin hydrogeomorphological features such as basin boundaries, stream networks, and slope and aspect maps. These hydrogeomorphological features are traditionally derived from topographic maps. Interpretation of drainage boundaries involves physically drawing a dividing line between two or more drainage basins on a topographic map. Basically, this means determining which direction the water flows from the highlands to the lowlands. Where the contour intervals are close together, which indicates appreciable relief, determining the divide is fairly easy. However, when the slope gradients are small as in a flatland area, interpretation becomes more difficult.

With the advent of modern computing techniques and data known as digital elevation models (DEMs), it has become possible to develop tools for the extraction and manipulation of components of river network systems (O'Callaghan and Mark, 1984; Band, 1986; Jenson and Domingue, 1988). Snell and Sivapalan (1994) have extended the work on the extraction of the catchment width function, to an automated extraction of the catchment area-distance function, the catchment area convergent to a specific flow distance from the outlet. There currently exists a suite of algorithms that automatically extracts basin hydrogeomorphology from DEMs (O'Callaghan and Mark, 1984; Band, 1986; Jenson and Domingue, 1988; Tarboton et al., 1991; Martz and Garbrecht, 1993; Tarboton, 1997).

Many researchers (Mason, 2000; Azagra, 1999; Wolock, 1996) demonstrated that the accuracy and detail of the hydrologic information which is automatically extracted from a DEM is directly related to the quality and resolution of the DEM itself. Since DEM data often contain subtle and striking errors like spikes, these errors can bias subbasin boundary and channel flow direction identification.

A depression filling procedure developed by O'Callaghan and Mark (1984) finds watersheds for cells that have no neighbors lower in elevation, identifies cells lower in elevation than the lowest boundary elevation for their watershed, and encodes these cells as being flat for use in the basin delineation process. A flat area is assigned in its entirety to the first watershed that touches it. This procedure does not include logic for finding looping depressions such as might occur when many depressions are located on a surface that is relatively flat. Jenson and Domingue (1988) developed an algorithm which follows depressions and fills the depressions first and treats these areas as flat areas where water can be routed. Their algorithm compares the elevations of its eight neighboring cells, and the steepest down-slope direction is assigned to each cell in the grid. Directions are also assigned to grid cells in flat areas to provide a continuous path from all cells in the watershed to the outlet of the watershed. This is accomplished by finding the neighboring cell with the steepest downslope direction and assigning that direction to the flat area cell. This algorithm is incorporated into ARC/INFO™ as part of that software's Surface Hydrologic Model. Under the guidance of Maidment (1994), ARC/INFO™'s Surface hydrologic model is widely used by the Center for Research in Water Resources at the University of Texas at Austin and where more than a dozen research papers are produced a year. In these research papers, there are many discussions of the resolution of the DEM data being used for flow direction identification and flow accumulation. The author used the ARC/INFO™'s Surface hydrographic analysis package which is commonly used by most of the hydrographic research workers, and the finest resolution DEM data over the Potomac River Basin area, for the delineation of subbasin boundaries and flow accumulation calculations.

Topography is recognized as an important factor in determining the stream flow response of drainage (Kirkby and Chorley, 1967; Dunne et al., 1975; Beven and Wood, 1983). A steeper slope results in greater energy - therefore the shape of a surface determines how water will flow across it. The author considered the topographic index as one of many predictor variables for this hydraulic geometry investigation.

Since the inception of topographic index concepts by Beven and Kirkby (1979) and by O'Loughlin (1981), the topographic index has become an important hydrologic modeling component because it reflects the spatial distribution of runoff generation processes (Zhang and Montgomery, 1994). The topographic index facilitates many hydrological simulations, most notably TOPMODEL (Beven and Kirkby, 1979; O'Loughlin, 1981; Moore et al., 1991; Wolock, 1993).

The topographic index, which represents "saturation" potential, is a function of the upstream contributing area and the slope of the landscape. In areas of no slope, the topographic index is obtained by substituting a slope of 0.001. This value is smaller than the smallest slope obtainable from a 30 m data set with a 1 m vertical resolution. The topographic index is calculated as $\ln(a/\tan\beta)$ which is the essence of the upslope area, as divided by surface slope gradient ($\tan\beta$). This approach was originally derived independently by Beven and Kirkby (1979) and by O'Loughlin (1981).

As in research on stream flow direction determination, elevation data resolution is continuously an issue in topographic index calculations. There has been considerable research on the impact of DEM data resolution for the calculation of the topographic index (Wolock, 1997; Thompson et al., 2001). It has been concluded that the finer horizontal and vertical resolution DEM data result in the more accurate topographic index values (Wolock et al., 2000; Wolock, 1997; Moore et al., 1991; Wolock et. al., 1995). Also, for the calculation of the topographic index in TOPMODEL, single flow direction versus multiple flow direction algorithms are being debated (Wolock, 1995 and Thompson et al., 2001). The single flow direction algorithm is based on Jenson and Domingue (1988); the multiple flow direction algorithm uses one set of computations for sloping areas in the watershed (grid cells with one or more downslope neighboring cells) and another set of computations for flat areas (Wolock et al., 1995). The comparison of the topographic indices computed from a single flow direction versus multiple flow direction algorithm revealed that the multiple flow direction algorithm results in a higher mean value ln (a / tan β). That means that probably the multiple flow direction algorithm provides higher mean values of the ln (a), since the calculation of the slope of the local angle (tan β) will be the same in both algorithms (Wolock et al., 2001).

However, many hydrological model users assumed that the areas within the basin possessing the same value of the topographic index would behave, hydrologically, the same, regardless of their location on the landscape. After many years of use of topographic indices and hydrological models, many efforts over the last several years have focused more on alterations of the form of the topographic index and on improvements in the methodology for computing the indices (Hornberger and Boyer, 1995).

Also, the assumption that the areas within the basin possessing the same topographic index value would behave hydrologically the same, regardless of their location on the landscape is debatable. The author believes that there are many topographic and spatial variabilities which could be a predictor variable for b, f, and m. As an example, Dubayah (1992) linked a radiation transfer algorithm with both satellite reflectance and digital terrain data to model the spatial variability in net solar radiation for FIFE (First ISLSCP Field Experiment, where ISLSCP is the acronym for International Satellite Land Surface Climatology Project). In this prairie environment, Dubayah (1992) concluded that topographic variability was the dominant factor affecting the variability of net incoming radiation. Blöschl et al. (1991) consider the topographic effects on radiation distribution and use this information to compute spatio-temporal patterns of snow accumulation and melt in an alpine basin.

2.3 At-A-Station Hydraulic Geometry

Leopold (1994) stated that one of the surprising characteristics of rivers is that each cross-section, on any river, has been shaped and dimensioned over time to accept a range of flows. He also stated that there is a consistency from one river to another, and from one cross-section to another, in the way in which the hydraulic parameters change from low flow to high flow.

It is easy to visualize that water depth increases as discharge in a river increases. But what happens to water velocity or river width is not so intuitively obvious. Hydraulic geometry is a way of describing these changes in quantitative terms. At a river cross-section, as discharge changes, the following generalities usually hold (Leopold, 1994):

- Both depth and velocity increase substantially with increasing discharge, and at about the same rate;
- Width increases slightly with discharge;
- Channel flow resistance or hydraulic roughness, which can be defined as Manning's roughness equation that is: $v = 1.486\ d^{2/3}\ s^{1/2}/n$, where s is water surface slope, n is Manning roughness coefficient, decreases slightly with increasing discharge; and
- Suspended load increases rapidly with discharge, and at a much higher rate than any other parameter.

On a given day, for example, a large flood with high w, d, and v values may be occurring in an upstream reach while flow conditions far downstream are normal. A comparison of the hydraulic variables in these two widely divergent frequencies of flow would be misleading. Obviously the frequency of the discharge must be considered for any observations to be valid.

Examining at-a-station hydraulic geometry relationships as a function of drainage area characteristics is different than examining downstream hydraulic geometry relationships. At-a-station hydraulic geometry, which is the focus of this research, and downstream hydraulic geometry, differ in that at-a-station compares flows of vastly different frequencies while downstream hydraulic geometry analyzes variables at the same frequency of Q, even though the absolute values in cubic feet per second (cfs) units are different. The most meaningful discharge for any analysis of channel morphology is the one that forms or maintains the channel. The concept of downstream hydraulic geometry involves spatial variation in channel form and process at a constant frequency of flow. At-a-station hydraulic geometry involves temporal variation, but is spatially invariant (a fixed point on a channel).

Engineers and hydrologists frequently are required to estimate flow characteristics at un-gaged sites. Conventional techniques have used relations between flow characteristics and physical characteristics of drainage basins, such as drainage area, to transfer information to the un-gaged sites. Understanding the relations between flow characteristics and stream-channel size offer a promising alternative (Wahl, 1984).

Methods of quantifying the interrelation between flow characteristics of rivers and channel size have developed only in recent years. The regime concept, as originated by Kennedy (1895) and Lindley (1919) and discussed by Leliavsky (1955), developed empirical relationships for the hydraulic properties of stable canals in India and Pakistan. However, this method was not extended to natural rivers in the United States until half a century later.

A channel is considered to be in regime if it can accommodate its flow for one or more years without a net change in its hydraulic characteristics (Blench, 1969). Within that period, scour or deposition may occur, in either the lateral or vertical direction, as long as they are transient phenomena. The morphology of regime canals has been the subject of many investigations since Kennedy stated his empirical equation of non-scouring velocity for canals of the Punjab in 1895 (Leliavsky, 1955). The basic principle generally was not applied to rivers in the United States, however, until Leopold and Maddock (1953) reported their analysis of the relationships between hydraulic properties of channel cross-section and river discharge. They theorized that the hydraulic geometry of river channels in approximate equilibrium could be expressed as exponential functions of discharge such that

$$W = aQ^b, \qquad (1)$$
$$D = cQ^f, \qquad (2)$$
$$V = kQ^m, \qquad (3)$$

where W is width, D is mean depth, V is velocity, Q is discharge, and a, c, k, b, f, and m are numerical constants.

Since Leopold and Maddock, there has been many empirical studies on hydraulic geometry, notably studies by Wolman (1955), and Hack (1957). Investigations by Leopold and Maddock (1953) determined that the sum of the exponents would be unit one due to the continuity equation for the hydraulic exponents holds for changes in discharge at-a-station and proposed the following equations.

$$\begin{aligned} Q &= \text{area} * \text{velocity} \\ &= wd * v \qquad (4) \end{aligned}$$

which yields $$\begin{aligned} Q &= aQ^b * cQ^f * kQ^m \\ &= ackQ^{b+f+m} \qquad (5) \end{aligned}$$

Therefore, $b + f + m = 1.0$, and

$$a * c * k = 1.0. \qquad (6)$$

Because the product of width, depth, and velocity must be discharge, the three equations are related to one another and the summation of the slopes has to be one.

Exponents of the first-order equations represent the rates of change of the dependent variables with changing discharge. Thus, exponents of the power functions are the slopes of the first-order equations. The slopes represent the rates of change of width, depth, and velocity with changing discharge. Comparison of the numerical values of the exponents indicates which variables show greater rates of change at which scale ranges.

As stated above, Leopold and Maddock (1953) were not the first to apply the regime concept to rivers, although their analysis was one of the first to gain wide acceptance. In 1930, Lacey extended his earlier empirical equations for Punjab canals by including limited data for rivers from the United States, Europe, and the Punjab (Mahmood and Shen, 1971); however, he grouped river data by discharge and used averages. Pettis (1937) independently developed similar regime equations based on natural streams in the Miami River basin of Ohio. Pettis' relations were intended for use in river channelization; therefore, his discharge was a flood discharge, apparently near bankfull (Pettis, 1937).

Leopold and Maddock's (1953) paper had an immediate impact on geomorphology, primarily because it and Horton's (1945) earlier paper on Erosional Development of Streams and Their Drainage Basins demonstrated quantitatively that there is order in landform development, and a series of papers demonstrating similar relations in other areas followed its publication (Brush, 1961; Wolman, 1955; Leopold and Miller, 1956; Nixon, 1959; Miller, 1958).

Five decades after Leopold and Maddock (1953) first applied the technique of setting width, depth, and velocity equal to a power function of discharge, there is still debate over the theoretical value of hydraulic geometry exponents. Leopold and Maddock (1953) claimed that the exponents of hydraulic geometry tend to be similar for rivers of different sizes in widely different physiographic settings. They stressed that the similarity of these exponents may be due to the fact that they are characteristic of a steady-state system comprised of force and proportional resistance. However, Mackin (1963) pointed out that the velocity exponents can vary markedly within a single drainage system, and Park (1977) found systematic differences in the width and velocity exponents between humid temperate and tropical streams, and between perennial and ephemeral semi-arid streams.

Yang et al., (1981) and Phillips and Harlin (1984) indicated that b, f, and m exponents reflect a tendency for minimum work in the stream channel, and so are similar for all rivers. However, the literature reveals that some researchers take a less restrictive view of controls on hydraulic geometry, and have emphasized variations in exponents as opposed to mean values (Knighton, 1974). While Chang and Toebes (1970) state that rivers over varying environments behave in similar fashion, Park (1977) argues that certain hydraulic exponents could be characteristic of different climatic and environmental regimes. Obviously, the more recent studies are not in good accord with an earlier model which forces discharge into the role of an independent variable.

Observed at-a-station hydraulic geometry relationships are quite variable. Exponents for at-a-station hydraulic geometry, reported in the literature, range at least from 0.0 to 0.84 for the width exponent, b; 0.01 to 0.84 for the depth exponent, f; and 0.03 to 0.99 for the velocity exponent, m using 587 sets of exponents (Rhodes, 1978). Park (1977) calculated values for 139 at-a-station data sets for streams in proglacial, humid temperate, semiarid, and tropical regions. Park found that exponent values for width fell within the class 0.0 to 0.1, for depth within the class 0.3 to 0.4, and for velocity within the class 0.4 to 0.5. Knighton (1975) reported average exponents for 206 cross sections in the United States as 0.16 for width, 0.43 for depth, and 0.42 for velocity. The most commonly cited average exponent values are those computed by Leopold and Maddock (1953) for " a large variety of rivers." The values are b = 0.26, f = 0.40, and m = 0.34. There are a wide range of mean b, f, and m values. Categorizing channels based on scale, similar geomorphic and environmental settings would reduce the range of mean b, f, and m values.

As data accumulated on the hydrology and morphology of rivers, it was inevitable that the “regime” approach would be applied to rivers, and this was done by Leopold and Maddock (Wahl, 1984). Leopold (1994) himself stated that due to the variances introduced to a variety of predictor variables, any combination of the b, f, and m values can be possible.

2.4 b, f, and m Computation

Basically, there are three methods of computing rate of changes in width, depth, and velocity with regard to changing discharge volume. Statistical and analytical modeling of channel form remains a major theme of current research on channel morphology (Rhoads, 1994).

As seen in the Leopold and Maddock’s power law, log transformations of variables allow equations (1) - (3) to be expressed as linear functions, and hence the equations define a log-linear model (LLM). Substitution of equations (1) - (3) into the mass continuity equation, (4), yields equations (5) and (6). The concept of hydraulic geometry has been used extensively to describe the behavior of natural river flows in a variety of physiographic and climatic regions (Leopold and Maddock, 1953; Wolman, 1955; Brush, 1961; Fahnestock, 1963; Carlston, 1969; Knighton, 1975; Park, 1977; Rhodes, 1977; Andrews, 1984). Some of these studies have used values of the exponents in equations (1) - (3) to compare the characteristics of different river sections and basins.

Several authors have questioned the validity of the LLM in general to adequately represent hydraulic geometry data for discharges less than channel capacity such as bankfull. Wolman (1955), Lewis (1966), Thornes (1970), Richards (1973), Williams (1978), and Eschner (1983) have noted breaks in the slopes of the hydraulic geometry relations at a number of sites (Bates, 1990). The origin of the breaks was discussed by Ferguson (1986), and Singh and Broeren, et al. (1987). Ferguson (1986) explained these breaks by cross-sectional shapes and frictional characteristics of natural river channel, and Singh, Broeren, et al. (1987) by water reference level. Ferguson (1986) stressed that the LLM will be valid only in situations where the width-depth and mean velocity-depth relationships conform to a power law (Bates, 1990).

Thornes (1970), Williams (1978), and Eschner (1983) have fitted piecewise linear relations to log-transformed hydraulic geometry data. Bates (1990) stated that "Although their work has shown that these relations can give improved fits to the data, there does not appear to be any evidence of a formal piecewise linear model of hydraulic geometry in the relevant literature".

Richards (1973) was strongly against the use of piecewise linear relations on the grounds that the fitting of polynomials is a more appropriate approach. Richards (1973) advocated the fitting of quadratic relations to log transformed data (Bates, 1990). Richard's log quadratic model (LQM) is defined by

$$\text{Log } w = b_1 + b_2 \log Q + b_3 (\log Q)^2 \quad (7)$$
$$\text{Log } d = f_1 + f_2 \log Q + f_3 (\log Q)^2 \quad (8)$$
$$\text{Log } v = m_1 + m_2 \log Q + m_3 (\log Q)^2 \quad (9)$$

Substitution of equations (7) - (9) into equation (4), and differentiation of both sides of the resulting terms with respect to log Q produces:

$$b_2 + f_2 + m_2 = 1 \quad (10)$$
$$b_3 + f_3 + m_3 = 0 \quad (11)$$

and

$$b_1 + f_1 + m_1 = 0 \quad (12)$$

which in turn becomes to the continuity equation.

Bates (1990) proposed a formal log piecewise linear model (LPM) for the computation of at-a-station hydraulic geometry to model non-linear trends, a more sophisticated method of Thornes' (1970) technique of fitting separate regression lines about a 'break point' in the hydraulic geometry data. Bates' (1990) LPM is for at-a-station hydraulic geometry of discharges below bankfull. Bates (1990) compared the results of his LPM computed b, f, and m on 22 stations on various rivers and creeks in Australia with Leopold and Maddock's (1953) LLM and Richards's (1973) LQM results and concluded that LPM provided objective means for identifying the breaks in the slopes of hydraulic geometry relations for a particular station. These breaks reflect changes in the physical constraints that control at-a-station variations in width, depth, and velocity with rising discharge.

Bates (1990) stated that by using fitted straight lines (LLM) or polynomials (LQM) to log-transformed data, important pieces of information which are manifested by break points are lost. He also concluded that further work is required to fully establish the physical bases of the LPM and application of the model to natural channel hydraulic geometry is necessary to determine unbiased parameter estimates and draw valid inferences on the regression models.

The author used LLM which has been employed by a majority of at-a-station hydraulic geometry researchers to compute b, f, and m where the width-depth and mean velocity-depth relationships conform to the power law and most of the 43 gage stations' b + f + m = l. LLM method is employed by this author because there are rich sources of hydraulic geometry data calculated by LLM methods. Comparing b, f, and m calculated by the same method would reduce variability introduced by other methods. The author plans to identify any breaks in slope and to explain these breaks by cross-sectional shapes and frictional characteristics of natural river channels and by a water reference level. The author used LQM for analyses of scale, and b, f, and m for log quadratic relationships.

2.5 Representation and Analyses of b, f, and m

The b, f, and m values from equations of hydraulic geometry have been used to describe and compare stream channels formed under the influence of many environments. However, the comparisons have been based almost solely on the numerical similarity of the exponents. Even though the numerical values of slopes and intercepts may not provide any visual picture of a river basin, comparison of the values of these factors among rivers has useful aspects.

Park (1977) and Rhodes (1977, 1978) independently proposed a far more extensive analysis of b, f, and m values. Both represented b, f, and m values on an equilateral triangle using a triangular coordinate system via a ternary diagram. The concept of the ternary diagram has been extensively used for soil classification by the American Association of State Highway and Transportation Officials and classification of Maryland coastal sediment sample classification (Shepard, 1954). However, Rhodes (1977) and Park (1977) were the first to portray b, f, and m exponential values on ternary diagram.

Rhodes (1977) and Park (1977) both used ternary diagram and classification systems to examine the simultaneous variations of hydraulic geometry exponents. They attempted to interpret at-a-station hydraulic geometry to show certain relationships between hydraulic geometry and channel pattern and group the data according to these relationships. However, Rhodes's and Park's analyses differed on the criterion used to classify the b, f, and m data. Park (1977) chose climatic differences such as representative values for regions of proglacial, humid temperate, semi-arid, and tropical environments as classification of b, f, and m data. Park (1977) concluded that his climatic grouping offered "relatively little explanation" of the variability of the data and concluded that; "it would seem logical to consider more local factors " to explain the variability of b, f, and m.

Rhodes (1977), Park (1977), and Ferguson (1986) collated available b, f, and m values from various research results such as Leopold and Maddock (1953), Wolman (1955), Leopold and Miller (1956), Leopold and Wolman (1957), Fahnestock (1963) and many more, and found there are huge scatters that cannot be explained by differences in the numerical values of b, f, and m. Histograms do not show the simultaneous values of these three exponents, which are of more interest because these three exponents are interrelated. Consequently ternary diagrams are preferred because almost any combination of exponents can be recorded in the triangle.

The implicit assumption in this type of analysis is that the channels, as characterized by a particular set of b, f, and m values, differ only in their rate of response to changing discharge. Rhodes' (1978) investigation challenged the assumption by demonstrating that channel responses may differ not only in degree but also in direction on a ternary diagram. This demonstration is based upon a graphical representation of at-a-station hydraulic geometry data and division of the ternary diagram based on empirical and hydrological principles. Park (1977) used recognition of different channel types which are delineated by the divisions of the diagram.

Rhodes (1977) attempted to analyze at-a-station hydraulic geometry exponents on the basis of local factors such as (1) width/depth ratio for stability of the channel ($b = f$), (2) competency of the channel ($f = m$), (3) Froude number ($m = f/2$), (4) velocity/cross-sectional area ratio ($m = b + f$), and (5) slope/roughness ratio ($m = 2/3f$). Rhodes classified the channels according to their dynamic and morphological responses to changing discharge. Using these five criteria, a ternary diagram is divided into ten regions. The first criterion of dividing the ternary diagram was the line by $b = f$ which divides the triangle by two regions where width exponents are bigger or smaller than depth exponents. The second criterion was checking the competency of the channel by comparing the depth and velocity exponents; the third criterion was stream flow condition by Froude numbers; the fourth, channel stability and flow resistance, and the last criterion was roughness in terms of depth and velocity exponents. The author followed Rhodes' criteria to categorize b, f, and m values of the study area and derived categorically similar regions based on the five criteria. The derivations of relationships within the b, f, and m equation for these five criteria are discussed in detail in Chapter 5. This additional information is used to understand the hydraulic geometry relationships and environmental setting for specific hydraulic geometry groups.

2.6 b, f, and m and Disparity

Hydraulic geometry is a versatile analytic technique, which can be used to describe and, in part, explain the interactions of measurable parameters in natural streams as discharge changes or as channel form is modified. However, the degree of variation in the hydraulic relations casts doubt on the validity of defining a mean at-a-station hydraulic geometry even for a single stream system or regional group of streams on the basis of existing empirical evidence. Knighton (1975) reported that the variation is apparently not random, but systematically related to channel pattern, straight reaches being distinguishable from meander and braided reaches in terms of the rates of change of width, velocity and resistance, and slope. Variability may be reduced by a systematic selection of stations of similar characteristics of streams flowing through either cohesive or non-cohesive materials and a mean geometry defined for each category.

There are many research reports which try to explain the disparity or wide range of the exponents values of at-a-station hydraulic geometry computed from observed width, depth, and velocity with the respect to the changing discharge volume. Even at-a-station interpretations of the hydraulic intercepts and exponents will be misleading for extremely low and high flows, that is, where the deviation from mean discharge is extreme. Rhodes (1978) noted that some researchers have found that exponent values for high-flow conditions can be vastly different than that for low-flows. Richards (1973) and Park (1977) have suggested that simple power functions may not be the best way of describing hydraulic geometry. This study investigates high and low flows in the subbasins where each b, f, and m value shows a wide range.

Eschner (1982) also found that on many of the hydraulic geometry plots breaks in the slopes of the width, depth, and velocity discharge relations are evident at a certain discharge in his study of the Platte River. He concluded that the width- and depth-discharge relations at breaks do not appear to follow a single power function model. Power functions fitted separately to the low and high ranges of discharge generally yielded large proportionate reductions in the variances of the dependent variables relative to the variances of the variables alone.

This complex hydraulic geometry is not peculiar to the Platte River (Eschner, 1982). Wolman (1955) stated of Brandywine Creek in Pennsylvania: "There is a suggestion in some of the data ... that the depth-discharge and velocity-discharge curves may actually plot as curved rather than straight lines on log log paper. Such a relationship of the at-a-station curves is not uncommon." Richards (1973) noted that non-linear changes of depth and velocity with discharge may result from non-linear changes of roughness with discharge. Richards (1976) also proposed that channel cross-section shape can produce breaks or dissimilarities in the width-discharge relationship.

The fact that hydraulic geometry, specifically at-a-station hydraulic geometry, is notoriously unpredictable in a deterministic sense, but demonstrates clear regularity and a degree of predictability in an aggregate probabilistic sense is described by Leopold and Maddock (1953), Williams (1978) and Phillips (1990, 1991, 1995). Richard (1977) stated that geographical patterns in the at-a-station exponent set may occur, but inter-regional differentiation is obscured by the more direct influence of bed and bank material.

As the scale of study diminishes, statements of equilibrium can only address "at-a-station" geometry, as each cross-section of the channel is adjusting to the discharge of water and sediment in a unique subsurface and surface environment (Abrahams, 1984). As the sample expands in space and/or time, the interpretation of hydraulic exponents becomes less and less meaningful. This does not mean that there is no value in establishing regional hydraulic exponents; however, a good deal of caution must be exercised before any assumption of transferability is made. Further analyses will almost always be demanded, as comparisons of coefficients and exponents are made within, or between, regions defined by physical parameters.

As stated earlier, using local environmental variability of the subbasin and channel characteristics, the author investigated the nature of b, f, and m values and the relationships among each other; the impact of the predictor variables on the b, f, and m; and the significance of their impact on the b, f, and m.

2.7 Heterogeneity of Environmental Factors

Leopold and Maddock (1953) claimed that the exponents of b, f, and m and the discharge relations tend to be similar for rivers of different sizes in widely different physiographic settings. However, Mackin (1963) pointed out that the velocity exponent can vary markedly within a single drainage system, and Park (1977) found systematic difference in the width and velocity exponents between humid temperate and tropical streams, and between perennial and ephemeral semi-arid streams.

While furthering the state of knowledge, most of the preceding studies, including the 1953 work of Leopold and Maddock, were of limited practical value because the hydraulic-geometry variables used were those of specific discharges and could not be identified with recognizable channel features. Lane's paper (1935) demonstrates clearly how empirical equations as well as the qualitative conclusions reached in one part of the world do not necessarily apply elsewhere because of the different climatic, physiographic, and geologic conditions. Wahl (1984), summarized these situations as: "The controversy involving the validity of equations developed locally but applied generally resembles some geologic controversies that were resolved when the investigators visited their opponents' field area."

As Leopold (1994) stated, stream channel morphology is directly influenced by channel slope, roughness of channel materials, sediment load, and sediment size. A change in any one of these variables sets up a series of channel adjustments which lead to a change in the others such as stream flow processes, resulting in channel pattern alteration and alteration of the hydraulic geometry. Because stream morphology influences hydraulic geometry, any changes in environmental controlling factors need to be investigated for their roles on b, f, and m changes.

2.7.1 Environmental Controlling Factors

As Riggs (1978) stated there is an extensive literature on channel morphology that established general relations among channel width, depth, slope, discharge, and velocity, and attempts to explain channel response to changes in streamflow regimen. These general relations among channel width, depth, discharge, and velocity are usually associated to only a few environmental controlling factors.

Orsborn and Stypula (1987) developed the interrelationships among the geometric characteristics of stream channels and streamflow from which the natural or modified states of streams could be determined. They suggested and developed a regional hydraulic geometry model for basins in Oregon based on the assumption that if the interactions of streamflows and freely deformable stream boundaries are governed by the same hydraulic forces, then stream channels of different sizes should have comparable dimensionless geometric and streamflow ratios. In this case, the influence of scale, scale defined as the differences in size of stream channel, on hydraulic geometry was completely ignored.

Ferguson (1986) showed that the cross-sectional shape of a channel determines the rate of increase of stream channel width with depth, whereas the laws of flow resistance determine the rate of increase of mean velocity with depth. In turn, factors that affect channel geometry include vegetation (Hadley, 1961; Zimmerman et al., 1967), bank cohesiveness and sediment size (Schumm, 1960; Wolman and Brush, 1961; Knighton, 1974; Maizels, 1988), changes in suspended load (Leopold and Maddock, 1953; Wolman, 1955; Thornes, 1970), seasonal variation (Thornes, 1970), channel sinuosity (Knighton, 1975), channel roughness or flow resistance (Knighton, 1975), riffle spacing (Harvey, 1975, Prestegaard, 1983), the processes of scour and fill (Foley, 1978; Andrews, 1979), landuse (Moglen and Berger, 1998), and stream size (scale factor) and order (Thornes, 1970; Miller and Onesti, 1977). All of these stream parameters are candidates as covariates of the hydraulic exponents.

Phillips and Harlin's analysis (1984) of a subalpine stream in a relatively homogeneous environment indicates that hydraulic exponents are not stable over space. Hydraulic exponents may be so influenced by local soil and other surface conditions that stressing pervasive stream behavior through b, f, and m values may prove of limited value. Unfortunately, Phillips did not discuss the specific hydraulic, geomorphic, or pedologic conditions that give rise to these contrasting hydraulic geometries. Consequently, it remains unclear whether comparable contrasts are to be expected in other environments.

Early attempts to apply channel size to furnish engineering answers were concentrated on identifying bankfull stage and on verifying the recurrence interval of the corresponding discharge. Among the studies of this type are those by Kilpatrick and Barnes (1964), Woodyer (1968), Potter, et al., (1968), Brown (1971), and Kellerhals, et al., (1972). Such studies generally did not produce a method for estimating a discharge corresponding to bankfull stage. These studies might be considered transitional between research in channel morphology and application of this research to estimating flow characteristics.

2.7.2 Water Reference Level

Ideally, a channel feature used as an index to discharge should be a unique recognizable feature of the channel. It should also be active, that is, free to adjust to changes in the flow regime. These considerations led to the attempts to relate an active, within-channel feature to discharge characteristics. According to Wahl's (1984) account, the approach was apparently first suggested by Langbein (USGS, written communication, 1966).

Comparing published results for different physiographic areas is difficult because the areas have morphological and hydrological differences. In addition, three different water flow reference levels could have been used in other studies. Singh et al. (1989), for stream habitat evaluation, developed a basin model that defines the average values of width, depth, and velocity for a given streamflow or for a given flow duration and drainage area. They concluded that width, depth, and velocity parameters increase with drainage area when compared at the same duration. They derived relationships linking a flow parameter to drainage area for a given stream network in a hydrologically homogenous basin: $\log (VAR) = a + bF + c (\log Ad)$, in which VAR: w, d, or v; F: the decimal flow duration; Ad: the drainage area; and a, b, and c are: coefficients. Even this concept is applicable only in a hydraulically homogeneous basin, this is the first step that drainage area and flow duration variables are introduced to determining width, depth, and velocity in a formal form.

Most researchers used mean annual discharge as the predictor variable because it provided a discharge of approximately the same frequency throughout the area of investigation, thus permitting comparison between relations. At first it appeared that the values of the exponents b, f, and m were relatively constant, and the average values agreed quite closely with previously defined values for regime canals. The coefficients a, c, and k, however, varied among river systems. Furthermore, flow characteristics in arid and semiarid regions generally are only weakly related to the size of the drainage basin.

Wolman's (1955) analysis of the Brandywine Creek drainage in Pennsylvania, in which he related hydraulic geometry to bankfull discharge, was significant. In addition, he analyzed the hydraulic-geometry relationships with flow of 50-, 15-, and 2-percent duration. The recurrence interval of flows exceeding bankfull on Brandywine Creek ranged between 1 and 3 years and averaged 2.2 years. Although simple in concept, bankfull stage may be interpreted in a number of different ways, each associated with different values of width and depth and yielding a different bankfull discharge. Williams (1978) gave a comprehensive review of definitions of bankfull stage. He identified and discussed eleven definitions that have been used by investigators.

There are three water reference levels referenced by most researchers. They are: within-channel, active-channel, and main-channel. The first published analysis using the within-channel feature was that by Moore (1968) for streams in Nevada. He graphically related mean annual discharge to the width and average depth of the channel cross-section defined by the tops of the channel bars and gave separate results for perennial and ephemeral streams.

The results are of limited practical use as only 34 percent of the sample variance was explained by an equation using width; a relation using only precipitation explained 83 percent of the sample variance. In an earlier study of small drainages in the Sleeper’s River basin of northern Vermont, Zimmerman et al., (1967) found that stream width did not increase in the downstream direction for drainage areas less than 0.8 square miles. They attributed this to the effect of vegetation, mostly tree roots, and to relatively small annual peak discharges.

While studying Kansas streams, Hedman (U.S. Geological Survey, written communication, 1972) recognized a channel feature somewhat higher than the in-channel bars that had been used previously. He first referred to this feature as the active flood plain but redefined it as the active channel (Hedman et al., 1974). Osterkamp and Hedman (1977) described the active channel as ". . . a short-term geomorphic feature subject to change by prevailing discharges. The upper limit is defined by a break in the relatively steep bank slope of the active channel to a more gently sloping surface beyond the channel edge. The break in slope normally coincides with the lower limit of permanent vegetation so that the two features, individually or in combination, define the active channel reference level. The section beneath the reference level is that portion of the stream entrenchment in which the channel is actively, if not totally, sculptured by the normal process of water and sediment discharge." Since then, the active-channel section has been used in numerous studies to define mean annual and flood flows in the Western States and in selected Eastern States.

Scott and Kunkler (1976) related the width of the active channel to characteristics of the 2- through 50-year floods in New Mexico. The relations using channel width gave significantly smaller standard errors of estimate than similar relations that used basin and climatic characteristics.

Osterkamp and Hedman (1982) expanded on the earlier Missouri River basin study by Hedman and Kastner (1977) by considering the effect of channel - sediment properties, channel gradient, and discharge variability. They concluded "Results show that channel width is best related to variables of discharge, but that significant improvement, or reduction of the standard errors of estimate, can be achieved by considering channel-sediment properties, channel gradient, and discharge variability."

The third and highest reference level used is the main channel section (also referred to as the whole-channel section). This section was described by Riggs (1974) as "… variously defined by breaks in bank slope, by the edges of the flood plain, or by lower limits of permanent vegetation."

Harenberg (1980) used the bankfull width to define relations for the 1.5- through 100-year floods for Idaho. Lanham developed a relation between the geometric mean of peak discharges (approximately the 2-year flood) and main-channel width for Wyoming that had an average standard error of estimate of 47 percent (Wahl, 1984).

Since at-a-station hydraulic geometry compares flows of vastly different frequencies, the author used all measurements during various water reference levels. However, the author will use the water reference level information of each hydrographic survey data for explanation of b, f, and m values.

2.7.3 Scale

The indications of the existence of the scaling factor in hydraulic geometry were not heeded by many geomorphology researchers, even though studying the effects of scale has become popular over the last few decades. Wilcock's (1971) observation on the relationship between increases in discharge and drainage area is a good example of the existence of scaling. He noted that the rate of increase of discharge with drainage area tends to be very much greater for lower than for higher duration flows. However, instead of the relationship between discharge and drainage area as a scale related approach, it is suggested that this is most probably the result of differences in topography and the consequent differences in the roles played by surface runoff and groundwater flow in the different parts of the catchment.

As Penning-Rowsell and Townshend (1978) stated, understanding of the effect of scale on hydrographical and geomorphological processes is noteworthy because there is a need to relate spatial patterns and forms to correct processes so that valid process model can be developed. To explain how spatial patterns and form of hydraulic geometry can be expected where we do not have data and understanding which variables have prominent influence on hydrographic geometry at which scale, including spatial and temporal aspects, are not fully understood yet.

Over the years, numerous field experiments have revealed that hydrological processes and parameters can show considerable spatial variability. Bloschl, et al. (1995) stated that hydraulic process varies over the size of a particular catchment and with other environmental parameters. It has increasingly been realized that hydraulic variables and processes usually exhibit a large spatial variability.

Rosso (1996) stated that there is an increasing awareness that the development of methods enabling transformation of data from one temporal or spatial scale to another can bring important and substantial developments in many hydrological applications. And Leopold (1994) compared the hydraulic geometry of three rivers of different basin sizes: Watts Branch drainage area, 3.7 square miles; Seneca Creek drainage area, 100 square miles; Amazon River at Obidos drainage area, 1.9 million square miles. Visual inspection of the scatter diagrams of discharge versus width, depth, and velocity for these three rivers of different size clearly indicates there are differences in the slopes of the three sets of the lines for each hydraulic exponents. Assuming all predictor variables for these three rivers are same, which might not be the case, it can be inferred that there is clearly scale effects on these three rivers of different drainage size. However, the author has not come-across any investigations of the scale effects on at-a-station hydraulic geometry yet.

Another scale related study is Hack's law. Rigon et al. (1996) reviewed Hack's law (1957) and explained Hack's law from scaling aspect such that the length of the longest stream has a power relationship with size of the basin. From the results, Rigon et al. (1996) suggested that a statistical framework referring to the scaling invariance of the entire basin structure should be used in the interpretation of Hack's law. Hack (1957) demonstrated the applicability of a power function relating length and area for streams of the Shenandoah Valley and adjacent mountains in Virginia. He found the equation $L = 1.4A^{0.6}$ where L is the length of the longest stream in miles from the outlet to the divide and the A is the corresponding area in square miles. Hack also corroborated this equation through the measurements of Langbein (1947), who had measured L and A for nearly 400 sites in the northeastern United States. Mueller (1973), on the basis of extensive data analysis of several thousand basins, found that the exponent in Hack's equation was not constant but that it changed from 0.6 for basins less than 8,000 square miles (20,720 km^2) to 0.5 for basins between 8,000 and 10^5 square miles (20,720-259,000km^2), which clearly shows a scale factor in Hack's equation.

Clearly, there has been considerable research on scaling factors in various hydrographic processes but the author is, other than Leopold's (1994) comparison of, b, f, and m in three different sizes of rivers and Griffiths' (2003) work on downstream hydraulic geometry, not aware of research on quantification of scale influence on at-a-station hydraulic geometry. Hence, the author investigated the impact or non-impact of scaling factors which is one of many environmental controlling factors in b, f, and m.

The author used many environmental controlling factors such as scale, channel shape, channel pattern, asymmetry of channel, topographic index for slope of study subbasin characteristics, subbasin size for scale influence, physiographic and bed and bank material, and landuse characteristics, as well as Rhodes' (1977) classification of the b, f, and m to synergistically investigate the relationships between b, f, and m and environmental controlling factors.

As Moglen and Bras (1995) stated, the presence of heterogeneities does not simply blur and smear analytical relationships. The heterogeneities themselves introduce new structure to the organization of the drainage basin. The author investigated the new structure to the organization of the drainage basin by synergistic analyses using significant variables to explain the relationships between b, f, and m and environmental controlling factors.

2.8 Need for Additional Study

A number of features, including the in-channel bar section, active-channel section, and the main-channel or whole-channel section, presently are being used to define flow characteristics. Consequently, it is difficult to make comparisons between studies, and the applicability of individual results is dependent on the ability of a user to identify the water reference level feature used in developing the relation.

Additional work is needed to determine the role of other variables. Several investigators (Schumm, 1960; Glazzard, 1981; Osterkamp and Hedman, 1982) have examined the relation between sediments in the bed and banks and channel size. Andrews (1984) examined data for gravel-bed streams in Colorado and separated the data into two groups depending on whether bank vegetation along the study reach was light or thick. He made width, depth, and velocity dimensionless by dividing each by the median particle diameter in the riverbed surface. Regression relations for hydraulic geometry exponents showed no significant difference between data for light and thick bank vegetation. This implies that role of bank vegetation was weak on hydraulic geometry for gravel-bed rivers in that study.

The inferences concerning the relationship between roughness and hydraulic geometry are speculative at present. As Richards (1973) pointed out in discussing this problem: "Achieving a point of entry into this system for the purpose of analysis is extremely difficult, since the interaction is complete." Much work remains to be done on the relationship of hydraulic geometry and channel roughness. The inferences derived from the b-f-m diagram indicate some possible lines of inquiry.

As Abrahams (1984) pointed out employing the hydraulic geometry model to answer questions pertaining to channel storage, flood potential, or sediment delivery would seem to prove difficult at best without constant re-evaluation in “steady-state” time. An inherent difficulty, the feedback in the system produces variables which, even in the short run and “at-a-station”, are never consistently dependent or independent.

Even more difficult to evaluate is the relative contribution of each of the factors to the observed changes. At present, each case must be considered individually, and this involves a detailed analysis of many variables. Then interaction among predictor variables to hydraulic geometry needs to be investigated so all predictor variables' roles on hydraulic geometry can be considered synergistically.

2.9 Conclusions

The working hypothesis of this study is that variations in hydraulic geometry exponents, (b, f, and m values), the change rates of channel width and depth, and flow velocity, are not random but there are systematic changes in hydraulic geometry exponents as a function of watershed scale and basin characteristics. In other words, there is a geographic scale factor in hydraulic geometry exponents such that b, f, and m values in Amazon-sized rivers are different from those of smaller rivers. This might explain why hydraulic geometry has different b, f, and m values where all other basin variables are the same or similar.

Using empirical field data, in addition to the overall scale function to b, f, and m, I will specifically test scale impacts of the four hydraulic and channel geomorphic process principles established by other researchers. They are: a) for sand-beds, roughness usually increases with Q due to bedforms, so velocity exponents are smaller than depth; and b) in gravel-bed channels, roughness decreases with Q due to increased relative submergence, and the velocity exponent is larger than the depth exponent.

As stated earlier, statistical analyses of predictor variables' impact on the b, f, and m will be explained with these categories within scale context.

CHAPTER 3

STUDY AREA: Selected Characteristics Of The Potomac River Basin And Demarcation Of Its Subbasins

3.1 General Study Area

The study area for this investigation of hydraulic geometry in various environmental settings is the Potomac River Basin shown as Figure 3.1. This Basin, covering a range of 38 to 40 degrees North and 76 to 80 degrees West, extends from the North Branch Potomac River near Luke, Maryland to the St. Marys River at Great Mills, Maryland, and from the headwaters of the North River near Burketown, Virginia, to Aquia Creek near Garrisonville, Virginia. The sources of the following description of characteristics of the Potomac River Basin are USGS Professional Papers and Technical Reports of the Interstate Commission on the Potomac River Basin.

In the eastern United States, the Potomac River Basin is part of the Chesapeake Bay drainage system. The Potomac River and its tributaries drain 14,670 square miles ($mile^2$)**,** including parts of Maryland, Virginia, West Virginia, Pennsylvania, and the entire District of Columbia: Virginia (5,723 $mile^2$), Maryland (3,818 $mile^2$), West Virginia (3,490 $mile^2$), Pennsylvania (1,570 $mile^2$), and Washington, D.C. (69 square miles) (Gerhart and Brakebill, 1996). The Potomac River flows through six physiographically distinct subunits which will be described later. Because of its large drainage area and diversity, the Potomac River Basin's environmental setting is complex, consisting of various combinations of natural and human characteristics. Knowledge of selected primary features that comprise the environmental setting is necessary to understand hydraulic geometry and the environmental impacts on hydraulic geometry.

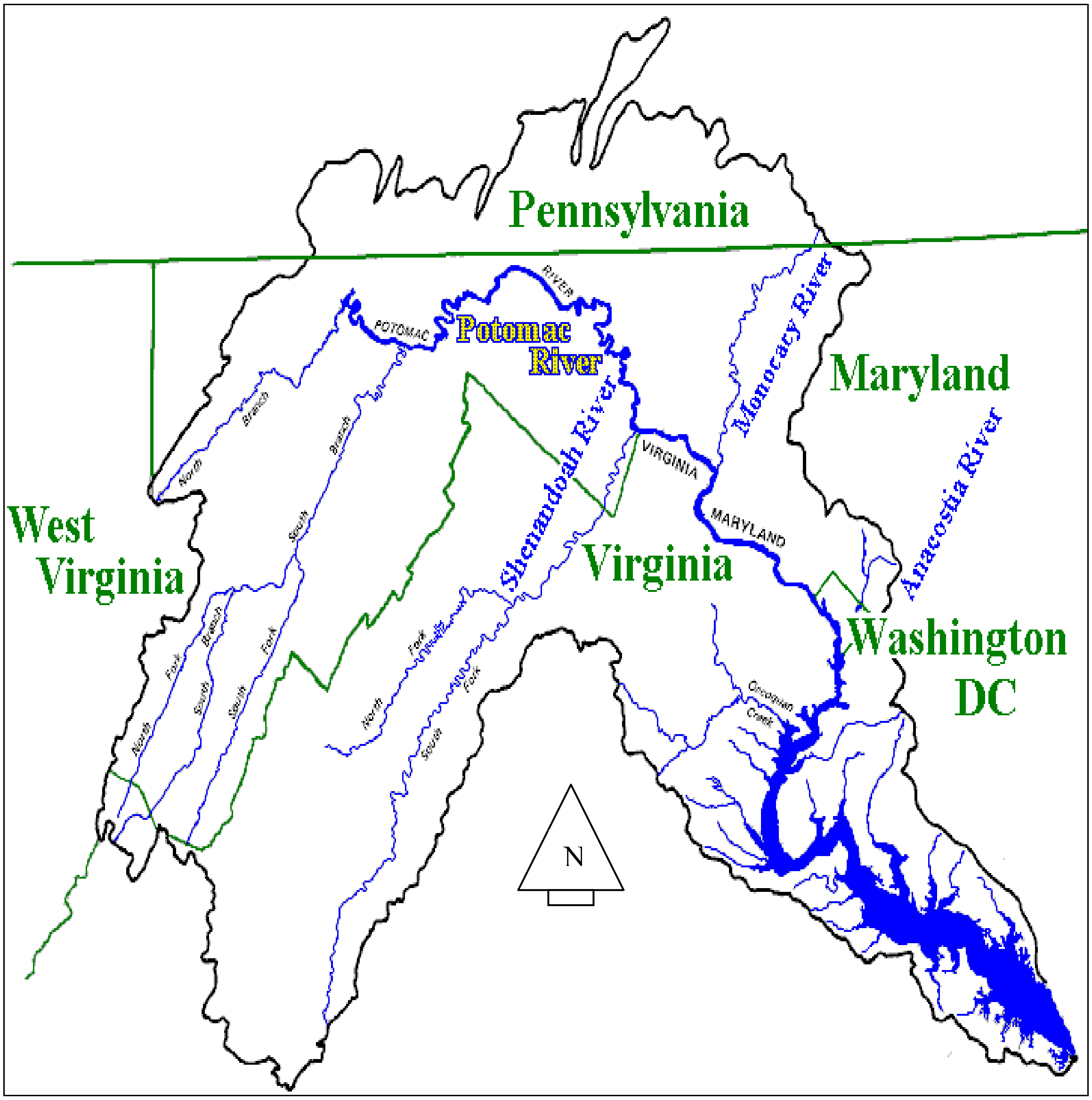


Figure 3.1 Study Area - Potomac River Basin
Source: US Geological Survey Water Resources Investigations Report 96-4034

3.1.1 History of the Study Area, Potomac River Basin

Before the Pleistocene glacial age, many great river systems drained the eastern slopes of long mountain ridges along the eastern North American continent. The greatest of these was the Susquehanna, which had a watershed of thousands of square miles with boundaries extending as far north as upstate New York and as far west as western Pennsylvania. As the Susquehanna meandered southward to the Atlantic, cutting through the Piedmont foothills, it was joined by waters from hundreds of streams, large and small (U. S. Department of the Army, 1973). The largest of these tributaries was the Potomac River, which drained the southwestern slopes of the mountain system. The Potomac, along with other southern tributaries (the York, James, and Rappahannock rivers of Virginia), cut deep channels across the ancient coastal plain ledges (U. S. Department of the Army, 1973).

At the end of the last Pleistocene glacial age, from about 15,000 to about 9,000 years ago, sea levels rose with the melting retreat of the glaciers and inundated the valleys of the coastal plain rivers (Schubel and Meade, 1977) eventually reaching the base of the Piedmont hills at what is now called the fall line. These tidal waters flooded the lower portions of the Susquehanna River basin, drowning the valleys inland for almost 180 statute miles (290 kilometers) (Cronin, 1973). Thus, as seawater intruded into the lower reaches of the Susquehanna basin, the Chesapeake Bay and the estuarine portions of all its tributaries, including the Potomac River, came into being (Lippson et al., 1979).

3.1.2 Present Potomac River Boundaries

The Potomac River begins as a small spring in West Virginia, at Fairfax Stone, and flows 383 miles through six physiographic provinces to its mouth at Point Lookout, Maryland, and Smith Point, Virginia, where it enters in the Chesapeake Bay (Figure 3.1). As discussed more fully later, it crosses six distinct physiographic regions on its journey to the bay, including the Appalachian Plateau, the Valley and Ridge Province, the Great Valley, the Blue Ridge, the Piedmont, and the Coastal Plain (Vokes and Edwards, 1974). The Potomac River Basin is bounded by the Susquehanna River basin on the north, the Ohio River basin on the west, the James and Rappahannock River basins on the south, and the Patuxent River basin and Chesapeake Bay drainage on the east. Flow of the Potomac River increases downstream so that when it reaches the Chesapeake Bay, it constitutes about 15 percent of the estimated 49,300 Mgal/d total inflow to the Bay (J.F. Hornlein, U.S. Geological Survey, oral communication, 1991).

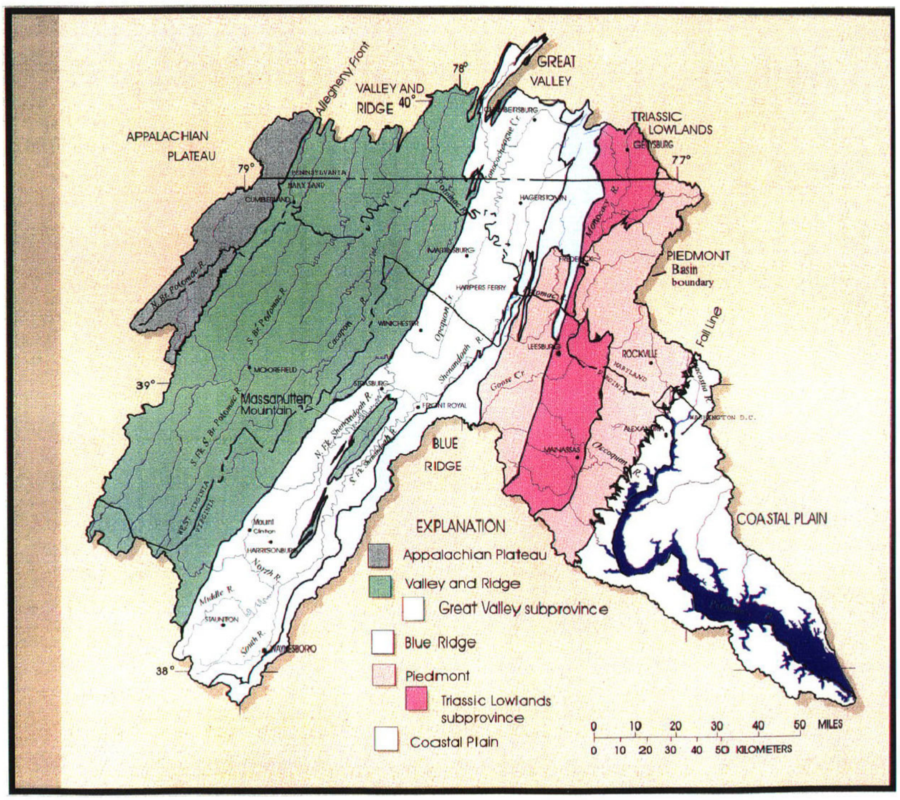


Figure 3.2 Physiographical Characteristics of the Study Area
Source: US Geological Survey Water Resources Investigations Report 96-4034

Major tributaries to the Potomac River (Figure 3.1) include the North Branch Potomac River, South Branch Potomac River, Cacapon River, Shenandoah River, Conococheague Creek, Monocacy River, and Occoquan River. The North Branch Potomac River drains the rugged northwestern part of the Potomac River Basin in Maryland, West Virginia, and Pennsylvania. The South Branch Potomac River and Cacapon River drain the mountainous West Virginia part of the basin. The Shenandoah River, the largest of the Potomac River's tributaries, drains the broad, relatively flat Shenandoah Valley in Virginia. Conococheague Creek and the Monocacy River drain the northern and northeastern parts of the basin in Maryland and Pennsylvania. The largest tributary in the eastern part of the basin is the Occoquan River in Virginia, which enters directly into the freshwater tidal Potomac River south of Washington, D.C. (Federal Energy Regulatory Commission, 1980).

The fresh headwaters originate high in the Appalachian mountain system, close to the southwest corner of Maryland. Here, the North Branch flows northeastward for 100 statute miles (161 km), forming a part of the Maryland and West Virginia border. As it passes eastward from Cumberland, many other large rivers, such as the South Branch, the Shenandoah, and the Monocacy, contribute substantially to the combined flow. These tributaries and many other smaller streams flow north through Virginia and West Virginia and south through Pennsylvania and Maryland to meet the Potomac. The riverine segment terminates near the fall line, which is demarked by a series of rapids at Washington, D.C. At Little Falls, 300 statute miles (483 km) from its source, the river comes under the influence of tides, and the estuary begins. The estuary runs another 113 statute miles (182 km) before it meets the Chesapeake Bay.

The Potomac River is free flowing and contains freshwater upstream from Washington, D.C. At Washington, below the scenic Great and Little Falls, the more than

100 miles of tidewater Potomac begins and gradually changes from a fresh tidal river to a salty estuary en-route to its mouth at the Bay. The total fall from this confluence to sea level at Washington, D.C., is 520 feet. The river contains freshwater and is tidal from Washington, D.C., to near Indian Head, Md., where the water becomes brackish. From Indian Head to Point Lookout, Md., the river water becomes progressively more salty as it approaches the Chesapeake Bay.

The basin has a generally temperate climate with extremes more pronounced in areas west of the Shenandoah River. The winters are seldom rigorous and usually result in heavy snowfall in only the northwest portion of the basin. The summers are generally warm. The mean annual temperatures range from 59 degrees Fahrenheit in tidewater areas to 51 degrees Fahrenheit in the Appalachian Highlands (Pang, et al., 1991). The prevailing winds are westerly with a mean velocity of about 10 miles per hour. Average annual precipitation ranges from 30 to 35 inches in the foothills of the Allegheny Mountains, to 50 inches along the western divide, and 45 inches along the crest of the Blue Ridge Mountains (Gerhart and Brakebill, 1996).

The watershed collects, on the average, a yearly precipitation of approximately 45 inches (1.1 meter), which results in a yearly average freshwater flow of 11,190 cubic feet (313 cubic meter) per second at the head of its estuary (Pang, et al., 1991). Precipitation is generally greatest from June to September with the lowest monthly total occurring in February or November. Snow falls in all sections of the basin and varies in depth from 10 inches along the Chesapeake to 100 inches along the western divide. The average annual runoff is about 0.95 cubic feet per second per square mile (12.8 inches). March and April are generally the months of greatest runoff, usually ranging from 4 to 8 times above normal, while September and October are generally the months of least runoff, usually ranging from 3 to 10 percent below the norm (Gerhart and Brakebill, 1996). Flood-producing storms occur in all seasons of the year. Summer and fall floods are related to tropical disturbances having intense rainfalls of short duration. Spring and winter floods usually result from sustained rainfall that sometimes contributes to large flood flows (Gerhart and Brakebill, 1996). Mean annual lake evaporation varies from 30 inches in the northern part of the Potomac River Basin to 40 inches in the southern portion. Approximately 70 percent of the evaporation occurs from May through October (Gerhart and Brakebill, 1996).

The major population center in the Potomac River Basin is the metropolitan area of Washington, D.C., at the eastern boundary of the basin (Figure 3.1). Other, much smaller, population clusters include Cumberland, Hagerstown, Frederick, Rockville, and Waldorf in Maryland; Staunton, Waynesboro, Harrisonburg, Front Royal, Winchester, Alexandria, Leesburg, and Manassas in Virginia; Petersburg, Moorefield, Harpers Ferry, and Martinsburg in West Virginia; and Chambersburg, Waynesboro, and Gettysburg in Pennsylvania. However, 75 percent of the basin's 1990 population lived in the Washington, D.C., metropolitan area (Gerhart and Brakebill, 1996).

The Potomac and its tributaries are used for many important purposes, such as public drinking water supplies, power plant cooling water, commercial and sports fishing, boating and other water-related recreation (Eastman, 1985). It is important to understand how the Potomac River's hydraulic processes will interact with changing river discharge volumes along with various physiographic settings such that future urban and hydrographic planners can prepare better urban and hydrologic modeling.

3.2 Study Area Physiography

The sources of the following description of physiography of the Potomac River Basin are: Fenneman and Johnson (1946); Interstate Commission on the Potomac River Basin (Gruessner, 1997); State of Maryland Department of Natural Resources (Edwards,1981); USGS Water Resource Investigations Report 96-4034 (Gerhart and Brakebill, 1996); and Geology of the Chesapeake and Ohio Canal National Historical Park and Potomac River Corridor, District of Columbia, Maryland, West Virginia, and Virginia by USGS geologist Southworth (2001).

The Potomac River Basin contains parts of six distinct physiographic provinces that extend from the southwest to northeast along the Atlantic Coast of the United States (Fenneman and Johnson, 1946). The physiographic provinces include the Appalachian Plateau, Valley and Ridge, Great Valley, Blue Ridge, Piedmont, and Coastal Plain (Figure 3.2). The Valley and Ridge is the largest province in the basin and includes the Great Valley subprovince. The Piedmont is the second largest province and contains the Triassic Lowlands subprovince. The varied topography of these six provinces forms a complex landscape within the Potomac River Basin that includes steep mountains, rolling hills, broad valleys, and plains. Many of the differences among physiographic settings are related to the geology of the Potomac River Basin area. The distribution of study subbasins by physiography is shown in Table 3.1.

Table 3.1 Physiographic Province Distribution of Study Subbasins

Physiography	Number of Subbasins	Percentage of Total Area (14,670 square miles)
Appalachian Plateau	2	4%
Great Valley	7	21%
Valley and Ridge	2	34%
Blue Ridge	15	6%
Piedmont	12	12%
Coastal Plain	5	22%

Source: USGS Water Resource Investigations Report 96 - 4034

The Appalachian Plateau is the westernmost province and comprises about 4 percent of the basin in Maryland, Pennsylvania, and West Virginia (Interstate Commission on the Potomac River Basin's The Potomac and the Chesapeake Report). It is characterized by narrow valleys and steep, rugged ridges creating local topographic relief of 500 to 2,000 ft. The Appalachian Plateau contains the highest point in the basin, Spruce Knob, which rises to an altitude of 4,860 ft. The North Branch Potomac River drains the Appalachian Plateau. The Appalachian Plateau is separated from the Valley and Ridge Province to the east by the Allegheny Front, a major escarpment with as much as 3,000 ft of local relief that trends northeast through the basin (Pang, et al., 1991).

The Valley and Ridge Province is the most extensive province in the basin and occurs in Virginia, West Virginia, Maryland, and Pennsylvania. This province comprises 34 percent of the basin excluding the Great Valley subprovince (Interstate Commission on the Potomac River Basin's The Potomac and the Chesapeake Report). The rocks in this province have been intensely folded and faulted, producing long, narrow, northeast-trending structures. Subsequent erosion and weathering have resulted in the distinctive topographic grain of this province, with ridges capped by resistant sandstone and valleys underlain by less-resistant shale and carbonate rocks. Topographic relief in the Valley and Ridge Province is considerable, ranging to as much as 1,800 ft. The trend of the ridges substantially affects surface drainage in the basin, so that the principal tributary streams, the South Branch Potomac and Cacapon Rivers, flow northeast to the Potomac River (Gerhart and Brakebill, 1996).

The Great Valley occupies the eastern part of the Valley and Ridge Province and is a broad valley, 15 to 20 miles wide, with minor relief over extensive areas. It covers 21 percent of the basin (Interstate Commission on the Potomac River Basin's The Potomac and the Chesapeake Report). Shale and siltstone underlie the central part of the Great Valley and are bordered by areas underlain by carbonate rocks. The carbonate rocks that make this subprovince favorable for farming also are susceptible to dissolution, resulting in numerous caves and other karstic features throughout most of the area. The Shenandoah River and Conococheague Creek are the major tributaries to the Potomac River that drain this subprovince.

The Great Valley, which is divided into carbonate and non-carbonate subunits, is a part of the Valley and Ridge Physiographic Province. The Great Valley is bounded by the Blue Ridge Mountains to the east and Great North Mountain to the west, and is interrupted by Massanutten Mountain in Virginia. Seventy percent of the Great Valley is underlain by carbonate (limestone and dolomite) bedrock (Denis and Blomquist, 1995), with numerous sinkholes and caverns. The major streams in the Great Valley include the North Fork Shenandoah River, South Fork Shenandoah River, the main stem Shenandoah River, Opequon Creek, Conococheague Creek, and Antietam Creek (Ferrari, 1999).

Bordering the Great Valley on the east is the Blue Ridge Province. It covers 6 percent of the basin and consists of a mass of crystalline rocks that rises about 1,500 to 2,000 ft above the lowlands on either side (Southworth, 2001). In Virginia, the Blue Ridge forms the southeastern boundary of the Potomac River Basin. In Maryland and Pennsylvania, it forms a major drainage divide within the basin, with all streamflow from west of the Blue Ridge flowing through the gap at Harpers Ferry, West Virginia. Because of relief and narrowness, most of the streams that drain the Blue Ridge are headwater tributaries of larger streams in the Great Valley or Piedmont (Southworth, et al., 2001).

The Piedmont Province lies to the east of the Blue Ridge and comprises about 12 percent (Interstate Commission on the Potomac River Basin's The Potomac and the Chesapeake Report) of the Potomac River Basin in Virginia, Maryland, Pennsylvania, and Washington, D. C. It is an area of gently rolling terrain with low to moderate relief. The eastern and western parts of the Piedmont are underlain by resistant crystalline rocks, whereas the central part, the Triassic Lowlands subprovince, 7-percent of the basin (Southworth, et al, 2001), is underlain by less-resistant sedimentary rocks of primarily Triassic age. The Triassic Lowlands subprovince is generally flatter than the surrounding Piedmont. The principal tributary to the Potomac River in the Piedmont Province is the Monocacy River, which also drains agricultural lands in the Triassic Lowlands subprovince (Southworth, et al, 2001).

The Fall Line separates the Piedmont from the Coastal Plain Province to the east. At the Fall Line, the rolling hills of the Piedmont drop in elevation to meet the gently sloping Coastal plain. Stream gradients abruptly steepen through the Fall Line as they enter the Coastal Plain. The Potomac River drops nearly 150 ft to near sea level as it flows through Great Falls and Little Falls near Washington, D. C. The Fall Line also marks the terminus of the upper Potomac River, which, at this point, drains about 11,670 square miles of the six provinces and subprovinces upstream. Smaller tributaries enter the tidal Potomac River after flowing from the Triassic Lowlands and Piedmont through the Fall Line onto the Coastal Plain.

The Coastal Plain Province is fundamentally different from the other physiographic provinces in that it is underlain by unconsolidated sediments that form a gentle seaward-sloping plain of low relief. It is in this province that the Potomac River is tidally affected, eventually becoming a broad estuary before entering the Chesapeake Bay. The estuary is typically flanked by broad lowlands that mark the sinuous and deep course of an ancestral Potomac River Valley now filled by unconsolidated sediments (Interstate Commission on the Potomac River Basin's The Potomac and the Chesapeake Report).

3.3 Study Area Geology and Lithology

The geology of the Potomac River Basin is complex and diverse, ranging from relatively undisturbed, unconsolidated sediments to intensely deformed crystalline rocks (Milici, 1963; Cleaves, 1968). The study subbasins are located in the many different physiographic settings. Four major types of rock are present in the region: Siliciclastic sedimentary (shale and sandstone), carbonate sedimentary (limestone and dolomite), crystalline metamorphic and igneous (gneiss, schist, and diabase dikes), unconsolidated sediments (sand, silt, and clay), and undivided (carbonated and silicrystalline). The most intensely deformed and the oldest rocks in the basin are crystalline rocks in the Piedmont and Blue Ridge Provinces. Predominant rock types are massive granite and layered gneiss, foliated phyllite and schist, quartzite, marble, and metadolomite. The folding and faulting associated with the tectonic stresses have produced very complex rock structures.

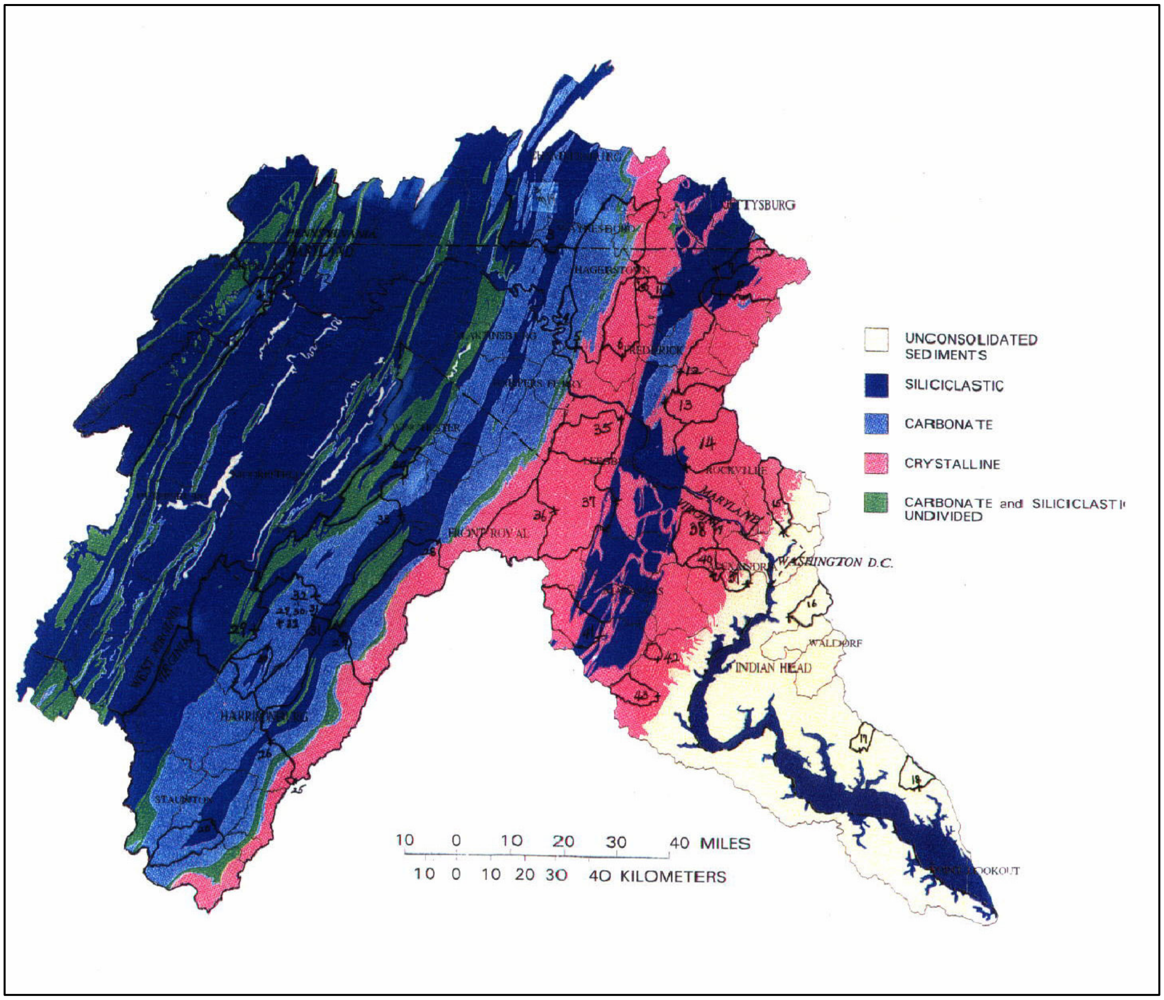


Figure 3.3 Study Area Lithology
Source: US Geological Survey Water Resources Investigations Report 96-4034

Sedimentary rocks of Cambrian through Pennsylvanian age underlie the Valley and Ridge and Appalachian Plateau Provinces. The rocks of the Valley and Ridge have been deformed by folding and thrust faulting into a series of plunging folds. Although folded and faulted, these rocks were farther away from the center of tectonic activity than the crystalline rocks of the Piedmont and Blue Ridge. Therefore, the rocks in the Valley and Ridge were not recrystallized during orogenic events. In the Valley and Ridge Province the rocks can be broadly categorized into siliciclastic and carbonate types. Rocks in the Appalachian Plateau Province are similar lithologically to the siliciclastic types in the Valley and Ridge with the exception that coal-bearing rocks are found in the Appalachian plateau. Although major thrust faults occur at depth, rocks in the Appalachian Plateau Province are relatively flat-lying and less deformed than rocks in the Valley and Ridge (Southworth, et al., 2001).

The youngest consolidated rocks in the basin are found to the east of the Blue Ridge Province, in the part of the Piedmont Province underlain by sedimentary rocks. These rocks were formed during the Late Triassic and Early Jurassic by streams discharging sediment into down-faulted rift basins. In the Potomac River Basin, the faulted margin of these basins borders the Blue Ridge, and other faults are present throughout the sequence. The sedimentary sequence is interrupted locally by igneous intrusive and extrusive rocks (Gerhart and Brakebill, 1996).

The youngest geologic units in the basin are in the Coastal Plain Province. These units consist of unconsolidated sediment that forms a southeastward-thickening wedge of interbedded sand, silt, and clay. Unconsolidated sediments underlie about 15 percent of the basin; carbonate sedimentary rocks underlie about 17 percent; siliciclastic sedimentary rocks underlie about 42 percent; and crystalline rocks underlie about 19 percent of the basin (Southworth, 2001). The remaining 7 percent consists of geologic units that contain significant proportions of both carbonate and siliciclastic sedimentary rocks (Southworth, et al., 2001). The distribution of the study gage stations over various geological settings is shown in Table 3.2.

Table 3.2 Geological and Lithological Distribution of Study Subbasins

Geology	Number of Subbasins
Undetermined	7
Siliclastic Sedimentary rocks	13
Carbonate Sedimentary	5
Unconsolidated Sedimentary	5
Crystalline Metamorphic rocks	13

Source: U.S. Geological Survey Open-File Report 01-188

Physical and geologic characteristics provide the primary factors affecting the hydrologic properties of the ground water and surface water systems and, thus, form the primary natural factors affecting hydraulic geometry within the basin. Because of the diverse physical characteristics of the Potomac River Basin, lithology has been divided into six subunits for the purpose of hydraulic geometry assessment. This subdivision was done using a hierarchical process considering basin physiography and geology (Figure 3.3). Physiographic provinces are used as the primary units of the subdivision because of their structural effects on the hydrologic systems. The six subunits will be referred to throughout this paper and will serve as one of areal comparisons of hydraulic geometry.

The Appalachian plateau subunit is composed primarily of siliciclastic rocks. The Valley and Ridge subunit is underlain by both siliciclastic and carbonate rocks. Some of its carbonate rocks are interbedded with siliciclastic rocks and are cemented by carbonate material. This interbedding is characteristic of the region. The Great Valley subprovince is divided into a carbonate subunit and a non-carbonate subunit because carbonate regions have unique hydrologic properties and because the carbonate units are areally contiguous and extensive. The Blue Ridge is formed by crystalline rocks. The Piedmont comprises the crystalline rock. As in the Blue Ridge subunit, the rocks underlying this subunit are crystalline. However, the rolling topography of this subunit provides a distinct hydrologic setting. The Coastal Plain subunit is underlain by unconsolidated sediments. Due to the distinct physiology and lithology the hydrologic factors affecting ground water and surface water flow in this subunit are unique within the Potomac River Basin Source (Interstate Commission on the Potomac River Basin's The Potomac and the Chesapeake Report).

3.4 Study Area Hydrology

The six major tributaries of North Branch Potomac River, South Branch Potomac River, Cacapon River, Conococheauge Creek, Shenandoah River, and Monocacy River, draining the Potomac River Basin are depicted in Figure 3.1. These six tributaries drain to the upper Potomac River upstream from the Fall Line. Additional tributaries drain directly to the tidal Potomac River and include the Anacostia and Occoquan Rivers.

Streams upstream from the Fall Line generally have steeper gradients and flow more swiftly than streams downstream from the Fall Line. The main stem Potomac River and major tributaries generally have bedrock bottoms, with alluvial sediments in depositional areas. Stream-bottom materials range from bedrock to small cobbles and gravel in upstream areas, to eroded fine sediments to gravel, sand, and silt in Coastal Plain streams. Several streams, notably Conococheague Creek and the South Fork

Shenandoah River, undergo considerable flood-plain meandering in their downstream reaches. Coastal Plain streams, downstream from the Fall Line, have shallow gradients and discharge to tidal creeks or wet-lands, which have considerable effect on stream flow and stream morphology.

Trainer and Watkins (1975) found that average base runoff from tributaries in the upper Potomac River Basin was approximately proportional to drainage area. The six major tributaries upstream from the Fall Line represent about 64 percent of the drainage area and contribute about 63 percent of the mean annual streamflow. At low flows, however, Trainer and Watkins (1975) found that the area underlain by carbonate rocks, which are mostly in the Great Valley subprovince, contribute a proportionately larger share of flow to the Potomac River at Washington, D. C. For example, the Shenandoah River contributes about 38 percent of the streamflow during low-flow conditions yet contains only 26 percent of the upper Potomac River Basin (Trainer and Watkins, 1975).

The ratio of runoff to precipitation is somewhat higher in the Appalachian Plateau and westernmost parts of the Valley and Ridge Province, where steep slopes, shallow soils, and less-permeable bedrock contribute to the greater total runoff. About 50 percent of precipitation becomes surface runoff in these mountain areas. In the remainder of the Potomac River basin, with generally flatter slopes, deeper soil profiles, and more fractured bedrock, karst terrain, or Coastal Plain deposits, about 35 percent of precipitation contributes to surface runoff.

Most streams in the Potomac River Basin generally have good year-round flow experienced notable hydrologic extremes. Rains from Tropical Storm Juan in November and infrequently experience very low or no flow. However, the Potomac River Basin has

1985 produced catastrophic flooding in the South Branch Potomac River and parts of the Shenandoah River (Carpenter, 1990).

Selected characteristics of environmental setting for the Potomac River Basin such as physiography, geology, lithology, and hydrology are describe in this chapter and these characteristics are used as predictor variables for the investigation of hydraulic geometry. The next chapter will discuss measurable characteristics of the study site and data types for the study.

CHAPTER 4

MEASUREMENTS OF SUBBASIN CHARACTERISTICS: Computation of Derived Data

In order to perform the empirical research for this investigation of at-a-station hydraulic geometry, the following primary data were required, and from these primary data many other datasets were derived.

- Gage Stations (4.1)
- Digital Elevation Data (4.2)
- Hydrographic Survey Data (4.3)

    -Water Discharge Volume Data

    -Channel Width

    -Channel Depth

    -Flow Velocity

    -Field Survey Data (4.4)

    -Bed and Bank Materials

- Physiography and Lithology (4.5)
- Landuse Information (4.6)
- Derived Data (4.7)

The items 4.1 thru 4.6 and portions of the Derived Data items (Section 4.7) are discussed in this Chapter 4, and the rest of the derived data are discussed in Chapter 5, Hydraulic Geometry and the Environmental Setting. These chapters discuss how the data were collected and used to generate more information on the study subbasins, and then analyzed to characterize subbasins via a variety of properties.

After the general area, the Potomac River Basin, was selected for study, the specific gage stations and hydrographic survey measurements to be included in the research were selected based on the duration of the hydrographic survey time and the size of each drainage subbasin as well as the highest number of survey measurements on a specific survey location at each gage station. Next, information for other selected environmental settings characteristic of each subbasin, such as physiography, lithology, geology, land use, and the nature of nested subbasins which reflects hierarchies of the streams such as the subbasin of a creek within a river subbasin, was collected. In addition, 43 gage station descriptions and historical streamflow daily values covering 1985-1995 were used for explanation of the results of the impact of the environment context for the hydraulic geometry analyses.

4.1 Gage Stations

Since 1896, and in cooperation with State agencies, the USGS has been collecting a large amount of data pertaining to the water resources of the nation, such as volume of surface water, width and depth of channel, velocity of flow, and water quality among others at a given gage station throughout the year and publishes some of the surface water discharge volume data each year. A gage station is identified as a particular site on a stream, canal, lake, or reservoir where systematic observations of hydrologic data are obtained. These data, accumulated during many water years, constitute a valuable database for developing an improved understanding of rivers.

The USGS established 178 permanent gage stations in the Potomac River Basin to perform hydrographic surface water discharge measurements. Each gage station is at a particular site on a stream where systematic observations of hydrologic data are made. Ninety-four surface water discharge gage stations are in Maryland and the District of Columbia, and 84 are in Virginia.

Of these 178 gage stations in the Potomac River Basin, 43 (18 in Maryland and 25 in Virginia) were selected for study based on the following criteria. The first criterion was the hydrographic survey time. In order to accommodate the impacts of latent hydrographic processes on stream channels, gage stations were selected that have continuous survey measurements performed from just before the "big flood" of the 1985s, until 1995, a ten-year period. The second criterion was the size of the drainage area subbasins, a necessary criterion for investigation of scale effects on hydraulic geometry. The sizes of the selected drainage areas range from 0.31 square miles (published by the USGS Water Resource Division as 0.38 square miles), for subbasin 01640980 (USGS gage station identification number), Bear Branch near Thurmont, Maryland, to 1632 square miles (published by the USGS Water Resource Division as 1,642 square miles), for subbasin 01629500, South Fork Shenandoah River at Front Royal, Virginia.

The selected gage stations are listed in Table 4.1 and are portrayed on Figures 4.3, and 4.4. Table 4.1 shows the USGS gage station identification numbers and sequentially numbered by the author's identification number, gage station name, location of gage station in geographical coordinates, UTM Zone identification, number of measurements that were used for the calculation of the b-f-m, measurement duration, exact location of the channel for hydrographic survey measurements, and measurement methods (wading or using cables).

Table 4.1 Selected Gage Stations

	ID	POTOMAC RIVER BASIN	USGS Gage Station	Latitude	Longitude	UTM Zone	Number of Surveys	Survey Duration	Survey location	Survey Method
		North Branch Potomac River at Pinto, MD								
1	m10	Wills Creek near Cumberland, MD	1601500	394007	784718	17	29	6/85-9/92	500' a	wading
2	m11	North Branch Potomac River near Cumberland, MD	1603000	393716	784624	17	21	2/85-6/93	150' a	not wading
		Potomac River at Hancock, MD								
3	m19	Conococheague Creek at Fairview, MD	1614500	394257	774928	18	45	1/85-8/94	at gage	not wading
4	m21	Marsh Run at Grimes, MD	1617800	393053	774638	18	47	2/85-2/94	10' b	wading
5	m24	Antietam Creek near Sharpsburg, MD	1619500	392701	774352	18	37	1/85-8/93	150' a	not wading
6	m26	Catoctin Creek near Middletown, MD	1637500	392535	773325	18	25	8/88-10/92	350' b	wading
		Potomac River at Point of Rocks, MD								
		Monocacy River at Bridgeport, MD								
7	m29	Piney Creek near Taneytown, MD	1639140	393938	771316	18	13	1/91-11/92	140' a	wading
8	m30	Big Pipe Creek at Bruceville, MD	1639500	393645	771410	18	43	11/88-8/95	150' a	wading
9	m31	Hunting Creek near Foxville, MD	1640965	393710	772800	18	38	1/85-5/94	100' b	wading
10	m311	Huntington Creek Tributary near Foxville	1640970	393742	772744	18	18	3/85-3/91	100' b	wading
11	m32	Bear Branch near Thurmont, MD	1640980	393715	772624	18	17	6/90-11/91	15' b	wading
12	m34	Monocacy River at Jug Bridge, MD	1643000	392413	772158	18	43	5/87-8/94	Reichs Ford	wading
13	m37	Bennett Creek at Park Mills, MD	1643500	391740	772430	18	26	6/85-7/93	150' a	wading
14	m38	Seneca Creek at Dawsonville, MD	1645000	390741	772013	18	28	6/88-3/95	600' b	wading
		Potomac River at Chain Bridge at Washington, DC								
		Northeast Branch Anacostia River at Riverdale, MD								
	m43	Northwest Branch Anacostia River near Hyattsville	1651000	385709	765800	18	56	2/85-8/94	2000' b gage	wading
16	m45	Piscataway Creek at Piscataway, MD	1653600	394220	765800	18	23	10/87-4/93	100' a	wading
17	m47	St. Clement Creek near Clements, MD	1661050	382000	764331	18	54	6/85-6/94	150' b	wading
18	m48	St. Marys River at Great Mills, MD	1661500	381436	763013	18	64	11/84-7/95	100' b	wading
19	v07	North River near Burketown	1622000	382025	785450	18	33	8/89-11/94	at gage	wading
		Middle River								

20	v12	Christians Creek near Fishersville	1624800	380742	785941	17	36	8/89-11/94	500' b	wading
21	v13	Middle River near Grottoes	1625000	381542	785144	17	9	9/89-7/92	300' a	wading
							13	8/89-12/93	Under DSS	wading
22	v15	South River near Waynesboro	1626000	380327	785430	17			bridge	
23	v17	South River near Dooms	1626850	380519	785238	17	25	9/85-12/94	700' b	wading
24	v18	South River at Harriston	1627500	381307	785013	17	18	8/89-2/93	500' b	wading
		South Fork Shenandoah River								
		Madison Run								
25	v19	White Oak Run near Grottoes	1628060	381501	784457	17	26	8/90-11/94	300' a	wading
		South Fork Shenandoah River near					9	2/93-8/94	1500' a gage	wading
26	v22	Lynnwood	1628500	381921	784518	17				
							17	8/89-12/94	50' a	wading
		South Fork Shenandoah River near								
27	v23	Luray	1629500	383846	783206	17				
		South Fork Shenandoah River at					64	2/85-12/94	0.7mi.USS	not wading
28	v24	Front Royal	1631000	385450	781240	17			bridge	
		North Fork Shenandoah River at Cootes					16	8/90-12/93	1,000' a gage	wading
29	v25	Store	1632000	383813	785111	17				
30	v26	Linville Creek at Broadway	1632082	383624	784813	17	17	11/85-12/94	150' b	wading
31	v27	Smith Creek near New Market	1632900	384136	783835	17	22	8/89-11/94	150' a	wading
		North Fork Shenandoah River at Mount					22	11/89-11/94	0.6 mi. b	wading
32	v28	Jackson	1633000	384443	783821	17				
		North Fork Shenandoah River near					45	3/85-10/94	100' a	wading
33	v29	Strasburg	1634000	385836	782011	17				
34	v30	Cedar Creek near Winchester	1634500	390452	781947	18	17	9/89-12/94	150' b	wading
35	v36	Catoctin Creek at Taylorstown	1638480	391518	773436	18	17	9/87-12/91	100' a	wading
		Potomac River at Point of Rocks, Md								
36	v38	Goose Creek near Middleburg	1643700	385911	774749	18	10	10/89-12/94	250' b	wading
37	v39	Goose Creek near Leesburg	1644000	390110	773440	18	13	5/91-12/94	1000' b	wading
38	v44	Difficult Run near Great Falls	1646000	385833	771446	18	16	9/89-12/94	under bridge	wading
		Potomac River at Chain Bridge at Washington, D. C.								
39	v48	Cameron Run at Alexandria	1653000	384823	770636	18	22	12/89-9/94	75' b	wading
40	v49	Accotink Creek near Annandale	1654000	384846	771343	18	9	2/85-10/94	100' a	wading
		Occoquan River								
41	v52	Cedar Run near Catlett	1656000	383812	773731	18	8	9/89-6/94	150' b	wading
		South Fork Quantico Creek near					10	9/90-8/94	100'D.S	from
42	v65	Independent Hill	1658500	383514	772544	18			bridge	bridge
43	v71	Aquia Creek near Garrisonville	1660400	382925	772602	18	10	8/87-12/94	400'b	wading

Sources: Water Resources Data Maryland and Delaware Water Year 1993, Volume 1, US Geological Survey Water Data Report MD-DE-93-1
Water Resources Data Virginia Water Year 1993, Volume 1, US Geological Survey Water Data Report VA-93-1

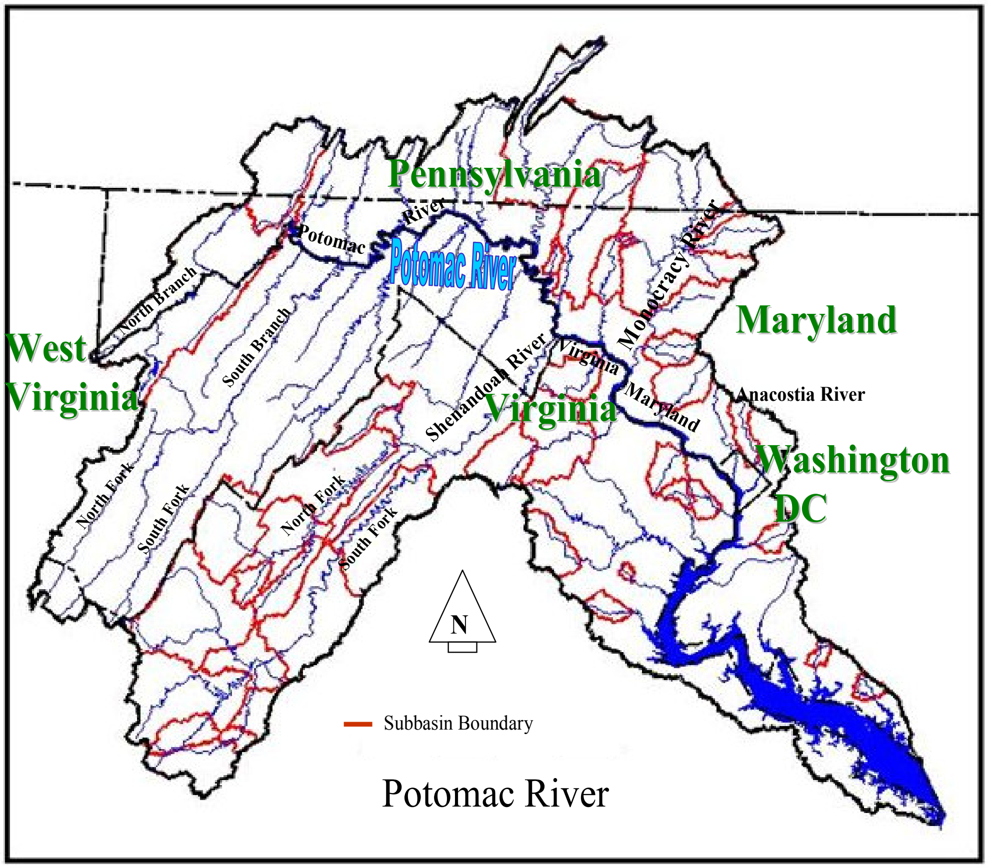


Figure 4.1 Subbasin Locations
Source: US Geological Survey Water Resources Investigations Report 96 – 4034

The geographic coordinates of the 43 gage stations, expressed in degrees, minutes, and seconds of latitude and longitude, were available via the USGS Gage Descriptions and Water-Data Reports published by the USGS for each year covering 1985-1995 (Table 4.1). This information on the gage station description and Water-Data Reports was digitized by the author and converted into decimal degrees. This location data was used as a seed point for subbasin delineation (Figure 4.1) and flow direction, and flow accumulation calculations for each subbasin.

After selecting the 43 gage stations, the next step was to select the specific hydrographic surveys within each subbasin that would best support this study. Because the USGS typically conducts hydrographic surveys at different points along a given channel, the author selected those surveys at the stream location that sustained the highest number of surveys over the 1985 - 1995 study periods. For example, some gage stations have up to 109 measurements and others have considerably less, but most of the selected 43 gage stations had around 30 surveys during the 1985 - 1995 time period. This hydrographic survey information was obtained from the USGS Field Folders, that also contained information about the location of the survey points along the channel for each hydrographic survey measurement, such as “the survey was made across the channel 100 feet above the gage station or 200 feet below the gage station”. All survey measurements for each gage station were then classified and tallied according to the location of the survey points (Appendix A). The number of survey measurements is shown in Table 4.1 for the selected gage stations.

4.2 Digital Elevation Data

The most universally accepted hydrologic models use digital elevation data to calculate flow path, flow accumulation, subbasin boundaries, and a topographic index. The common inputs for these hydrological models are the uniformly spaced digital elevation model (DEM) data that the USGS produces. DEMs are inputs to the Arc/Info™ Hydrologic Model and topographic index generation AML™ used by the author.

Recently, there have been attempts to use other forms of digital elevation data, rather than the regularly spaced DEM data, such as the Triangulated Irregular Network

(TIN) data in hydrological modeling (Azagra, 1999). However, the benefits of using the TIN hydrological model are not conclusive and models using other than DEM data are still maturing. Hence, the Arc/Info™ Hydrologic Model and topographic index AML™ were chosen because of their ease of use and because they facilitate easy comparison of study results with numerous published hydrological empirical research that employed regular lattice rather than TIN data structures.

For this study, the majority of the DEMs that were used are 7.5 minute by 7.5 minute data with the resolution of 30 meter post spacing. Where there was no 7.5 minute coverage at the 1:24,000 scale DEM, which was for two DEMs, 1:250,000 scale DEMs were used. The 7.5 minute DEMs are derived from stereo-profiling or image correlation and the 30 minute DEMs are derived from Digital Line Graphs of 7.5 minute quadrangle maps produced by the USGS.

The finer resolution of DEMs could be better for the delineation and calculation of a topographic index. However, the 30 meter spacing DEMs was sufficient for this research. The rationale is that the smallest subbasin, 0.38 square miles (984,455 square meters), is covered by 31 cells by 31 cells of 30 meter DEMs which is more than the minimum number of cells, 9, needed for a meaningful hydrologic model.

4.3 Hydrographic Survey Data

For this study, stream discharge (volume per second), channel width, depth, and flow velocity, as well as cross-section information, were needed. From these data, hydraulic geometry, mid-point of channel, channel asymmetry, channel pattern and channel shape as well as channel profiles were derived.

USGS hydrologists observe channel cross-sections from an initial point on one side of the bank at 1 or 2 foot intervals, in most cases, to the other side of the bank to obtain data on cross-section width, mean flow velocity, channel depth, and cross-section area size within a measurement of total discharge. The author converted their field notes to machine readable form. The author accompanied a USGS hydrologist during his field observations to see how the measurements are taken at riffle, pool, and intermediate points.

The USGS makes streamflow discharge measurements at gage stations using current-meter measurement methods (Buchanan and Somers, 1969). A current-meter measurement is the summation of the products of the partial areas of the stream cross-section and their respective average velocities. The area extends laterally from half the distance from the preceding meter location to half the distance to the next and vertically, from the water surface to the sounded depth (Figure 4.2).

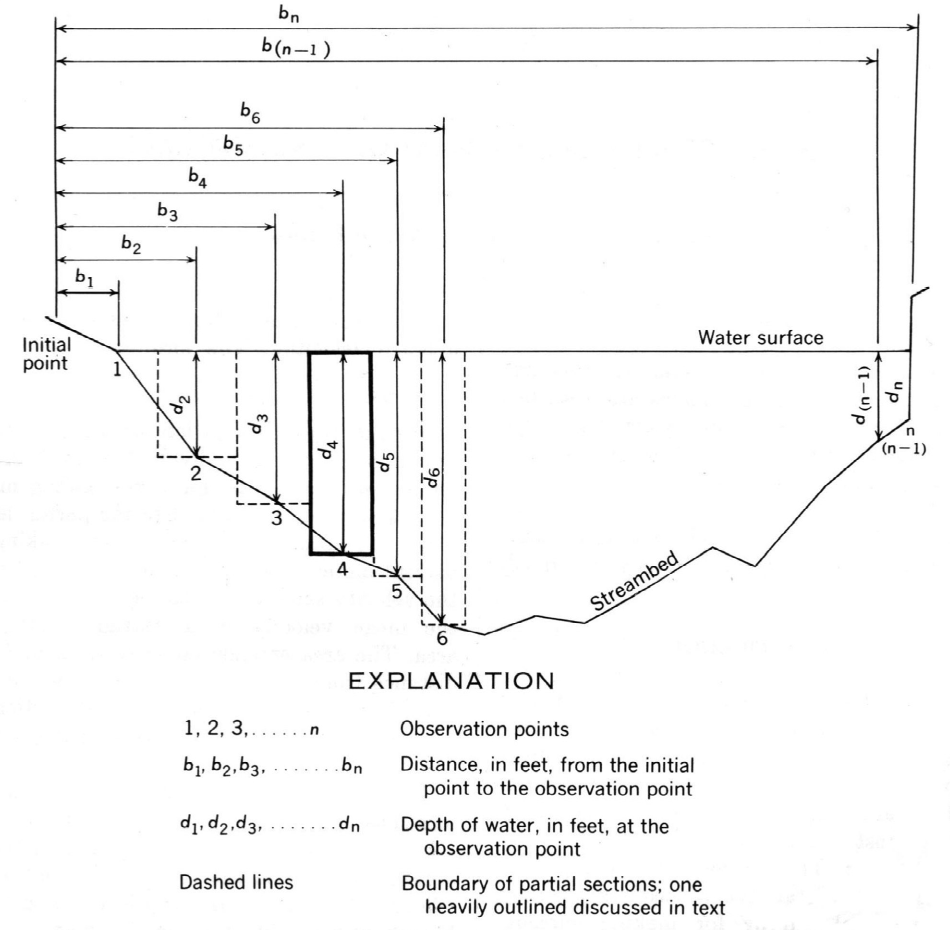


Figure 4.2 Midsection Method of Computing Cross-Section Area for Discharge Measurements

Source: Discharge Measurements at Gage Stations: U.S. Geological Survey Techniques, Water Resources Investigation Book 3, Chapter A8

The cross-section is defined by depths at locations 1, 2, 3, 4, ….., n. At each location the velocities are sampled by a current meter to obtain the mean of the vertical distribution of velocity. The partial discharge is computed for any partial section at location x as

$$q_x = v_x \, [(b_x - b_{(x-1)} /2 + (b_{(x+1)} - b_x)/2] \, d_x$$

$$= v_x \, [(b_{(x+1)} - b_{(x-1)} /2] \, d_x$$

where

q_x = discharge through partial section x,

v_x = mean velocity at location x,

b_x = distance from initial point to location x,

$b_{(x-1)}$ = distance from initial point to preceding location,

$b_{(x+1)}$ = distance from initial point to next location,

d_x = depth of water at location x.

Thus, for example, the discharge through partial section 4 (heavily outlined in Figure 4.2) is

$$Q_4 = v_4 [(b_5 – b_3 /2] d_4.$$

The summation of the discharges for all the partial sections is the total discharge of the stream. Streamflow velocity is measured at a point on each sub-cross-section which consists of 30 - 40 such points per each sub-cross-section measurement. The mean velocity in a vertical section is obtained from observations at many points in that vertical plane.

The USGS stores average channel width, depth, and flow velocity as well as flow discharge volume information obtained from each hydrographic survey in digital form as a one-line entry in Electronic 9207. For the 1,132 hydrographic surveys comprising this study (43 subbasins * approximately 30 surveys per subbasin), the author used these data to calculate the hydraulic geometry exponents.

As shown in Figure 4.2, an average of 30 segments for each survey were measured from one stream bank to the other and recorded in hand written Discharge Measurement Notes by the USGS. The author obtained and digitized these data and used them to calculate channel mid-point, asymmetry of channel and cross-section profiles. These cross-section profiles were used to characterize channel patterns and channel shapes of each subbasin.

The Discharge Measurement Notes data which provide sectional views of the channel are analyzed to identify the channel shape such as shallow and wide or deep and narrow channels, and the asymmetry of the 43 channels. Based on the conditions of flow, such as even or uneven flow, slow flow, cross-section such as rocky or firm, free of leaves or debris, etc., each hydrographic survey measurement was rated by the surveyor as excellent, good, fair, and poor. Excellent is defined as 2 percent error rate; good, 5 percent; fair, 8 percent; and poor, over 8 percent. The majority of the hydrographic surveys that this study used are rated as good or fair.

4.4 Field Surveys

To supplement the USGS Water Resource's Description of Gage Station and Discharge Measurement Notes which describe overall information of bed and bank materials of the subbasin, the author accompanied USGS hydrographers on several surveys and conducted independent field surveys to verify and/or collect bed material and bank material information. These field surveys were visual identifications of the bed and bank material such as clay, sand, silt, gravel, cobble, and rock. Types of bed and bank material for each subbasin were recorded in digital form for statistical characterization and were analyzed in the environmental setting.

4.5 Physiography and Lithology

The author acquired the physiography and lithology of the study area in the Arc/Info™ file format from the USGS Geographic Information Scientist, John W. Brakebill, who published a sampling strategy for a water-quality assessment of the Potomac River Basin (Water-Resource Investigations Report 96-4034). Hardcopy forms of physiography and lithology information are readily available through many USGS publications such as Geology of the Chesapeake and Ohio Canal National Historical Park and Potomac River Corridor, District of Columbia, Maryland, West Virginia, and Virginia (Southworth et al., 2001). Now, some of these information are in digital form too.

4.6 Landuse

General land use information is readily available through many USGS publications and the Interstate Commission on Potomac River Basin (ICPRB) such as: Potomac River Basin Land Use Data: Evaluation and Methodology to Determine Basin Land Use from Non-Digitized County Land Use Data—ICPRB Report 89-8 (Camacho, 1989); various National Water-Quality Assessment Program reports; and in Geology of the Chesapeake and Ohio Canal National Historical Park and Potomac River Corridor, District of Columbia, Maryland, West Virginia, and Virginia (Southworth, et al., 2001).

The land use information was acquired in hardcopy maps from the authors of the USGS Water-Resources Investigations Report 96-4034. The land use information was created by USGS Geographic Information Scientists using mid-1970's and updated using

1990 Census data. The land use type information for the study area was also acquired in Arc/Info™ file format from the USGS Geographic Information Scientist, John W. Brakebill.

4.7 Derived Data

In order to understand the hydraulic geometry values and the effects of subbasins characteristics on the hydraulic geometry, the following data were needed and the author derived them using digital elevation data and hydrographic survey data. They are:

(1) subbasin boundaries and sizes, and a

(2) topographic index, both of which are covered in this chapter; as well

(3) hydraulic geometry,

(4) channel pattern,

(5) channel shape,

(6) cross-section profile, and

(7) channel asymmetry, all of which are dealt with in Chapter 5.

With DEMs and gage station location information, drainage boundaries for subbasins were delineated. Also flow direction, flow accumulation, and topographic index, also referred to as Wetness Index, a function of upstream contributing area and the slope of the subbasin, were calculated. Using the primary data, specifically hydrographic survey measurement data, hydraulic geometry exponents were calculated and asymmetry of channel, and channel profile (for categorization of channel shape) were derived.

4.7.1 Subbasin Boundaries

A uniformly and accurately determined drainage area boundary for each of the 43 gage stations is necessary for this hydrologic study, in which the size of the drainage area is considered one of the predictor variables for analyzing hydraulic geometry. A drainage subbasin is an area that drains water and other substances to a common outlet as concentrated drainage. This area is normally defined as the total area flowing to a given outlet, the pour point. The location of a gage station is used as the pour point of each subbasin in this research. This is the lowest point along the boundary of the drainage basin. The USGS Water Resource Division's annual water year books publish the sizes of the drainage area for each gage station which were derived from digitizing USGS 7 ½ -minute topographical maps along divides indicated by contour elevations.

4.7.2 Alternative Method of Drainage Delineation

An alternative method, used by this author, is to delineate a drainage subbasin system using algorithms implemented in GIS software like Arc/Info™ for input of grid-based DEMs. These, an array of elevation values provide an estimate of terrain surfaces useful in computer-based hydrogeomorphological analysis, such as the automated extraction of topographic relief, elevation contours, subbasin stream networks, and subbasin boundaries (O'Callaghan and Mark, 1984; Band, 1986; and Moore et al., 1991).

4.7.3 Digital Elevation Model (DEM) Preparation

Two hundred and one DEMs covering 7 ½ minute quadrangle areas with 30 meter by 30 meter data spacing, and two DEMs covering 30 minutes by 30 minutes of arc, with

100 meter by 100 meter data spacing, were acquired from the USGS EROS Data Center in Sioux Falls, SD. After associated DEMs were manually identified for each gage station's subbasin boundary, the geographic coordinates of the gage station were converted to UTM Grid coordinates. This was necessary because the computer software required an input of a grid coverage consisting solely of the seed point for the delineation of each subbasin drainage boundary.

Many researchers (Mason and Maidment, 2000; Azagra, 1999; and Wolock, 1996) have demonstrated that the accuracy and detail of the hydrologic information which is automatically extracted from a DEM is directly related to the quality and resolution of the DEM itself. DEM data often contain subtle elevation errors which influence watershed delineation in flat areas. In order to resolve this problem, many algorithms condition terrain data.

The most common problem with DEMs results from errors in the sampling process which includes false elevations, no data, or artificial peaks and sinks. A sink is a topographic condition in which water collects to a point which has no outfall. For hydrologic analysis, artificial sinks are more worrisome than peaks because they could reduce the number of cells that should be contributing to the drainage area. Therefore, it was necessary to treat the DEMs by filling sinks using the Arc/Info™ software.

4.7.4 Subbasin Boundary Delineation

The author used several tools such as ESRI's Arc/Info™, ERDAS' IMAGINE™, and a couple of commonly used Arc/Info™ Macro Language routines for viewing and merging DEMs for drainage boundary delineation. These tools provide the capability to determine, for any location in a grid, the upslope area contributing to that point and the down slope path water would follow.

The drainage boundary delineation AML™ routine is based on water flow direction, flow accumulation, and watershed delineation. In addition, the calculation for the slope of the drainage area was added to the Arc/Info™ hydrologic model via an AML™. This was necessary to generate a topographic index (see later) for each subbasin area. Through this AML™ algorithm, the flow direction, flow accumulation, drainage boundary delineation, topographic index, and size of the drainage areas, were generated for the 43 subbasins in this study of the Potomac River Basin.

The following procedures were undertaken for determinations of channel flow direction, flow accumulation, and delineation of subbasin boundaries, and subbasin size.

1. Removed all sinks from the DEM using GRID command FILL,

A DEM with depressions ("sinks") need to be treated by smoothing or filling the depressions. The smoothing approach removes shallow depressions, but deeper depressions remain. A second approach is to "fill" depressions by increasing the value of cells in each depression to the value of the cell with the lowest value on the depression boundary.

2. Computed flow directions using the GRID command FLOWDIRECTION,

Most computer programs that automate the identification of drainage basins use neighborhood functions to determine the direction of flow for each cell in a grid elevation file. One of the complicated problems using DEM is encountering the allocation of an outward drainage direction to the depression points and the drainage basin with no outlet, i.e., the flow lines make a loop or the chain of flow line is broken at the depressed point.

Jenson and Domingue (1991) encoded the flow direction for a cell to correspond to the orientation of one of the eight cells that surrounds the cell. Jenson and Domingue's (1991) approach to delineate watershed boundaries and stream networks from DEM were incorporated through the ArcView™ extensions Spatial Analyst™ and Watershed Delineator™, both distributed by ESRI™ (Mason and Maidment, 2000).

After filling, the resulting grid was then run through the flow direction process. In this step, the flow direction of each cell in the grid was determined by examination of the elevations in each surrounding cell. Thus, the steepest slope determines the cell's flow direction. This procedure is to determine the direction of flow from every cell in the grid. The direction of flow is determined by finding the direction of steepest descent from each cell.

3. Computed the flow accumulation (number of cells contributing to a cell – not actual flow volume or rate) using the GRID command FLOWACCUMULATION,

This function uses the newly created flow direction grid to determine the number of upstream cells above each point in the basin. The flow accumulation process counts the number of cells that contribute flow to a cell using the flow direction grid. At any given cell, the drainage area to the cell (but not including the cell) is the product of the flow accumulation value and the cell area.

4. Subbasin Boundary Delineation

Once the flow accumulation grid was created, the information about each gage site location in latitude and longitude was used as a seed point to delineate watersheds. The seed points must be placed in the proper locations on the flow accumulation grid in order to generate the final results. Considering the accuracies of published gage station locations, snappour 100 meters radius was included in the Process.aml (Appendix B) to allow gage site to be on its own stream. Next, the seed point grid was used as inputs into the watershed function to create the watershed delineations.

4.7.5 Subbasin Drainage Area Size Computation

Average area is determined by counting flow accumulation cells. The flow accumulation process counted the number of cells (pixels) that contribute flow to a cell using the flow direction and flow accumulation grid. At any given pixel, the drainage area to the pixel is the product of the flow accumulation value and the grid cell area. Thus, by checking the flow accumulation value at a point, only a simple calculation is needed to find the drainage area. Subsequently, the subbasin drainage area size is calculated as: Drainage Area (mile^2) = # of cells * cell size^2 (meter^2) / 2,589,988 (meter^2 / mile^2). The USGS published subbasin drainage sizes and the calculated subbasin sizes for the 43 subbasins are listed as Table 4.2.

Table 4.2 USGS Published and Calculated Subbasin Size in Square Miles and Miles

ID	ID	Published (mi2)	Calculated (mi2)	Perimeter (mi)	Difference	Percentage
1	m10	247	247.34	108.09	-0.34	99.86
2	m11	875	876.97	285.08	-1.97	99.78
3	m19	494	508.06	248.34	-14.06	97.23
4	m21	18.9	18.56	35.55	0.34	101.83
5	m24	281	281.52	137.23	-0.52	99.82
46	m26	66.9	67.19	59.69	-0.29	99.57
7	m29	31.3	31.31	44.04	-0.01	99.97
8	m30	102	102.63	77.58	-0.63	99.39
9	m31	2.14	2.17	9.2	-0.03	98.62
10	m311	4.01	3.96	12.07	0.05	101.26
11	m32	0.38	0.31	2.94	0.07	122.58
12	m34	817	721.43	204.18	95.57	113.25
13	m37	62.8	63.28	56.52	-0.48	99.24
14	m38	101	102.03	65.54	-1.03	98.99
15	m43	49.4	49.44	59.84	-0.04	99.92
16	m45	39.5	39.49	49.74	0.01	100.03
17	m47	18.5	18.1	29.77	0.4	102.21
18	m48	24	24.58	32.12	-0.58	97.64
19	v07	379	374.01	143.04	4.99	101.33
20	v12	70.1	72.89	63.16	-2.79	96.17
21	v13	375	372.38	138.46	2.62	100.7
22	v15	127	126.56	89.5	0.44	100.35
23	v17	149	150.96	101.31	-1.96	98.7
24	v18	212	211.23	131.27	0.77	100.36
25	v19	1.94	1.96	7.71	-0.02	98.98
26	v22	1084	1077.3	245.21	6.7	100.62
27	v23	1377	1370.3	323.53	6.7	100.49
28	v24	1642	1632.4	394.92	9.6	100.59
29	v25	210	209.97	98.81	0.03	100.01
30	v26	45.5	45.07	50.71	0.43	100.95
31	v27	93.2	94.57	76.76	-1.37	98.55
32	v28	506	508.8	171.28	-2.8	99.45
33	v29	768	771.33	229.56	-3.33	99.57
34	v30	103	101.87	84.24	1.13	101.11
35	v36	89.6	89.69	63.83	-0.09	99.9
36	v38	123	117.88	80.56	5.12	104.34
37	v39	332	325.58	137.9	6.42	101.97
38	v44	57.9	57.75	50.75	0.15	100.26
39	v48	33.7	34.09	41.54	-0.39	98.86
40	v49	23.5	23.82	36.29	-0.32	98.66
41	v52	93.4	93.39	68.78	0.01	100.01
42	v65	7.64	7.65	18.07	-0.01	99.87
43	v71	34.9	35.25	40.8	-0.35	99.01

Source: Water Resources Data Maryland and Delaware Water Year 1993, Volume 1, US Geological Survey Water Data Report MD-DE-93-1, and author calculated

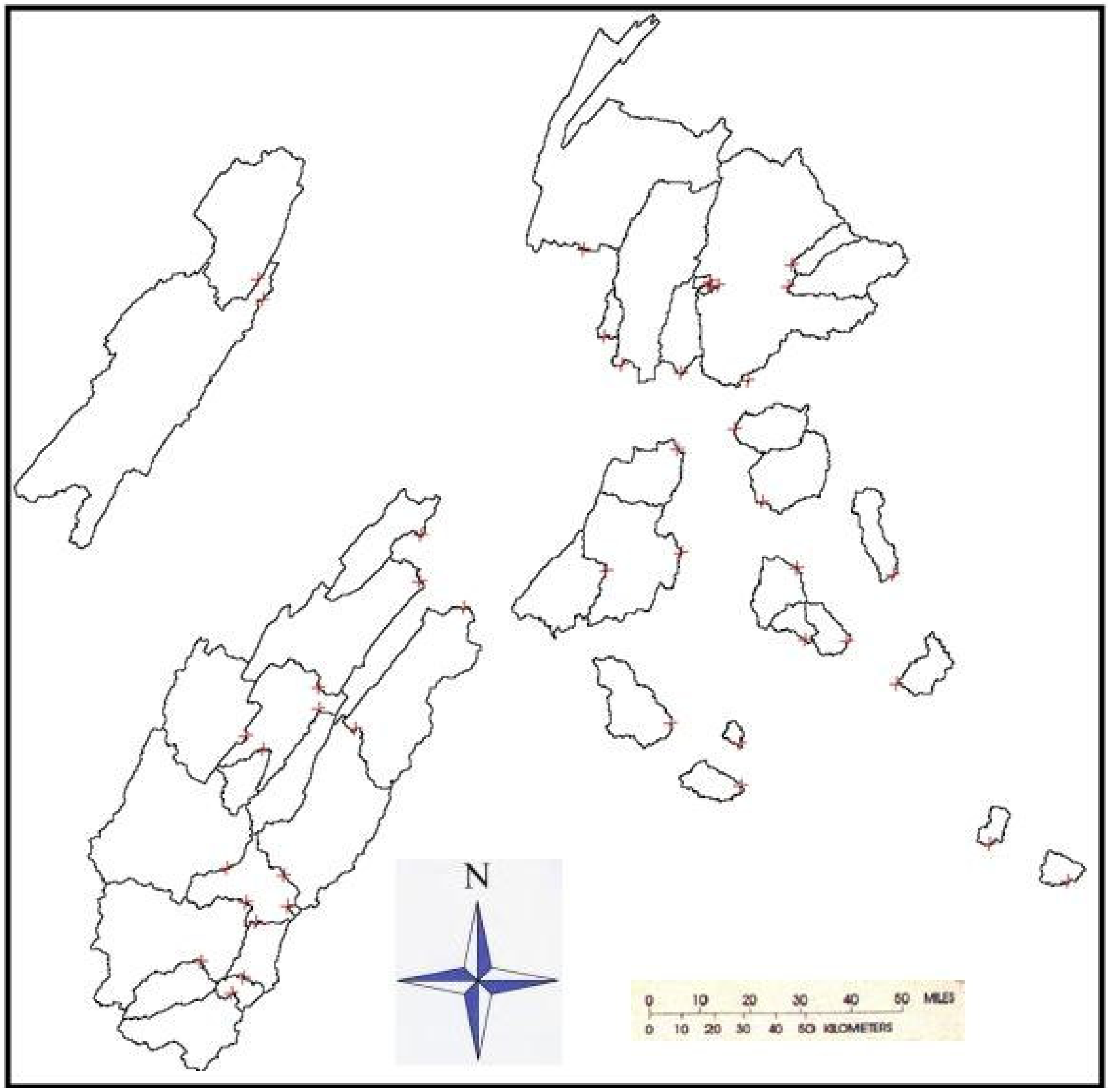


Figure 4.3 (a) Delineated Subbasins with Gage Stations
Source: USGS Water Data Reports MD-DE-93-1 and VA–93-1 and Author-Delineated Subbasin Boundary

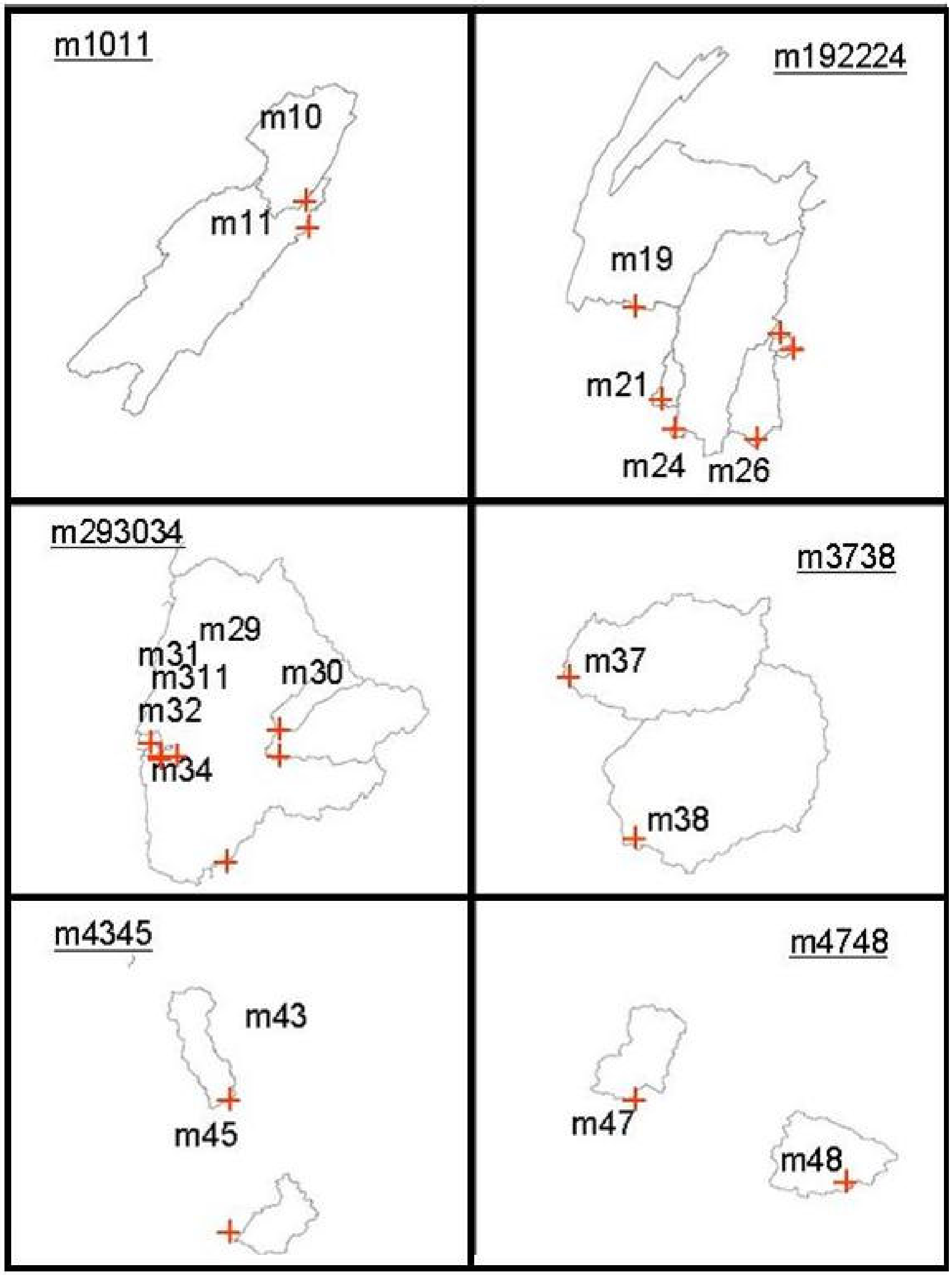


Figure 4.3 (b) Delineated Subbasins with Gage Stations
Source: USGS Water Data Reports MD-DE-93-1 and VA–93-1 and Author-Delineated Subbasin Boundary

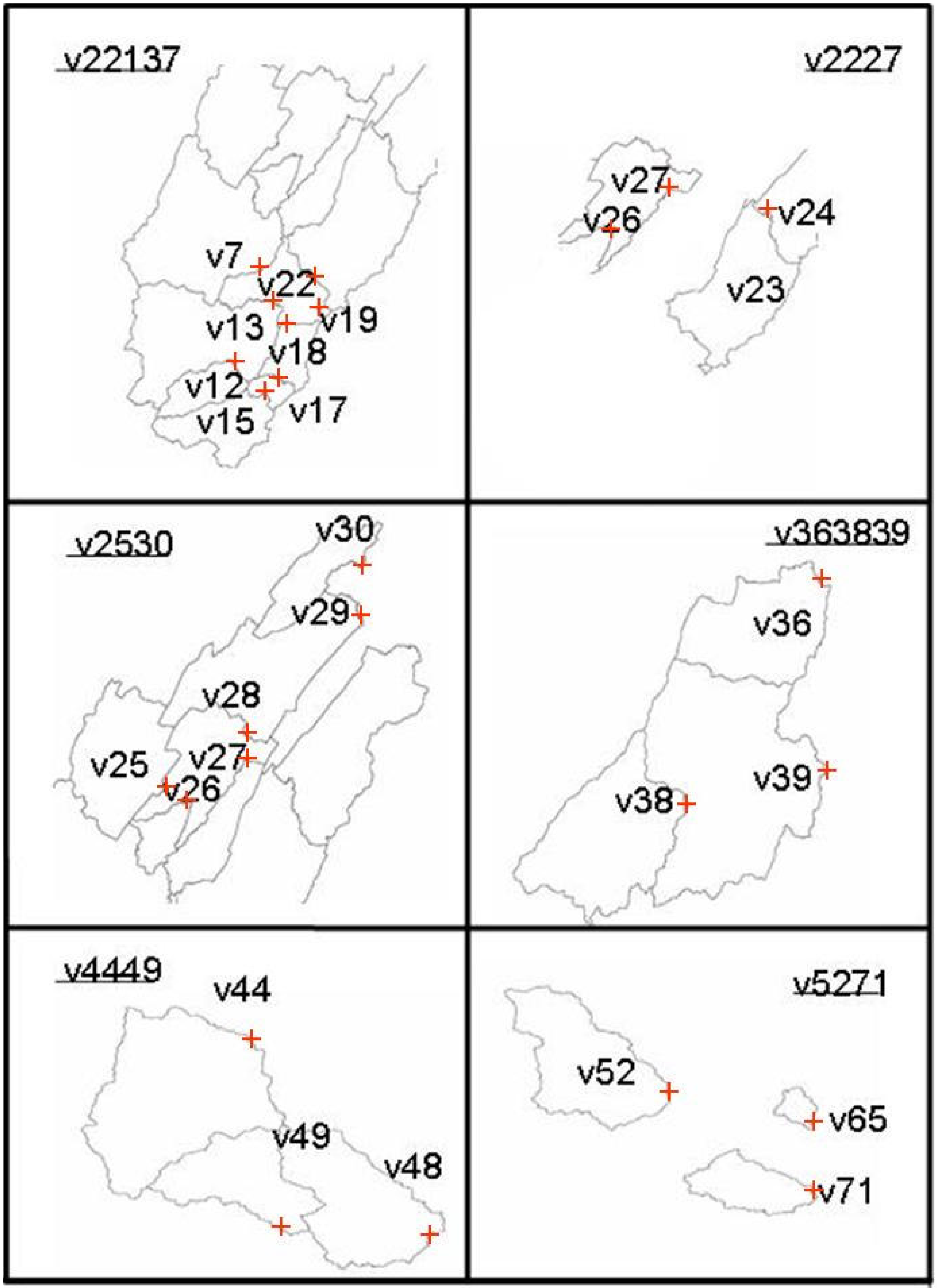


Figure 4.4 Study Area Subbasin Groups
Note: Not to Scale

The comparison of the USGS reported subbasin size values and the author-calculated subbasin size values shows that, except for four subbasins, the differences in size values were within an acceptable range, above 97%. For the subbasin with the largest size discrepancy (122.6% difference), subbasin m32, the actual difference of only 0.07 square miles (published value of 0.38 square miles versus the calculated subbasin size of 0.31 square mile), was considered insignificant to this analysis of subbasin size impacts on hydraulic geometry. The rest of the subbasins' size discrepancies were also treated as insignificant for this analysis. The rationale was that even considering the discrepancies; this does not have an impact on size rankings of the subbasin with respect to one another. An exception is subbasin m34 (discrepancy of 113.3%) where the calculated subbasin size results in a smaller subbasin than subbasin v29. However, if published size is corrected and is used for analysis, m34 is larger than subbasin v29. Therefore, these two subbasins get special attention in the size analysis in Chapter 6.

4.7.6 Topographic Index

Topography is recognized as an important factor in determining the stream flow response of drainage (Kirkby and Chorley, 1967; Dunne, et al., 1975; Beven and Wood, 1983; Moore et al., 1991; Wood, et al., 2000). Topography determines the effects of gravity on the movement of water in the drainage, and therefore it influences many aspects of geomorphic and hydrologic systems. The energy of stream flow is determined by the slope of the surface. A steeper slope results in greater energy, and as the energy of a stream increases, its ability to transport more and larger particles also increases.

Therefore, steeper slopes result in a greater potential for erosion. Topography has been shown to affect the flow path that precipitation follows before it becomes stream flow (Wolock, et al., 1990). And the shape of a surface determines how water will flow across it. Therefore, characterization of the topography of the subbasins should provide a significant dimension of information about the environmental setting of subbasins.

Kirkby and Weyman (1974) first introduced the concept of a topographic index, $k = a / \tan \beta$, where a is the area draining through a point from upslope and $\tan \beta$ is the local slope angle (Beven, 1977). The topographic index has been used (Wolock et al., 1995) to study a range of topics including flood frequency derivation (Beven, 1986, 1987), analysis of spatial scale effects in hydrologic processes (Beven et al., 1988; Famiglietti and Wood, 1991; Wood et al., 1988, 1990); analysis of the topographic effects on streamflow (Beven and Wood, 1983; Beven et al., 1984; Kirkby, 1986).

This index is used as an index of hydrological similarity (Wolock and McCabe, 1995) and one of the first parameters directly considering the spatial distribution of topography in hydrological modeling. All points with a similar index value are assumed to respond in a hydrologically similar way to hydrological processes (Beven and Kirkby, 1979; Hornberger et al., 1985; Wolock et al., 1989, 1990, 1995; Wolock, 1997).

Simplicity and the possibility of visualizing the predictions of the model in a spatial context enabled a topographic index to become a key component of the TOPMODEL, a topography-based watershed hydrology model (Beven and Kirkby, 1979). In part, because of this wide usage, the author selected topographic index as one of the predictor variables to investigate the impact of environmental settings on hydraulic geometry.

Since the topographic index characterizes ability to transport discharge of the subbasin, and the discharge can be equated to the drainage size, the topographic index is an important indicator in this study of environmental setting effects on hydraulic geometry. The modatn.aml algorithm, which was written by Wolock (1995) and modified by the author and used as a part of the inserted in the Arc/Info™ , produced topographic indices for the study subbasins. Higher values of ln (a/tan β) indicate greater potential for development of saturation. High values of ln (a/tan β) occur at locations where large upslope areas are drained (high value of a) and where the local gravitational gradient is low (low value of tan β).

Once the topographic index values are computed, the minimum, maximum, and mean topographic index values with standard deviations are tabulated for each subbasins. The topographic index values, maximum, mean, minimum, and standard deviation of each subbasin are shown in Table 4.3.

Table 4.3 Topographic Index Values for Study Subbasins

ID	ID	USGS ID	Topographic Index Minimum	Topographic Index Maximum	Topographic Index Mean	Topographic index stdev
1	m10	1601500	3.165	20.624	6.828	1.991
2	m11	1603000	-3.578	21.89	6.965	2.023
3	m19	1614500	-3.588	21.344	7.588	2.125
4	m21	1617800	2.952	20.754	7.427	2.168
5	m24	1619500	4.404	18.557	7.935	1.994
6	m26	1637500	4.163	15.878	7.112	1.722
7	m29	1639140	4.317	12.207	6.812	1.434
8	m30	1639500	-3.59	21.695	7.644	2.075
9	m31	1640965	3.711	19.261	7.17	2.134
10	m311	1640970	3.219	19.392	7.438	2.018
11	m32	1640980	-2.393	19.014	7.448	2.055
12	m34	1643000	1.475	18.789	7.325	2.181
13	m37	1643500	4.995	18.315	8.212	1.809
14	m38	1645000	3.912	18.035	7.548	2.177
15	m43	1651000	3.47	19.321	7.087	2.076
16	m45	1653600	3.544	19.745	7.463	2.1
17	m47	1661050	3.584	16.491	7.277	1.96
18	m48	1661500	3.807	18.009	7.04	2.148
19	v07	1622000	2.832	21.033	6.868	2.143
20	v12	1624800	3.507	19.403	6.967	2.309
21	v13	1625000	1.2	21.033	6.997	2.287
22	v15	1626000	2.996	19.954	6.923	2.286
23	v17	1626850	2.996	20.13	6.934	2.288
24	v18	1627500	2.974	20.467	6.982	2.285
25	v19	1628060	3.551	15.779	6.048	1.801
26	v22	1628500	1.2	22.093	6.998	2.236
27	v23	1629500	1.2	22.335	6.982	2.236
28	v24	1631000	1.2	22.509	6.972	2.239
29	v25	1632000	2.567	20.46	6.396	2.128
30	v26	1632082	3.667	18.922	7.173	2.18
31	v27	1632900	2.742	19.663	7.158	2.137
32	v28	1633000	2.567	21.251	6.867	2.182
33	v29	1634000	2.567	21.761	6.964	2.186
34	v30	1634500	3.387	19.701	6.885	2.078
35	v36	1638480	3.584	19.61	7.406	2.136
36	v38	1643700	3.501	19.88	7.096	2.087
37	v39	1644000	3.368	20.897	7.284	2.11
38	v44	1646000	4.002	19.17	7.343	2.078
39	v48	1653000	4.099	18.643	7.592	2.035
40	v49	1654000	4.327	18.284	7.567	2.008
41	v52	1656000	3.832	19.65	7.635	2.082
42	v65	1658500	4.3	17.148	7.539	1.966
43	v71	1660400	4.078	18.676	7.551	2.062

Source: Calculated by the author

The maximum topographic index value ranges from 22.509 to 12.207 (subbasin m29). The low minimum value occurs on subbasins m11, m19, m30, and m32 as -3.578, -3.588, -3.59, and -2.393. The highest maximum topographic index value occurs on subbasins v23 and v24 as 22.335 and 22.509. These two subbasins, v23 and v24, show low minimum topographic index values.

In this chapter, discussion of needed data such as DEM, hydrographic survey data, field survey data, data for physiography and lithology, and land use information, including derived data such as subbasin boundary delineation and topographic index values, for the environmental setting's impact on hydraulic geometry on Potomac River Basin have been presented. Derived data, particularly the delineation of subbasins and topographic indices, were created using 30-meter spacing DEM data for the study area, are described here. The rest of the derived data such as channel pattern, channel shape, channel cross-section profiles, and channel asymmetry are discussed in the next chapter.

CHAPTER 5

HYDRAULIC GEOMETRY AND THE ENVIRONMENTAL SETTING: Computation of Hydraulic Geometry Exponents

To understand the at-a-site hydraulic geometry of the study sites in the Potomac River basin, a first step in this analysis was to derive the hydraulic geometry exponents, b, f, and m, for each site from hydraulic survey data. In addition, to augment characterization based on hydrologic principles and empirically tested theory, a categorization of the b, f, and m values was conducted. Secondly, to provide a basis for subsequent investigation of the statistical relationships between watershed (subbasin) and hydrologic variables, an array of variables such as channel pattern, channel shape, cross-section profile, and channel asymmetry was constructed from field-based hydrologic survey data collected during this study. In this chapter, the methodologies of calculation and classification of at-a-station hydraulic geometry of the study area are discussed to identify how channel width, depth, and stream flow velocity change due to increased stream discharge volumes. Thirdly, methodologies to collect and compute all other predictor variables such as channel patterns, channel shapes, channel symmetry, and environmental controls such as bank and bed material, land use, and water reference level, listed in Chapter 4, are discussed in this chapter (Section 5.5).

5.1 Potomac River At-A-Station Hydraulic Geometry

Hydraulic geometry is concerned with variations in width, depth, velocity, and other hydraulic and geometry parameters such as channel slope in response to changes in channel discharge volume. The hydraulic geometry exponents, b, f, and m, provide quantitative descriptions and data on the variations of the rate of changes in channel width and depth, and stream flow velocity in different environmental settings. Careful collection and analysis of this information can provide insight into the relevant controlling conditions for specific channels.

This research paper deals with at-a-station rather than downstream hydraulic geometry. Downstream hydraulic geometry refers to changes at different locations along a stream channel, or between different channels at discharges of comparable frequencies. At-a-station hydraulic geometry is the response of a given cross-section of a channel to imposed flows of water and sediment regardless of discharge frequencies. So, at-a-station hydraulic geometry predicts the changes in water width, depth, and velocity as discharge varies within a channel of imposed size and shape, whereas downstream hydraulic geometry predicts the adjustment of channel size and shape to an imposed discharge.

Fluvial geomorphologists are primarily interested in hydraulic geometry because of its implications for drainage network evolution, stream channel response to environmental change, and mutual adjustments between channels and the flows they carry. River engineers are concerned with hydraulic geometry (or river regime, as it is sometimes called) for its applications in channel design, predictions of channel failure, and river channel management. This research is concerned with natural channels in the Potomac River Basin. The term 'natural' here is used to differentiate stream channels from ditches, canals, or aqueducts completely constructed by man but do not exclude natural channels altered by man.

Geometric characteristics of stream channels are usually viewed in the three perspectives of cross-section, profile, and plan. For purposes of study efforts on stream discharge, this study considers only the cross-sectional channel relationships to streamflow. The three parameters of water surface width, W, mean hydraulic depth, D, and average velocity, V, are related to streamflow, Q, through power functions (Leopold and Maddock, 1953).

$$W = aQ^b \quad (1)$$
$$D = cQ^f \quad (2)$$
$$V = kQ^m \quad (3)$$

These relations should satisfy the continuity equation (Q = AV) so that

$$Q = WDV \quad (4)$$
$$Q = (aQ^b)\ (cQ^f)\ (kQ^m) = (ack)\ Q\ (b+f+m) \quad (5)$$

The exponents sum to unity (b + f + m = 1.0). The constants a, c, and k vary from locality to locality but the exponents, b, f, and m, exhibit a remarkable degree of consistency. The exponents, b, f, and m, indicate rates of changes in width and depth of channel and velocity of the flow with respect to changing stream discharge. This study focuses on only these hydraulic exponents.

The exponents b, f, and m were found to vary somewhat between river systems in 'downstream' analyses but normally b > f > m, with typical values of 0.5, 0.4, 0.1. At-a-station exponents are more variable but typically f > m > b, with mean values of 0.40, 0.34, and 0.26 in Leopold and Maddock’s study (1953).

For this calculation of at-a-station hydraulic geometry, the author used field survey measurement data which were created by hydrographers from the USGS Water Resource Division, Maryland State Geological Survey, and Virginia's Environmental Quality Department. Field surveying produced data on discharge, mean depth, width of the water surface, mean velocity of the flow, and cross-sectional area size measurements. This location-specific measurement data were used for the calculation of the rate of changes for width, b; depth, f; and flow velocity, m.

The relationships between discharge with width, depth, and velocity were estimated using logarithmic regression analysis. Each predicted variable (b, f, and m) is regressed onto the predictor variable, water discharge, individually. The resulting regressions are b to water discharge, f to water discharge, and m to water discharge; therefore there is no guarantee that the summation of estimated b, f, and m would be 1.

The coefficients and exponents in equations (1), (2), and (3) for the 43 at-a-station sites are presented in Table 5. 1 which lists the summation of b, f, and m, and the coefficients of determination for b, f, and m as R^2_b, R^2_f, and R^2_m, respectively.

Table 5.1 b, f, and m Value

Id	Sample Size	b	f	m	b+f+m	R^2b	R^2f	R^2m	Code*
m10	29	0.1416	0.3605	0.4981	1.0002	0.9131	0.9219	0.9518	W
m11	21	0.1084	0.5349	0.3567	1.0000	0.7935	0.9504	0.9017	W
m19	45	0.0989	0.3936	0.5078	1.0003	0.7106	0.9803	0.9863	W
m21	47	0.1699	0.3841	0.4467	1.0007	0.6658	0.8829	0.8233	M
m24	37	0.2441	0.1891	0.5661	0.9993	0.7892	0.5779	0.9186	M
m26	25	0.3477	0.2669	0.3842	0.9988	0.8330	0.8586	0.9366	M
m29	13	0.2250	0.2597	0.5119	0.9966	0.8202	0.9504	0.9593	W
m30	43	0.1121	0.3941	0.4962	1.0024	0.5477	0.9011	0.9431	W
m31	38	0.4607	0.2403	0.2895	0.9905	0.8976	0.6526	0.6337	P
m311	18	0.5622	0.1442	0.2976	1.0040	0.8572	0.6398	0.5965	P
m32	17	0.2972	0.0906	0.6336	1.0214	0.7895	0.3591	0.9464	P
m34	43	-0.0080	0.4667	0.5736	1.0323	0.0430	0.9094	0.9351	W
m37	26	0.0400	0.3581	0.6011	0.9992	0.5444	0.6955	0.8422	P
m38	28	0.0650	0.4289	0.5113	1.0052	0.2848	0.6401	0.7579	P
m43	56	0.2741	0.2663	0.4630	1.0034	0.5398	0.6137	0.6852	P
m45	23	0.1868	0.4474	0.3668	1.0010	0.7062	0.9019	0.8661	M
m47	54	0.2769	0.2784	0.4488	1.0041	0.7572	0.5859	0.7215	P
m48	64	0.1000	0.2326	0.6684	1.0010	0.5985	0.6546	0.9483	P
v07	33	0.0340	0.3570	0.6072	0.9982	0.6629	0.9822	0.9937	W
v12	36	0.1302	0.4717	0.3992	1.0011	0.1673	0.9202	0.6548	P
v13	9	0.2286	0.2081	0.5632	0.9999	0.6505	0.2715	0.8763	P
v15	13	0.0906	0.2665	0.6411	0.9982	0.5794	0.5553	0.9231	P
v17	25	0.0507	0.3832	0.5697	1.0036	0.2590	0.8192	0.9348	M
v18	18	0.1761	0.5368	0.2872	1.0001	0.7248	0.8336	0.4825	P
v19	26	0.3773	0.2978	0.3461	1.0212	0.8283	0.8779	0.5866	M
v22	9	0.0573	0.3363	0.6063	0.9999	0.5277	0.9558	0.9653	W
v23	17	0.2195	0.3008	0.4797	1.0000	0.2939	0.7433	0.6886	P
v24	64	0.0839	0.2954	0.6208	1.0001	0.4869	0.9316	0.9428	W
v25	16	0.3390	0.4160	0.2443	0.9993	0.8090	0.9053	0.5166	M
v26	17	0.1865	0.2601	0.5550	1.0016	0.4982	0.6006	0.8906	P
v27	22	0.1437	0.2687	0.5870	0.9994	0.5452	0.4415	0.8253	P
v28	22	0.2729	0.1612	0.5681	1.0022	0.7521	0.4234	0.8501	P
v29	45	0.0075	0.2406	0.7541	1.0022	0.0744	0.7411	0.9702	P
v30	17	0.2061	0.1703	0.6242	1.0006	0.7256	0.7549	0.9596	P
v36	17	0.2498	0.2162	0.5363	1.0023	0.8083	0.6485	0.8392	M
v38	10	0.4398	0.3903	0.1676	0.9977	0.7857	0.9425	0.2271	P
v39	13	0.1930	0.2523	0.5559	1.0012	0.6237	0.9454	0.9340	W
v44	16	0.1671	0.3015	0.5314	1.0000	0.8933	0.6869	0.8603	M
v48	22	0.1374	0.3277	0.5730	1.0381	0.5222	0.8102	0.8190	M
v49	9	0.3637	0.2618	0.3754	1.0009	0.6266	0.7312	0.7599	P
v52	8	0.4685	0.3194	0.2123	1.0002	0.9202	0.8726	0.6361	M
v65	10	0.3515	0.3744	0.2646	0.9905	0.8479	0.8321	0.4832	M
v71	10	0.2404	0.3590	0.4032	1.0026	0.9085	0.9050	0.8491	W

Note: Calculated using an Splus™ function. Well (W), Moderately (M), or Poorly (P) constrained are based on at least 2 exponents having R^2 of 0.9 (W), 0.8 (M), and lower (P).

The fact that the summation of the three slopes (exponents) is a unit was used as a means to check the validity of the derivation of hydraulic geometry relationships as developed by Leopold and Maddock (1953). In addition, the fact that the product of width, depth, and velocity equals to discharge was also used to check the validity of the field-observed hydraulic geometry data. Also, using the R^2 values of the b, f, and m, each subbasin is categorized as W - well constrained (at least two exponents have R^2 of 0.9); M - moderately constrained (at least two exponents have R^2 of 0.8), and P - poorly constrained (other than W or M). Out of the 43 study sites, two sites show the sum of three exponents as 1.038 and 1.032, and two sites show 1.0214 and 1.0212. The rest of the sites are all within ± 0.01 from the unit. So 95% of the total study sites fall in ± 0.03 from the unit. And 93% of the total study sites fall in ± 0.02, 88% within ± 0.01. It is expected that the summation of b, f, and m would be 1, however, for some subbasins the summations for b, f, and m fall in ± 0.04 of 1. These subbasins have low coefficients of determination (R^2) in b, f, or m; therefore, their b, f, and m values might not be highly trustworthy. However, overall, the summation of b, f, and m, very close to 1, reasonably well meets the continuity equation of Leopold and Maddock (1953).

In addition, the coefficients of determination (R^2) for the power relationships between discharge and width (R^2_b), depth (R^2_f), and velocity (R^2_m) were reviewed for the appropriateness of the calculation of each subbasin's b, f, and m values. The results, in Table 5.1, show the average value of coefficients of determination for b is lowest, and that of f is in the middle, and that of m is highest. It is interesting that b, f, and m values are also in this same order, but further reflection is delayed until Chapter 6.

The coefficient of determination for the power relationships between discharge and width (R^2_b) shows the least correlation among the three coefficients, b, f, and m. The average coefficient of determination for width exponents among the 43 study sites is 0.64. Six subbasins have R^2_b lower than 0.5 and 8 subbasins have R^2_b at the 0.5 level, 4 at the 0.6 level, 7 subbasins have R^2_b at the 0.7 level, 12 at the 0.8 and 6 at 0.9 level.

Table 5.2 Coefficient of Determination for Width Exponent (b)

R^2_b	Number of Subbasins	Accumulated Number of Subbasins					
< 0.5	6	43					
0.5	8		37				
0.6	4			29			
0.7	7				25		
0.8	12					18	
0.9	6						6

Source: Calculated and observed by author
Note: R^2_b denotes coefficient of determination for width exponent (b)

Cumulatively, 58% of the total study sites (22 out of 43) have R^2_b at the 0.7 and 68% of the total study sites have R^2_b at the 0.6 level. From these statistics, we might expect that the wide range of rates of changes in width (low R^2_b value) requires that the various environmental settings of subbasins needs to be investigated. This is also discussed in Chapter 6[1]. One case is worthy of special note. The gage station m34 has a negative value of b (-0.008) with a coefficient of determination of 0.043, and, hence, m34 falls outside the ternary diagram. It is assumed that the b value of m34 is 0.000 for this

[1] One case is worthy of special note. The gage station m34 has a negative value of b (-0.008) with a coefficient of determination of 0.043, and, hence, m34 falls outside the ternary diagram. It is assumed that the b value of m34 is 0.000 for this study. This station has b, f, and m summation of 1.032 which is the second highest discrepancy value from 1. The coefficients of determination for f and m are 0.904 and 0.9351, respectively, which indicates that f and m are highly correlated.

study. This station has b, f, and m summation of 1.032 which is the second highest discrepancy value from 1. The coefficients of determination for f and m are 0.904 and 0.9351, respectively, which indicates that f and m are highly correlated.

The coefficient of determination for the power relationship between discharge and depth (R^2_f) shows better correlation than that of width (R^2_b). The average coefficient of determination for depth exponents among the 43 study sites is 0.76. Four subbasins have R^2_f lower than 0.3 and three subbasins have R^2_f at the 0.5 level, nine at 0.6 level, four subbasins have R^2_f at the 0.7 level, eight at the 0.8, and 15 at the 0.9 levels.

Table 5.3 Coefficient of Determination for Depth Exponent (f)

R^2_f	Number of Subbasins	Accumulated Number of Subbasins
< 0.5	4	43
0.5	3	39
0.6	9	36
0.7	4	27
0.8	8	23
0.9	15	15

Source: Calculated and observed by author
Note: R^2_f denotes coefficient of determination for depth exponent (f)

Cumulatively, 63 % of the total study sites (27 out of 43) has R^2_f at 0.7 and 84 % of total study site has R^2_f at 0.6 level. From the statistics of R^2_b and R^2_f we can expect that depth change rate is much better explained than width change rate. The coefficient of determination for depth exponents values are much higher than that of width exponents meaning that variation of depth exponents are much less and proportion of variation left unexplained are smaller than that of width exponents.

The coefficient of determination for the power relationship between discharge and velocity (R^2_m) shows the highest correlation among the three coefficients. The average coefficient of determination for velocity exponents among the 43 study sites is 0.81. One subbasin has R^2_m lower than 0.5, three subbasins have R^2_m at the 0.5 level, four for 0.6, four subbasins have R^2_m at the 0.7 level, eight at the 0.8 level, and 23 at the 0.9 level. Out of 23 subbasins which have R^2_m higher than 0.91, seven subbasins have a greater than 0.95 correlation coefficient.

Table 5.4 Coefficient of Determination for Velocity Exponent (m)

R^2_m	Number of Subbasins	Accumulated Number of Subbasins					
< 0.5	1	43					
0.5	3		42				
0.6	4			39			
0.7	4				35		
0.8	8					31	
0.9	23						23

Source: Calculated and observed by author
Note: R^2_m denotes coefficient of determination for velocity exponent (m)

Cumulatively, 81% of total study sites have R^2_m at the 0.7 level, 91% of total study sites has R^2_m at the 0.6 level, and 98% of the total study sites (42 out of 43) have R^2_m at the 0.5 level. The coefficient of determination for velocity exponents values are higher than that of width or depth exponents, meaning that the variation of velocity exponents is much less than that of width or depth exponents. So, we can assume that the ranges of width and depth changes rates are wide and validity of b and f are less than m.

The average exponent values calculated by the author for this study are b: 0.207, f: 0.314, and m: 0.481. These average values fall within the wide range of Park (1977), Rhodes (1978), and Leopold (1994) studies. The sample of 139 sets of exponents which Park (1977) used and the 587 sets of exponents computed by Rhodes (1978) indicate that the exponents ranges are b: 0.00 to 0.84; f: 0.01 to 0.84; m: 0.03 to 0.99; and Leopold (1994) indicates b: 0.26; f: 0.40, and m: 0.34 as the most common values for exponents. However, the values to be used in the present analysis are those for individual cross-sections and not the averaged values from a particular channel. The rationale for discarding the average exponent values is that the study channels are in heterogeneous environmental setting and they differ so much in their responses to changing discharge that the idea of an average condition is itself of doubtful utility.

Respective coefficients of determination are 0.642, 0.763, and 0.810. There appears to be a relationship between hydraulic geometry exponent values and the coefficients of determination. That is, the lower the hydraulic geometry exponents, the lower the coefficients of determination.

5.2 A Ternary Diagram Portrayal of the Streamflow Exponents

While numerical values of b, f, and m provide some sense of the rate of width, depth, and velocity changes with changing discharges, these three numbers at-a-station do not intuitively show the relative proportions of the three components. Following Leopold (1994), Rhodes (1978), and Park (1977), a ternary plot (Figure 5.1) of the exponents provides a means of examining and comparing the simultaneous variations of all three exponents. A ternary diagram[2] plot also provides more information than simple numerical comparisons of the values. Since the plotting position of a set of exponents supplies information on the results of hydrological principles on the cross-section, the ternary diagram is a very useful tool to understand how a channel adjusts itself to morphologic and dynamic factors such as changing discharge.

Most of the hydraulic geometry exponents are clustered in the lower left area of the ternary diagram which is the area of 0.3 to 0.0 for b, 0.2 to 0.4 of f value, and 0.5 to 0.6 of m value. In order to derive more information from these b, f, and m values, the ternary diagram of the hydrologic geometry is divided on the basis of hydrologic principles and empirically tested theories as follows. Similarity of hydraulic geometry data can be inferred based on the plotted position on the ternary diagram. However, as Rhodes (1977) reported, the usefulness of the plot and the possible inferences derived from it may be increased by meaningful division of the diagram.

---

[2]Note: Ternary diagrams are used to represent the relative fraction of the three components. The "composition" of any point plotted on a ternary diagram can be determined (or any point can be plotted). Fractional values for b are read from zero along the lateral line (axis) at the left of the diagram to 1 at the vertex of the triangle. Similarly, values for f are read from zero along the lateral line of right side of the triangle to 1 at the lower right vertex. And, finally, values for m are read from zero along the lower right vertex to 1 at the lower left vertex. At any point in the triangle, the distances to b, f, and m must add up to 1.0. Along the line connecting b and f, f must be zero. At any apex, one component is 1.0 while both others are zero. Often the requirement of the three components have to sum to unit 1 which meant that some sites needed to be normalized them to 1, may have to be met by rounding. However for the values of this study, using 2 decimal places, no normalization was necessary.

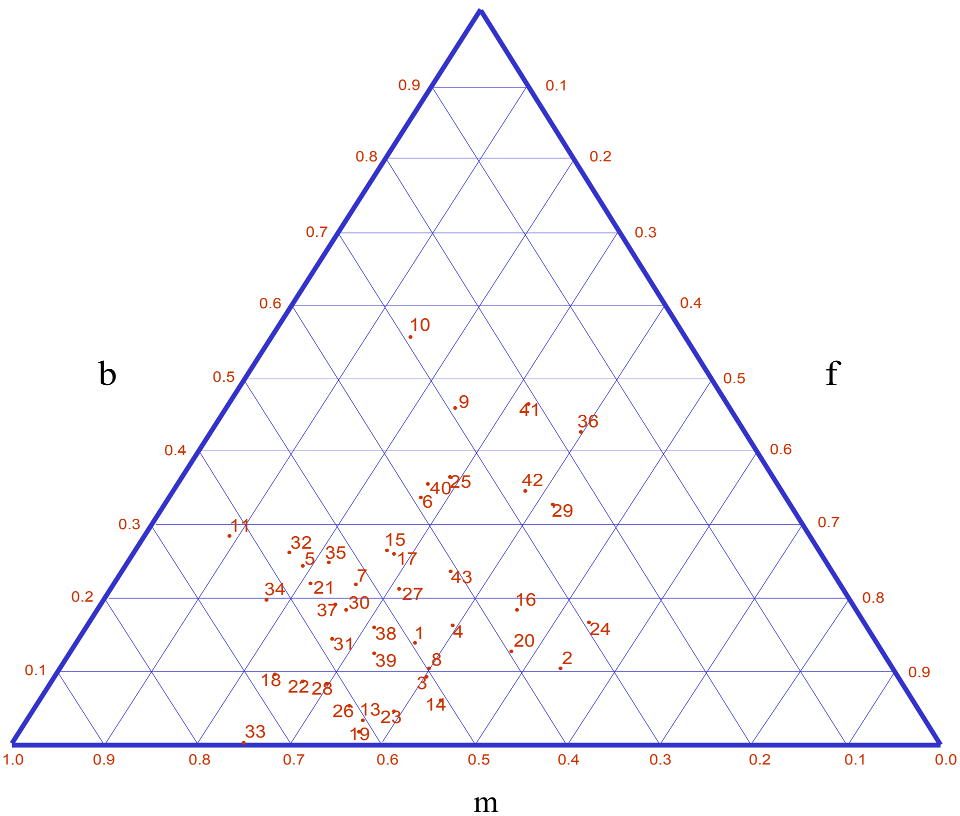
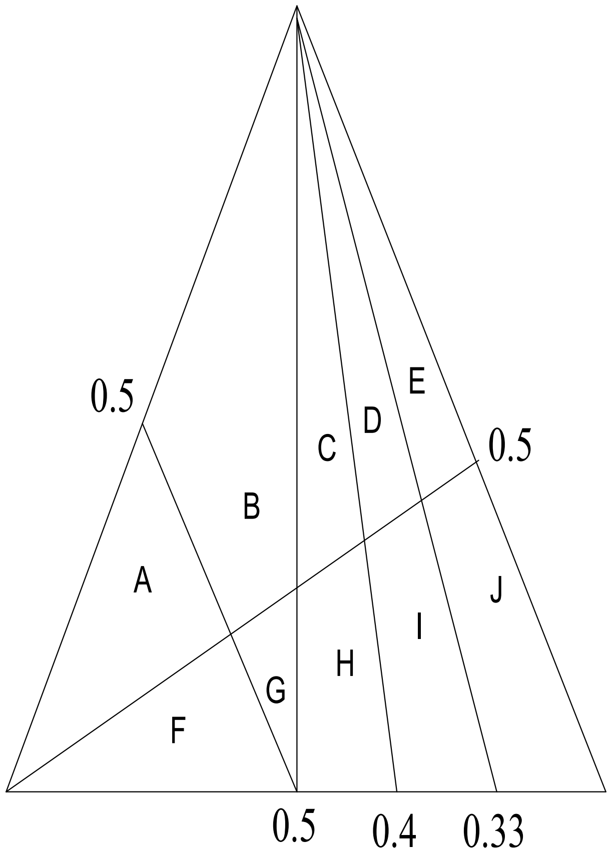


Figure 5.1 Ternary Diagram for Hydraulic Geometry Exponents Values of Potomac River Subbasins

Accordingly, the author divided the ternary diagram for the Potomac River subbasin into ten regions (Figure 5.2). This follows Shepard (1954) who used ten regions for classification of the Maryland coastal sediment samples, based on Rhodes' (1978) five criteria, which are themselves based on their dynamic and morphological responses to changing discharge. The dividing lines (Figure 5.3) for the five criteria are: (1) constant values of width-depth ratio (b = f), (2) competence (m = f), (3) Froude number (m = f/2), (4) velocity-cross-sectional area ratio (related to the Darcy-Weisbach friction factor) (m = b + f), and (5) slope-roughness ratio which is related to the Manning equation (m/f = 2/3).



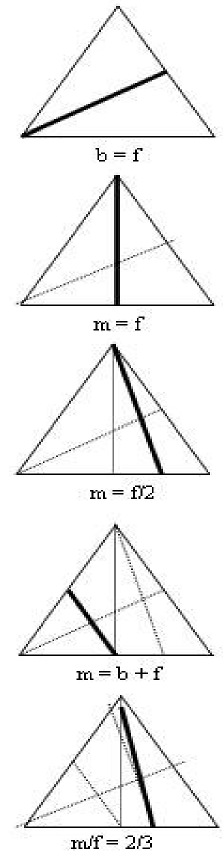


Figure 5.2 Ten Regions Determined by Five Criteria

Figure 5.3 Five Criteria

5.3 Explanation for the b-f-m Values

Understanding of the ramification of b, f, and m values is facilitated by an examination of the classification of b, f, and m values, which reveals similarities of response to changes in discharge. Each exponent is presented separately for the five situations shown in Figure 5.2. The overall classification follows as section 5.4.

5.3.1 Ratio of Width and Depth Exponents (b = f)

The b-to-f ratio gives an indication of the change in shape of the channel cross-section with changing discharge. The width-to-depth ratio of a channel varies with increasing discharge, manifested as channel stability. Rhodes (1977) rationalized that since $w = aQ^b$, and $d = cQ^f$, therefore $w/d = aQ^b / cQ^f = a/c\ Q^{b-f}$. Eliminating the constants, it becomes $w/d \propto Q^{b-f}$. Consequently, the ternary diagram is divided by the line where b = f line, as shown on Figure 5.3 (1), resulting in b > f and b < f regions. The b–to–f ratio indicates changes in the width-depth relationship and not the absolute values of the parameters. A cross-section may have a relatively large width-to-depth ratio at all stages even though f > b. Changes in width and depth with increasing discharge may occur either by erosion of banks and bed or by progressive filling of a stable channel. Interpretation of this ratio provides information about (1) relative stability of channel via bed and bank material erodability; (2) channel shape, and (3) channel adjustment to transport of bed load (Rhodes, 1977).

Channel shape and the relative stability of bed and bank materials are interrelated (Schumm, 1960). Where b > f, the stream is considered that the banks of the stream are more readily eroded than the bed, and where f > b, the stream is implied that bed is more eroded than the banks of the stream. If the channel is stable under normal discharge conditions, then the situation where f > b indicates a tendency for the channel cross-section to become proportionally deeper and narrower with respect to increasing discharge (lower w/d).

If b > f, then width-to-depth ratio increases with discharge, and the tendency is toward a wide shallow channel. For stable channels, only those with the shape of an equilateral triangle will have a constant width-to-depth ratio (b = f) with increasing discharge (Rhodes, 1977). Rectangular and parabolic channels will have decreased width-to-depth ratios extreme case b = 0 and f and m make unit 1. The rate of decrease is greater for rectangular channels than for the other shapes (Leopold, 1994).

The change of width-to-depth ratio with discharge is an important consideration in fluvial sediment transport. Rhodes (1977) stated that several workers have noted that the wide-shallow cross-section is the type best adapted to the transport of a large bed load (Lane, 1937; Mackin, 1948; Leopold and Maddock; 1953; Morisawa, 1968). He stated that channels that plot on the above the line half of the ternary diagram (Figure 5.3 (1)) should have a greater potential for bed load transport than those channels that plot on the below half other factors being equal.

On the other hand, Leopold and Maddock (1953) stated that deep, narrow channels are associated with larger suspended sediment loads than are wide, shallow channels. At a given discharge, different rivers exhibit different values of width and depth. Those with fine-grained cohesive banks tend to be deep and narrow, and those with sandy, friable banks tend to be wide and shallow (Rhodes, 1977). Thus, those channels that plot on the upper half of first ternary diagram shown in Figure 5.3 (1) may have shapes that are best adapted to the transport of fine-grained sediments.

5.3.2. Ratio of Depth and Velocity Exponents for Competency (m = f)

After Rhodes'(1977) classification , the criterion for the second division of the ternary diagram is based on the ratio of depth and velocity change rates. The inferences as to its significance are based on empirical studies and not on rigorous hydrodynamic principles. This ratio has been cited as important in considerations of sediment transport by Rhodes (1977). The line of m/f = 1 is drawn on the ternary diagram as shown on the second triangle in Figure 5.3 (2).

Wilcock (1971) studied the relationships between the rate of change of depth (f) and that of velocity (m), and competence. Based on considerations of a critical tractive force necessary for the initiation of particle motion, Wilcock (1971) concluded that, "Competence will tend to increase only when the rate of increase in velocity (m) equals or exceeds the rate of increase in depth (f)." Based on this assertion, Rhodes (1977) stated that those channels that are represented by points to the left side of the line m = f on Figure 5.3 (2) should experience an increase in competence with increasing discharge.

Leopold, Wolman, and Miller (1964) stated "The ratio m/f can be related to the transportation of load through the interdependence of the various channel factors". Their finding from measurement data indicate that the higher m/f ratio, the more rapid the increase of measured sediment load with increase of discharge. The ratio of the rate of change of velocity to the rate of change of depth has been associated by Leopold and Maddock (1953) with the rate of increase of suspended load (Rhodes, 1977). They stated "For a given width, and at a given discharge, an increase in suspended sediment requires an increase in velocity and a reduction in depth ". That is for conditions of increasing discharge, velocity must increase faster than depth, or m/f must be greater than 1, if suspended sediment load is to increase (at a constant width). If width changes with discharge, which it usually does, the relationship is complicated. The rate of increase of suspended sediment with discharge is inversely related to the rate of increase of width (Leopold and Maddock, 1953).

5.3.3 Ratio of Half of Depth and Velocity Exponents ($m = f / 2$)

Hydraulic geometry values also were classified using Rhodes' (1977) third criteria which is based on hydrodynamic considerations, water flow condition usually expressed as the Froude number, F, which describes the type of flow present. The Froude number, the ratio of an inertial force to gravitational forces, is defined as $F = v / (gd)^{1/2}$.

Since $v = k\,Q^m$, and $d = cQ^f$, $F = k\,Q^m / (g\,(cQ^f))^{1/2}$. At the critical value $F = 1$, $v / (gd)^{1/2} = 1$, $v = (gd)^{1/2}$, and $k\,Q^m = g^{1/2}(cQ^f)^{1/2}$. Eliminating the constants, $Q^m \infty Q^{f/2}$ therefore, $m = f/2$ if the Froude number does not change with discharge. When $m > f/2$ (points left of the line), the Froude number increases with increasing discharge; if $m< f/2$ (points right of the line), F decreases with increasing discharge (Figure 5.3 (3)).

According to Rhodes' (1977) explanation, if the geometry of a channel causes the velocity exponents to decrease with increasing discharge such as case v38, then that channel may be incapable of sediment transport (Simons et al., 1965), because the critical Froude number will not be attained. Transportation of large particles would require supercritical flow. Channels that have this relationship will plot at the left side of the line $m = f/2$. Many of the streams with such graph positions may never achieve supercritical flow because the channel dimensions would be exceeded before the necessary criteria could be met. However, it is clear that those channels that plot to the right side of the line will not reach supercritical flow on a rising stage and will therefore be unable to accomplish some types of sediment transport.

5.3.4 Rate of Velocity and Depth Exponents for Channel Stability and Flow Resistance ($m = b + f$ or $m = 0.50$)

Following Rhodes' (1977) criteria, the fourth division of the diagram is based on ratio of velocity and combined width and depth exponents ($m / b + f$), the line $m = b + f$ or $m = 0.50$. This criterion is based on Rhodes' understanding that if velocity increases faster than the area of the channel cross-section that means the resistance must decrease rapidly with increasing discharge. This notion is based on Richards' (1973) statement "a very rapid increase in velocity with increasing discharge ($m > 0.5$) is associated with a rapid decrease in f'." The symbol f' represents the Darcy-Weisbach friction factor. The condition $m > b + f$ indicates that the mean velocity is increasing faster than the cross-sectional area (channel width and channel depth) of the channel. If velocity is increasing at the same rate as cross-sectional area, then $m = b + f$.

In order for velocity to increase faster than channel area, channel must be quite stable (Rhodes, 1977). Rhodes' assumption is that neither the bed nor banks are subject to significant erosion by the velocities attained. He also noticed that the very high rates of f are associated with stable channels. So he used the rate of increase of the width-to-depth ratio (b / f) for channel stability (decreasing w/d ratios indicating stable sections).

Points plotting the left side of the $m < b + f$, that is $m < 0.5$ line represent channels that experience very rapid increase in velocity with discharge. From such rapid increases several inferences may be made regarding channel stability and flow resistance. Channels characterized by $m > b + f$ are quite stable and experience greatly decreased resistance with increased discharge.

5.3.5 Ratio of Depth and Velocity Exponents for Roughness (m/f = 2/3)

Following Rhodes' (1977) criteria, the fifth division was based on the Manning roughness coefficient. The b-f-m diagram is divided by the line m/f = 2/3. The Manning equation is: $v = 1.486\ d^{2/3}\ s^{1/2} / n$, where s is water surface slope, n is Manning roughness coefficient (Rhodes, 1977). Slope has been defined as $S \infty Q^z$ and the Manning coefficient as $n \infty Q^y$ (Leopold, Wolman, and Miller, 1964). The equation can be rewritten as:

$kQ^m = 1.486\ (cQ^f)^{2/3}\ (Q^z)^{1/2} / Q^y\ = 1.486\ (Q^{2/3\ f\ +\ ½\ z\ -y})$

$Q^m \infty Q^{(2/3)f\ +\ (1/2)\ z\text{-}y}$, or $m = (2/3)f + z / 2 - y$

If $m > (2/3)\ f$ (left side of the line), then $z/2 - y < 0$, or $s^{1/2}/n$ must decrease with discharge. Likewise, if $m < (2/3)\ f$ (right side of the line), then $z/2 - y > 0$, or $s^{1/2}/n$ must increase with increasing discharge. If $m = (2/3)\ f$, $z/2 = y$, and $s^{1/2}/n$ does not change with discharge. Rhodes (1977) stated that data gathered from several sources (Leopold and Maddock, 1953; Leopold, Wolman, and Miller, 1964; Langbein and Leopold, 1964; Harms and Fahnestock, 1965) indicated that slope changes little with discharge. Therefore, it is assumed that roughness is the factor that experiences the greatest change.

Resistance or roughness in a hydraulic sense cannot be measured directly but it can be computed from observation of velocity, depth, and slope (Leopold et al., 1964). Direct measurements of these factors at a specific cross-section at various discharges such as Wolman's (1961) Brandywine Creek, Pennsylvania data show that resistance decreases with increasing discharge at-a-station with the order of magnitude.

There are many reasons that roughness can increase or decrease in different situations such as channel size, bed material, bank material, water reference level, etc. As Rhodes (1977) pointed out roughness might decrease at-a-station for a number of reasons. Relatively small channels with large bed roughness elements (cobbles, boulders, and dunes) decrease in roughness with increasing discharge, because the effects of the bed elements are diminished as they are submerged (Wolman, 1955). Roughness may also decrease on a rising stage because the flow becomes better aligned with the channel, thus minimizing resistance due to flow distortion (Leopold, Wolman, and Miller, 1964). As shown in the equation, velocity increases with depth and slope decreases with increasing resistance to flow or bed roughness. Increased suspended sediment concentration may also result in decreased roughness (Vanoni, 1941; Leopold and Maddock, 1953).

Decreased flow roughness occurs because suspended sediment increases the effective viscosity of the fluid, and the increased viscosity reduces turbulence. Roughness might increase with discharge because of the growth of bed roughness elements (dunes) or because at higher stages the channel geometry or vegetation along the banks causes greater turbulence.

The Manning formula, representing a numerical value for roughness, does not explain the cause of roughness. Therefore it is difficult, in a particular instance, to be sure which elements contribute to the changes in roughness. In addition to the evaluation of the individual factor's contribution, the evaluation of the relative contribution of each of the factors is much more difficult.

At present each case must be considered individually, involving a detailed analysis of many variables. The inferences concerning the relationship between roughness and hydraulic geometry are speculative. As Richards (1973) points out in discussing this problem: "Achieving a point of entry into this system for the purpose of analysis is extremely difficult, since the interaction is complete." Much work remains to be done on the relationship of hydraulic geometry and channel roughness. The inferences derived from the b-f-m diagram indicate some possible lines of inquiry. Therefore many environmental setting variables are investigated for the role of their impact on at-a-station hydraulic geometry. The next section 5.4 will identify and discuss those environmental settings and analyses and discussion will be in Chapter 6.

5.4 Classification of b-f-m Values

The characteristics of the hydraulic geometry values of the ten regions are shown in Figure 5.4 and Table 5.3.

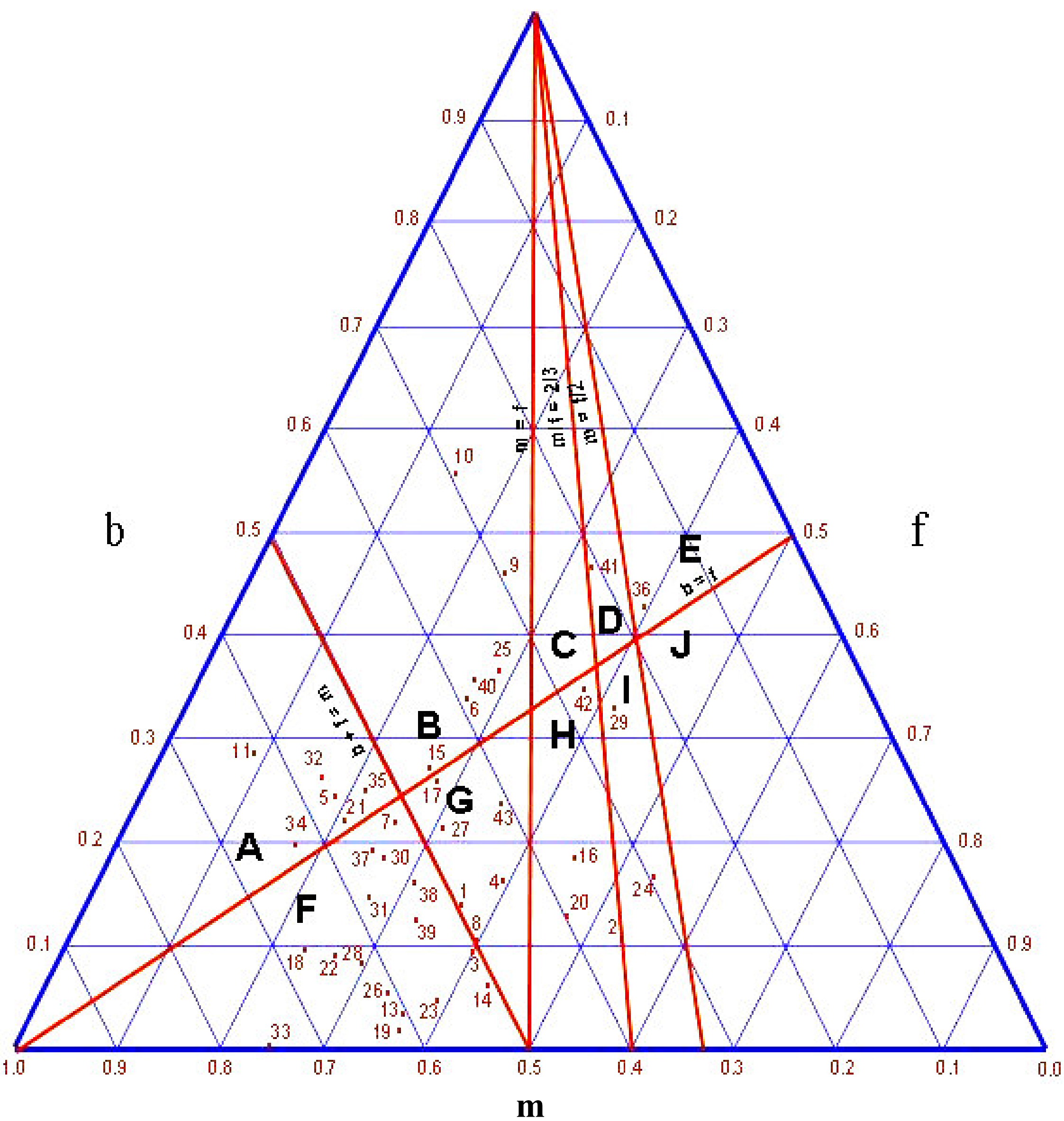


Figure 5.4 b, f, and m Values with 5 Classification Criteria

In Figure 5.4 the ten regions of the ternary diagram are labeled. Table 5.5 summarizes the expected relationships between increasing discharge and various fluvial parameters for each region. The labeling scheme for the regions is arbitrary.

Table 5.5 Ten Regions Characterized by Five Criteria

Region	b=f		m=f		m=f2		m=b+f		m/f=2/3		Subbasin Identification
	b >f	b<f	m >f	m<f	m>f/2	m<f2	m>b+f	m<b+f	m/f>2/3	m/f<2/3	
A	X		X		X		X		X		11,32,34,21,5, 35
B	X		X		X			X	X		6, 10, 9, 25 40, 15
C	X			X	X			X	X		None
D	X			X	X			X		X	41
E	X			X		X		X		X	36
F		X	X		X		X		X		7,14,37,30, 31, 38, 39, 22, 28, 26, 13, 23, 33, 19, 18
G		X	X		X			X	X		17,27,43,4,1,8
H		X		X	X			X	X		16,20,2,42
I		X		X	X			X		X	24, 29
J		X		X		X		X		X	None

Source: Derived by author

5.5 Environmental Settings

The differences in channel systems, as well as their similarities under diverse environmental settings, pose a real challenge for study. Underlying these complexities is an assortment of interrelated environmental variables that determine the dimensions, patterns, shapes, and profiles of present-day channels. The resulting physical appearance and character of the channel is a product of an adjustment of its boundaries to current streamflow, and these streamflow characteristics can be expressed via hydraulic geometry exponents. Inversely, given current streamflow and hydraulic geometry characteristics, the channel boundaries and changes can be deduced.

Since streams of similar types tend to act in similar ways (Leopold, 1994), environmental controls, which influence the hydraulic geometry exponents, and channel flow characteristics are investigated for their cause and effect relationships. These relevant factors include channel width/depth ratios, patterns, shapes, and cross-section profiles.

In order to investigate the relationships between channel forms and hydraulic geometry exponents, the characteristics of the channel forms and other environmental controls are classified based on commonly used criteria. Although any classification scheme risks oversimplification of very complex channel forms, researchers have found statistically discernible correlations between hydraulic geometry and environmental controls (Ferguson, 1986, Leopold, 1994). Many previous studies (Ferguson, 1986 and Knighton, 1979) indicate that there is a correlation between different channel forms and different hydraulic geometry. Leopold (1994) stated that at a given discharge, different rivers exhibit different values of width and depth. Those with fine-grained cohesive banks tend to be deep and narrow, and those with sandy, friable banks tend to be wide and shallow. Leopold (1994) asserted that a wide, dish-shaped channel would have rapid rate of increase in width with increasing discharge; a boxlike channel with straight steep sides—such as one might expect to find in cohesive materials—would have a low value for b and a high value for f.

5.5.1 Channel Pattern

Channel pattern, the term used to describe how a river looks from above, has been differentiated as meandering, braided, or straight. There is no sharp distinction among these patterns. The subjectivity of these types of pattern has long been noted.

A meandering channel can be highly convoluted or merely sinuous, but maintains a single thread in curves having a definite geometric shape. The meandering pattern is the most common pattern seen in rivers and roughly 85-90 percent of the world rivers are classified as meandering (Leopold, 1994).

Since river channels are seldom straight through a distance greater than about ten times of the channel width, the designation “straight” may imply irregular, sinuous, or non-meandering. Straight channels are typical for short reaches along tectonic or lithological lines are sinuous but apparently random in the occurrence of bends. Even where the channel is straight, it is usual for the thalweg, line of maximum depth, to wander back and forth from near one bank to the other (Leopold et al., 1964). Opposite to the point of greatest depth, there is usually a bar or an accumulation of mud along the bank, and these bars tend to alternate from one side of the channel to the other.

Braided channels are those with multiple streams separated by bars and islands, and streams with shallow channels in coarse alluvium carrying multiple threads of fast flow that subdivide and rejoin repeatedly, continually shifting their location. Their characteristics are usually unstable banks, large amount of transported sediments, slopes are steep with variations in flow. Pools and riffles are less well developed in braided than in straight, but non-meandering channels (Leopold, 1994). Braided channels are often not always associated with sandy or friable bank materials. Also, vegetation has similar effects; a change from non-braided to braided character is sometimes associated with a change from dense vegetation along the channel banks to sparse or no vegetation (Ferguson, 1986).

High current velocities seem to be required, and because high velocities are most readily achieved on steep slopes, it automatically follows that most braided channels are found on streams with steep longitudinal gradients. As slope increases, channels tend to become braided. Braided channels seem to be the product of a complex interaction among the flow velocity of the stream, the availability of sediment, the grain size distribution of the sediment, and flow volume irregularity.

Knighton (1975) found a lower rate of change of width on straight-reach sections than in meander sections. Knighton and Rhodes (1977) stated that channel pattern has an important influence on hydraulic geometry of rivers, but the absence of adequate data has hindered definitive conclusions. However, through USGS hydrologists' field notes, data for width and depth of cross-sections in average 30 segments per each observation per gage station were collected and used to classify channels by their patterns. With these data, the ratio of lowest depth (d1) and its accompanying narrowest width (w1) and ratio of highest depth (d2) and its corresponding widest width (w2) were calculated.

The morphological variables can and do change even in short distances along a river channel, due to such influences of change as geology and tributaries. Therefore, the morphological description level incorporates field measurements from selected reaches, so that the stream channel types used apply only to individual reaches of channel. Data from individual reaches are not averaged over entire basins to describe a stream system.

To distinguish channel patterns, Rhodes (1977) classified channels as the ratio of the narrowest width (w1) with the associated depth (d1) to the widest width (w2) with the associated depth (d2). By adapting the Rhodes (1977)'s width and depth ratio at different stages, each channel pattern is assigned to each subbasin (Table 5.3):

straight channel: w1 / d1 / w2 / d2 > 1.8,

meander channel: w1 / d1 / w2 / d2 ---1.8 to 1.0, and

braided channel: w1 / d1 / w2 / d2 < 1.0.

In the study sites, the width and depth ratios range from

w1 / d1 --2.45 (m31) - 137.77 (v22),

w2 / d2 -- 9.72 (m32) - 125.49 (v48),

w1 / d1 / w2 / d2--- 0.101 (m311) - 2.256 (m11).

These classification results are compared with topographic maps, delineated subbasin drainage, and the USGS Form 9-197 which describes each gage station. For example, the channel section of the USGS Form 9-197 for Willis Creek near Cumberland, Maryland (USGS gage station 01601500) (m10) is described as “One channel at all stages. Channel is straight for 700 ft above gage and 2,000 ft below gage. Streambed is composed of gravel, rocks, and boulders. Right bank is high, rocky, and covered with brush. It will be overflowed only during extreme floods. Left bank is low and wooded and extends to railroad embankment. Embankment overflowed in extreme flood only.” Comparing the USGS’s gage station descriptions and calculated channel patterns by width and depth ratio, some discrepancies are revealed. For example, channel patterns for m24, v19, v25, v29, v48, and v49 are calculated as braided, but they are described as one channel at all stages on the USGS’s gage station description. In these cases, and in view of the resolution of the delineated subbasin drainage, 30 by 30 meter lattice data, and the generality of the gage station descriptions of channels, the author decided to use the calculated width and depth ratio to classify channel patterns.

Table 5.6 Width and Depth Ratio and Channel Pattern

ID	USGS ID	Size	w1/d1	w2/d2	w1/d1/w2/d2	Channel Pattern
m10	1601500	247	90.32	45.51	1.985	S
m11	1603000	875	83.6	37.06	2.256	S
m19	1614500	494	88.92	75.8	1.173	M
m21	1617800	18.9	29.55	22.5	1.313	M
m24	1619500	281	24.88	32.02	0.777	B
m26	1637500	66.9	50.29	67.52	0.745	B
m29	1639140	31.3	33.67	39.94	0.843	B
m30	1639500	102	63.83	57.12	1.117	M
m31	1640965	2.14	2.45	16.79	0.146	M
m311	1640970	4.01	4.09	40.47	0.101	M
m32	1640980	0.38	3.24	9.72	0.333	B
m34	1643000	817	84.32	160.65	0.525	B
m37	1643500	62.8	77.87	37.72	2.064	S
m38	1645000	101	31.54	34.13	0.924	B
m43	1651000	49.4	15.15	48.26	0.314	B
m45	1653600	39.5	48.01	21.93	2.189	S
m47	1661050	18.5	12.01	50.8	0.236	B
m48	1661500	24	28.44	39.22	0.725	B
v07	1622000	379	75.28	40.82	1.844	S
v12	1624800	70.1	29.4	24.64	1.193	M
v13	1625000	375	36.42	45.3	0.804	B
v15	1626000	127	64.47	38.4	1.679	M
v17	1626850	149	78.3	35.64	2.197	S
v18	1627500	212	59.38	37.79	1.571	M
v19	1628060	1.94	3.6	22.78	0.158	B
v22	1628500	1084	137.77	120.74	1.141	M
v23	1629500	1377	100.18	120.16	0.834	B
v24	1631000	1642	43.3	20.25	2.138	S
v25	1632000	210	28.24	40.24	0.702	B
v26	1632082	45.5	20.42	48.77	0.419	B
v27	1632900	93.2	36.45	31.17	1.169	M
v28	1633000	506	19.29	37.97	0.508	B
v29	1634000	768	94.44	97.26	0.971	B
v30	1634500	103	37.34	68.93	0.542	B
v36	1638480	89.6	30.39	29.25	1.039	M
v38	1643700	123	29.21	37.33	0.782	B
v39	1644000	332	39.17	49.49	0.791	B
v44	1646000	57.9	37.71	24.54	1.537	M
v48	1653000	33.7	101.38	125.49	0.808	B
v49	1654000	23.5	11.14	51.61	0.216	B
v52	1656000	93.4	13.75	54.31	0.253	B
v65	1658500	7.64	28.13	23.76	1.184	M
v71	1660400	34.9	53.75	32.14	1.672	M

Out of 43 channels, 7 channels were classified as straight, 14 as meandering, and 22 as braided (Table 5.6). All 7 straight channels fall in the b-f-m ternary diagram Regions F, G, and H regions, and 14 meandering channels fall in A, B, E, F, G, and I Regions. The 22 braided channels fall in A, B, F, G, and H regions. Each channel within a channel pattern type is related to the b, f, and m regions of the ternary diagram (Table 5.6). This is to better understand the channel patterns and b, f, and m relationship.

5.5.2 Channel Cross-Section Shape

The shape of the cross-section of any river channel is a function of the flow, the quantity, and character of the sediment in motion through the cross-section, and the character or composition of the materials (including the vegetation) that make up the bed and banks of the channel. The position of the channel is constantly varying, but the form of the cross-section is stable, meaning more or less constant (Ferguson, 1986). Therefore, cross-sectional information is visually portrayed for the investigation of relationships between channel cross-section and hydraulic geometry and how channels adjust to changes in discharge.

Ferguson (1986) classified channels by the shape of their cross-sections and noted different rates of increase of channel width with depth. The hydraulic exponents for shallow but wide channels (high value of width / depth) differ from the exponents for deep but narrow channels. Differences in channel shape cause b / f to vary from 0 for a rectangular to 1 for a triangular section. And a change in frictional characteristics alters m/f. Williams (1978) also noted that, in a deep and narrow channel, water depth increased more rapidly with increases in discharge.

Ferguson (1986) defined that: (1) the rectangular channel cross-section shape R typifies a rock-walled channel or one with cohesive and vegetated alluvial banks, and has constant width as depth and discharge increase so that b = 0 and f + m = 1; (2) the triangular channel cross-section, T typifies banks of non-cohesive material at a constant angle of repose and has w ∞ d so that b = f; (3) parabolic shape, P, which represents the most real world case where the angle of repose of sand or gravel decreases below the waterline to give approximately a parabolic shape (P in Fig 5.5) with w ∞ d1/2 and therefore b = f / 2; and (4) B shape of channel cross-section which represents a curved channel with cut bank and point bar, the latter convex upwards so that width increases faster than depth from medium to high discharges.

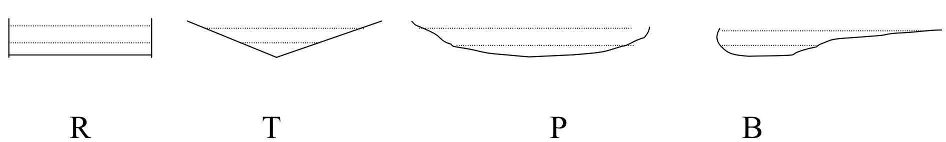


Figure 5.5 Ferguson's Four Channel Shapes
Source: Ferguson (1986)

Width multiplied by depth creates cross-section area. In order to categorize channels by visual inspection, channel profiles were created to classify the channels into rectangular, triangular, parabolic, and braided chanel shapes. The visual inspection was based on Ferguson's four channel shapes, however his categorization criteria (ratio of b and f) were not used to classify the channels in this study. Using File Maker Pro™, a macro program was written to calculate cumulative width, area, and distance from the mid-point for each segment. In order to draw the channel profile, the depth values were expressed as a negative value. The channel cross-section profile is drawn for each survey measurements in a given subbasin. An example of the cross-section profiles is shown in Figure 5.6.

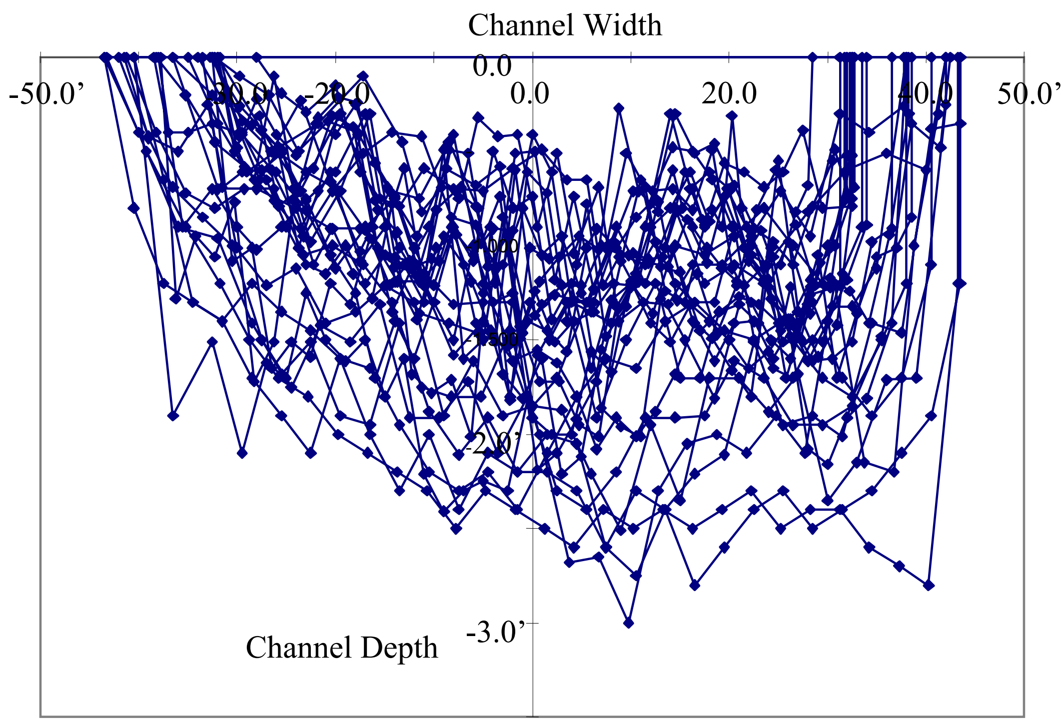


Figure 5.6 An Example of Cross-section Profiles for Wills Creek near Cumberland, Maryland (m10)
Source: Created by author using Excel™ program

Based on visual inspection of the channel cross-section profiles, the 43 channel cross-sections are classified as one of the four shapes, Rectangular (R), Triangular (T), Parabolic (P), and curved channel with cut bank and point bar (B). This classification of the cross-section profile is shown in Table 5.6. Fourteen channel cross-sections were identified as Rectangular, 12 as Triangular, 7 Parabolic, and 10 curved channels with cut banks.

Table 5.7 Subbasin Channel Pattern and Channel Shape

ID	ID	USGS Gage	Size	Region	Pattern	Shape
1	m10	1601500	247	G	S	B
2	m11	1603000	875	H	S	P
3	m19	1614500	494	F	M	B
4	m21	1617800	18.9	G	M	R
5	m24	1619500	281	A	B	P
6	m26	1637500	66.9	B	B	R
7	m29	1639140	31.3	F	B	T
8	m30	1639500	102	G	M	R
9	m31	1640965	2.14	B	M	R
10	m311	1640970	4.01	B	M	R
11	m32	1640980	0.38	A	B	R
12	m34	1643000	817	outside	B	P
13	m37	1643500	62.8	F	S	B
14	m38	1645000	101	F	B	R
15	m43	1651000	49.4	B	B	B
16	m45	1653600	39.5	H	S	B
17	m47	1661050	18.5	G	B	T
18	m48	1661500	24	F	B	R
19	v07	1622000	379	F	S	R
20	v12	1624800	70.1	H	M	B
21	v13	1625000	375	A	B	P
22	v15	1626000	127	F	M	T
23	v17	1626850	149	F	S	R
24	v18	1627500	212	I	M	T
25	v19	1628060	1.94	B	B	B
26	v22	1628500	1084	F	M	R
27	v23	1629500	1377	G	B	B
28	v24	1631000	1642	F	S	R
29	v25	1632000	210	I	B	T
30	v26	1632082	45.5	F	B	T
31	v27	1632900	93.2	F	M	P
32	v28	1633000	506	A	B	T
33	v29	1634000	768	F	B	R
34	v30	1634500	103	A	B	T
35	v36	1638480	89.6	A	M	T
36	v38	1643700	123	E	B	R
37	v39	1644000	332	F	B	B
38	v44	1646000	57.9	F	M	T
39	v48	1653000	33.7	F	B	P
40	v49	1654000	23.5	B	B	P
41	v52	1656000	93.4	D	B	T
42	v65	1658500	7.64	H	M	T
43	v71	1660400	34.9	G	M	B

Source: Observed and visually inspected by author

5.5.3 Channel Asymmetry

As Ferguson (1986) identified, whether the channel volume container is symmetric or asymmetric also gives impact on hydraulic geometry. Comparing the shape of the channel basin area in terms of symmetry provides another characteristic of the channel. Therefore, the asymmetry of each channel, calculated for each observation using Knighton's (1981) index, and is treated as a predictor variables for environmental controls and hydraulic geometry relationships.

The Knighton (1981) index of asymmetry was defined as:

$$As = (Ar - Al) / A$$

where As is the asymmetry index, Ar and Al are the cross-sectional areas to the right and the left of the channel centerline, respectively; and A = Ar + Al is the total area of the channel. If the right side occupies a larger channel area than the left side, the As will have a positive asymmetry, if the left side occupies larger channel area at that specific cross-section, then the channel will have a negative asymmetry.

Areas that occupy the channel at any observation point were calculated by multiplying distance, the measurement from the previous measurement point to the observation point, by the current measurement point depth (depth of water at the observation point). Each observed point area is accumulated to calculate the right or left side of channel total area. The center point of the channel is indicated as half of the total width of the channel, distance between right and left bank. The right side of channel area is the accumulation of all the observed areas from the initial point to the mid-point of the channel, and the left channel area is the accumulation of all observed areas from the center point of the channel to the opposite bank of the initial point.

A File Maker Pro™ macro was written to calculate; (1) the distance from the initial point to the next observation point up to the other side of bank for calculation of the mid-point of channel width; (2) the size of the area at each observed point and accumulation of these areas up to the past observed point area; and (3) the asymmetry index of channel area for each survey. The right side of the areas is accumulated up to the mid-point which is the cross-sectional areas of to the right side of the channel. The left side area of the channel was calculated by subtracting the right side banks area from the total channel area. And the asymmetry for each observation was calculated by As = (Ar - Al) / A.

For example, as shown Appendix A which has all 1130 rows of surveys, an asymmetry index for Wills Creek near Cumberland, Maryland (m10) observed on June 18, 1985, is calculated as:

As = (Ar - Al) / A

= (27.13 - 48.93) / 76.06

= -0.287

On June 18 1985, at the cross-section at 500' above gage station, right side area of the cross-section was 28.7% smaller than the left. Two out of 29 observations show a left and right side asymmetry index of 0.0. After individual asymmetry calculations were performed for each hydrographic survey, the asymmetric indices values were averaged within each given subbasin.

Within each subbasin, the channel asymmetry indices are averaged and standard deviation and averaged symmetry index for each subbasin are shown Appendix A and Appendix C. The averaged asymmetry index during 18 June 1985 through 4 September 1992 is -0.131 with standard deviation of 0.147.

At this point, data needed for the investigation of relationships between the hydraulic geometry and the predictor variables for the study subbasins have been identified, collected, and discussed (Appendix C). Statistical relationships are investigated for each predictor variable and hydraulic geometry exponents and findings are presented in Chapter 6.

CHAPTER 6

INVESTIGATION OF THE ROLES OF SCALE AND OTHER SELECTED WATERSHED VARIABLES

At-a-station hydraulic geometry is a function of the interactions of many hydraulic and physical drainage system characteristics including physiography and lithology, channel pattern and shape, bed and bank materials, the sizes of channels and subbasins, the downstream locations of channels, hill slope and valley floor, and channel hierarchy in the drainage system. Leopold (1994) clearly illustrated the differences among the average slope lines of the hydraulic geometry exponents in three different sizes of drainage areas. Yet, the spatial variable, geographical scale (subbasin size) has received less research attention than its impacts on the rates of changes in channel width and depth and flow velocity (b, f, and m values) may warrant. This chapter describes and characterizes the hydraulic geometry exponents in the context of geographical scale as expressed by varying areal sizes of the study subbasins.

The working hypothesis of this study is that variations in hydraulic geometry exponents, the change rates of channel width and depth, and flow velocity, are not random but that there are systematic changes in hydraulic geometry exponents as a function of subbasin size as well as subbasin and channel physical and environmental characteristics. In simple words, the b, f, and m exponent values in Amazon-size rivers are different (lower b and f and higher m values) from those of smaller rivers. My assumption is that this scale factor might explain why hydraulic geometry has different b, f, and m values where all other physical variables are the same or similar regardless of subbasin size.

My research attempts to discern relationships between a geographical scale factor (subbasin size) and b, f, and m via empirical correlations, and to explain roles of the possible predictor variables for b, f, and m in the scale context. Testing the overall hypothesis that b, f, and m values are functions of subbasin size will use a model:

$b = a_{0.b} + a_{1.b}$ * scale factor in square miles;

$f = a_{0.f} + a_{1.f}$ * scale factor in square miles; and

$m = a_{0.m} + a_{1.m}$ * scale factor in square miles

where, $a_{0.b}$, $a_{0.f,}$ and $a_{0.m}$ are constants and $a_{1.b}$, $a_{1.f,}$ and $a_{1.m}$ are the scale factor coefficients. Theoretically, as stream discharge increases, channel width and depth, and flow velocity would increase as well, but the rates of these increases can be either positive or negative. The focus of the study is the slope term, $a_{1.b}$, $a_{1.f,}$ and $a_{1.m}$ rather than the intercept (which is a positive value). The null hypotheses are $H_{0.b}$: $a_{1.b} = 0$, $H_{0.f}$: $a_{1.f} = 0$, and $H_{0.m}$: $a_{1.m} = 0$ and the alternative hypotheses are $H_{1.b}$: $a_{1.b} \neq 0$, $H_{1.f}$: $a_{1.f} \neq 0$, and $H_{1.m}$: $a_{1.m} \neq 0$.

The sensitivity of the hypothesis test to chance results will be discussed in terms of the calculated probability numbers rather than a pre-determined level of confidence such that readers can judge the statistical significance. If there is insufficient evidence against $H_{0.b}$, $H_{0.f}$, and $H_{0.m}$ in favor of $H_{1.b}$, $H_{1.f}$, and $H_{1.m}$, I will try to further explain the outcome in terms of the physical and hydraulic characteristics, such as whether the channel bed material is non-cohesive sand vs. cohesive clay. If the hypothesis testing indicates a discernable role for the scale factor, the magnitude of the scale effect will be investigated by analyzing the a_1 value.

This investigation also identifies the strength of relationships between each predictor variable and hydraulic geometry exponents, and which predictor variables play dominant roles for b, f, and m. For each selected predictor variable, the hydraulic geometry exponents are modeled in the context of scale such that: $b = a_{0.b} + a_{1.b}$ * scale factor in square miles + $a_{2.b}$ * predictor variable (such as physiography, channel pattern, etc.); $f = a_{0.f} + a_{1.f}$ * scale factor in square miles + $a_{2.f}$ * predictor variable; and $m = a_{0.m} + a_{1.m}$ * scale factor in square miles + $a_{2.m}$ * predictor variable for each basin characteristic group, where, $a_{0.b}$, $a_{0.f}$, and $a_{0.m}$, are constants and $a_{1.b}$, $a_{1.f}$, and $a_{1.m}$ and $a_{2.b}$, $a_{2.f}$, and $a_{2.m}$ are scale factor coefficients.

This chapter will discuss influences of scale, each predictor variable, and the combination of scale and each predictor on b, f, and m separately, and conclude with investigation of the most influential variables of b, f, and m via stepwise multi-variable regression. In addition, empirical findings of $f > m$ in sand bed and $f < m$ in gravel bed with increasing stream discharge are investigated in a scale context. Unless otherwise noted, tables and figures are created by the author.

To further examine the validity of the statistical results, two additional analyses are conducted. First of all, I examined a subset of subbasins which meet criteria of constraints, and, secondly, I analyzed all the subbasins using weighted sample sizes. Using the R^2 values of the b, f, and m, each subbasin is categorized as well constrained (at least two out of three exponents have R^2 of 0.9), moderately constrained (at least of two exponents have R^2 of 0.8), or poorly constrained subbasins, poorly constrained subbasins (personal communication with Dr. Karen Prestegaard, Oct. 2005).

6.1 Hydraulic Geometry and Scale

Trainer and Watkins (1975) found that average base runoff from tributaries in the upper Potomac River Basin was approximately proportional to the drainage area, which accords with numerous studies that concluded that the size of a subbasin has a linear relationship to the volume of discharge. I have hypothesized that the size of a subbasin, a surrogate scale indicator, is a principal influence on discharge volume.

Scale problems in hydrology arise because different hydrological processes are dominant at different scales. Process description or parameterizations that have been derived at the laboratory scales of the experimental plot do not necessarily hold true at the much larger scales of the subbasins. And, there is demonstrated evidence of systematic differences of b, f, and m in different sizes of subbasins. Notable examples are the average slopes of b, f, and m values on discharge lines in the hydraulic geometry of three rivers of different size: Watts Branch drainage area in Potomac River, 3.7 square miles; Seneca Creek in Potomac River, 100; and Amazon River at Obiodos drainage area of 1.9 million square miles (Leopold, 1994).

For my Potomac River study, the 43 subbasin sizes range from 0.38 square miles to 1,642 square miles (Figure 6.1). Except for three subbasins, all are less than 1,000 square miles. Most of the subbasins are between 10 and 100, and from 100 to 1,000 square miles.

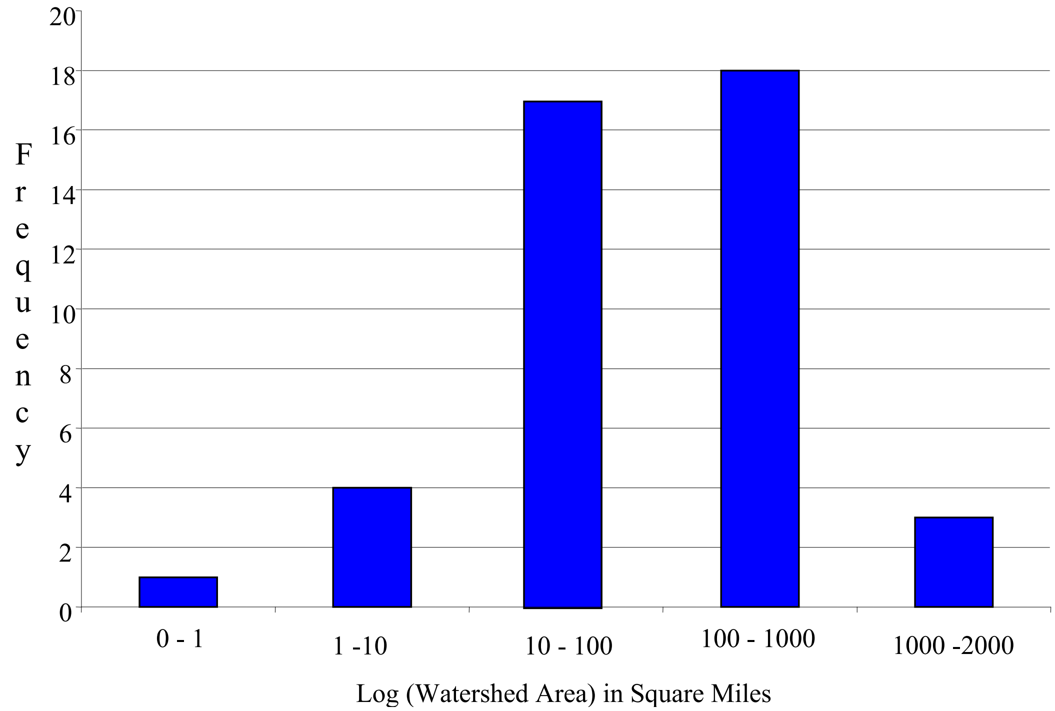


Figure 6.1 Subbasin Size Histogram
Source: Except where otherwise noted, all figures in Chapter 6 have been produced from the author's research.

The scatter plots of b, f, and m versus subbasin size are first examined via simple regression analysis using linear equations (Figure 6.2). The rate of width change (R^2 = 0.154) gets smaller as the subbasin size increases, while the change rates of depth (R^2 = 0.017) and velocity (R^2 = 0.083) increase as the subbasin size increases. This does not mean actual width will decrease in larger subbasins. Actual width might get wider in larger subbasins, but the rate of width change decreases in the larger subbasins of the study area.

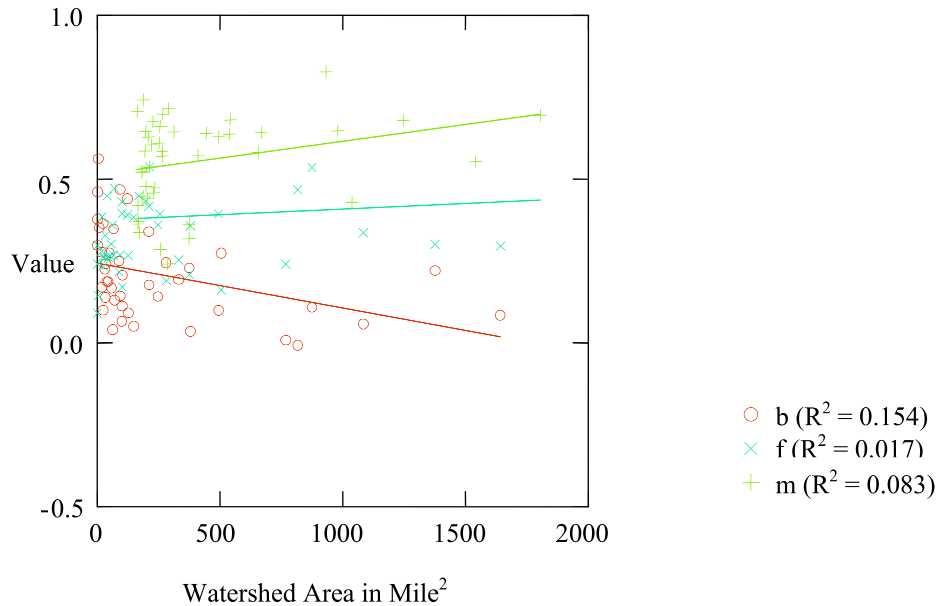


Figure 6.2 b, f, and m Values and Subbasin Size with Linear Regression

Notwithstanding the paucity of research using a non-linear model, it is of some value to empirically examine the size-exponent relationship using quadratic and logarithmic models. Regression results, shown as Table 6.1, the quadratic goodness of fit lines for b, f, and m indicate an improved coefficient of determination (R^2), and the logarithmic goodness of fit lines further improves R^2 from the quadratic regression. However, just looking at the correlation coefficient, the correlation is not strong. The small R^2 is due to the heterogeneity of the watershed variables. The quadratic regression (Figure 6.3) shows change in the trend lines at around 1,000 square miles. This is consistent with Leopold's (1994) analysis of the hydraulic geometry in three different drainage sizes.[3]

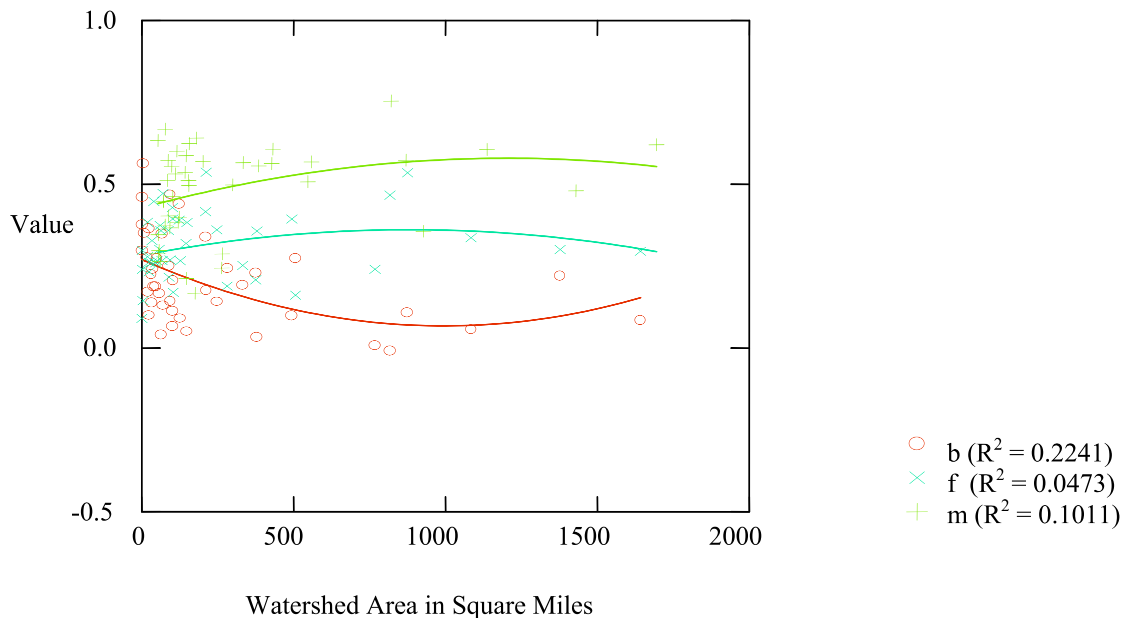


Figure 6.3 b, f, and m Values and Size with Quadratic Regression

As shown, for subbasins of up to 1,000 square miles there is an inverse relationship between subbasin size and b. However, that relationship reverses to become proportionate when the subbasin size becomes larger than 1,000 square miles (Table 6.1). Based on these final results, when subbasin size becomes 1,000 square miles, b becomes

[3] Cubic regression could show the trend lines more definitively. At the same time, there is no apparent scientific reason for the use of quadratic versus cubic regression, and going beyond quadratic and cubic regressions, more terms will be added to the regression equation, causing loss of degrees of freedom.

0.0627, and when subbasin size becomes 1,500 square miles, b becomes 0.109. This trend is consistent with visual inspection of Leopold's (1994) b slope lines in three different sizes of streams, in that small, medium, and larger size of subbasins have different rates of width changes.

Even if it is based on only a few cases and polynomial relationship meant to curve, the positive proportionate relationships between the subbasin size applies to both f and m up to about 1,000 square miles. However, the relationship reverses for both exponents, when the subbasin size becomes bigger than 1,000 square miles. This trend is consistent with visual inspection of Leopold's (1994) f and m slope lines in three different sizes of streams.

Table 6.1 Regression of b, f, and m with Subbasin Size

b regressed on Subbasin Size (Linear, Quadratic, and Log, Log Quad)				
	Linear	Quadratic	Logarithmic	Log Quad
R2	0.1542	0.2241	0.3105	0.3105
t (Size)	-2.7239	-2.6940	-4.2968	-1.3502
t (Size*Size)		1.8851		-0.0467
Significance/	0.0094	0.0102	0.0001	0.1845
Probability[1]		0.0667		0.9630
Coefficient	-0.0001	-0.0004	-0.0941	-0.0910
		0.0000		-0.0009

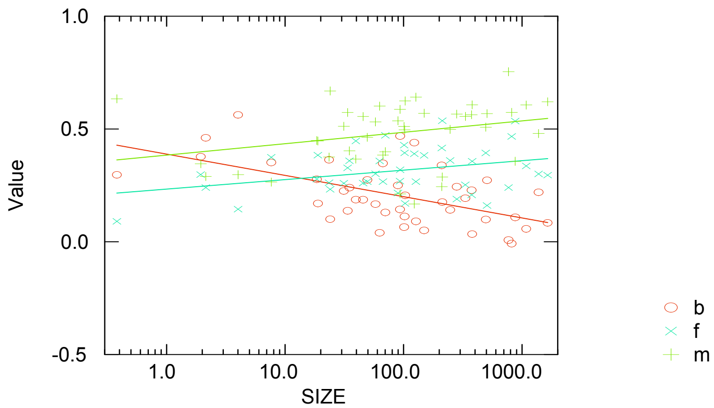
f regressed on Subbasin Size (Linear, Quadratic, and Log, Log Quad)				
	Linear	Quadratic	Logarithmic	Log Quad
R2	0.0171	0.0473	0.1091	0.1566
t (Size)	0.8443	1.3411	2.2409	2.1651
t (Size*Size)		-1.1267		-1.5011
Significance/	0.4034	0.1875	0.0305	0.0364
Probability[1]		0.2666		0.1412
Coefficient	0.0000	0.0002	0.0420	0.1218
		0.0000		-0.0245

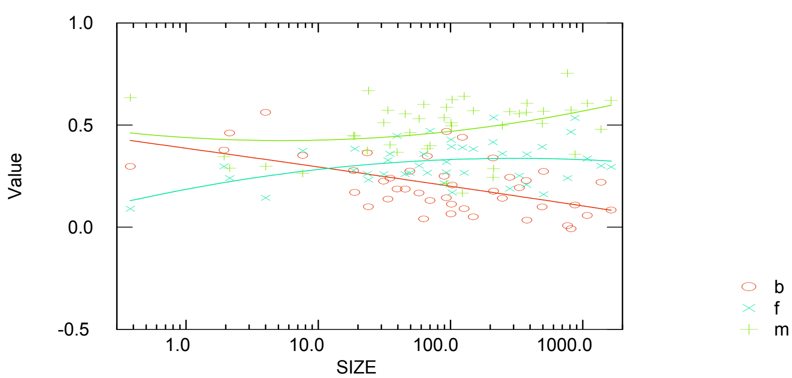
m regressed on Subbasin Size (Linear, Quadratic, and Log, Log Quad)				
	Linear	Quadratic	Logarithmic	Log Quad
R2	0.0834	0.1010	0.0857	0.1200
t (Size)	1.9317	1.4665	1.9602	-0.5308
t (Size*Size)		-0.8875		1.2484
Significance/	0.0603	0.1503	0.0570	0.5985
Probability[1]		0.3801		0.2191
Coefficient	0.0001	0.0002	0.0505	-0.0413
		0.0000		0.0281

Note: [1] With degree of freedom 41, the critical t value at .0.01 probability is 2.704; 0.05 level, 2.021 and 0.1, 1.684.

Source: All tables in Chapter 6 have been produced from the author's research.

Since the size of the study subbasins cover a wide range and the majority of subbasins are between 10 and 100 square miles, with a small numbers of subbasins under 10 and above 1, 000 square miles, it makes sense also to examine subbasin sizes in $\log_{10}$ form. The scatter plots of the study subbasin b, f, and m values and the subbasin in $\log_{10}$ size with linear and quadratic regression are shown in Figures 6.4 and 6.5, respectively. Table 6.1 incorporates the results of this version of the basic model.





Figures 6.4 and 6.5 b, f, and m Values and Log Size with Linear and Quadratic Regressions

Because the quadratic term in $\log_{10}$ size for each b, f, and m is not statistically significant and does not add any more statistical significance (see Table 6.1), the logarithmic linear relationships between b, f, and m with $\log_{10}$ subbasin size are the basis for the subsequent analyses. Because all correlations appear low and there is a paucity of research using a non-linear model, therefore it is hard to determine the expected theoretical or empirical values of R^2 of b, f, and m. Also, since there is no theoretical reasoning of selecting specific probability levels, the author opts to choose the probability level at 0.05 or 0.01.

To test the hypotheses that b, f, and m change systematically with the size of the subbasin and, hence, that b, f, and m exponents are a function of subbasin scale, a model b (f and m) = $a_0 + a_1$ * scale factor in square miles for each subbasin is set. That is to say, the model now is:

b = 0.389 - 0.094 * log subbasin size,

f = 0.233 + 0.042 * log subbasin size, and

m = 0.3843 + 0.050 * log subbasin size.

Since the calculated t value for b, 4.300, is greater than 3.307, the null hypothesis ($a_1 = 0$) is rejected with more than 0.999 probabilities and the alternative hypothesis ($a_1 \neq 0$) accepted. That is, b is a function of geographical scale (Table 6.1).

In that the calculated t statistic for f is 2.241, therefore, the null hypothesis is rejected with more than 0.950 probabilities, and it is declared that f is a function of the scale factor at 0.950. The calculated t statistic for m is 1.960. Because the calculated t value, 1.960 < 2.021, the null hypothesis ($a_1 = 0$) cannot be rejected, and it is declared that $a_1 \neq 0$, meaning m values do not change systematically with the size of subbasin and m is not function of a scale factor (subbasin size in square miles) at 0.95 probability.

In summary, the relationships between scale and b, f, and m are not strong, but the results of this study support the hypothesis that there are systematic changes in hydraulic

1geometry exponents except for m as a function of subbasin size at the 0.05 level of the statistical significance. Using the log of subbasin size, the R^2 improved in both b and f. However because of the scarcity of research on geographic scale and at-a-station hydraulic geometry, it is hard to judge the universal goodness of the particular R^2 as shown by this research. Nonetheless, recognizing the high probability of the relationship being as stated, and considering the heterogeneous nature of the subbasins in terms of physiography, lithology, channel pattern and shape, bed and bank material, the statistically discernible relationships between scale and b and f are notable (but not m).

6.2 Going Beyond Size: Selected Predictor Variables

Ridenour and Giardino (1991) stated that Ferguson (1986) showed that the cross-sectional shape of a channel determines the rate of increase of stream width with depth, whereas the laws of flow resistance determine the rate of increase of mean velocity with depth. In turn, factors that affect channel geometry include vegetation (Hadley, 1961; Zimmerman et al., 1967), bank cohesiveness and sediment size (Schumm, 1960; Wolman and Brush, 1961; Knighton, 1974; Maizels, 1988), changes in suspended load (Leopold and Maddock, 1953; Wolman, 1955; Thornes, 1970), seasonal variation (Thornes, 1970), channel sinuosity (Knighton, 1975), channel roughness or flow resistance (Knighton, 1975), riffle spacing (Harvey, 1975), the processes of scour and fill (Foley, 1978; Andrews, 1979), and stream size and order (Thornes, 1970; Miller and Onesti, 1977). Hence, all of these stream parameters are candidates as covariates of the hydraulic geometry exponents.

The selected predictor variables, in addition to subbasin size, that are determinative in influencing the physical and environmental characteristics of the subbasins and channels are, as described in some detail in the previous chapters: physiography, lithology, landuse, channel pattern, channel shape, bed and bank materials, asymmetry of channel, topographic indices, and subbasin slope. These correlates will be examined in four ways: (1) by visually comparing b, f, and m with predictor variable categories; (2) by determining the importance of each predictor variable category by t-tests for the difference of mean values for one category vs. all others; (3) by analyses using underlying basic principles such as rank order of physiography-based erodability; and (4) by investigating the predictor variables and b, f, and m values in the context of scale. The b, f, and m are analyzed with interaction terms and by portraying residuals from size regression by predictor variable categories.

The tests for difference of mean values of b, f, and m between each categorical predictor variable (e.g., Blue Ridge vs. non-Blue Ridge or Piedmont vs. non-Piedmont provinces) are created using dummy variables. Dummy variables are specified as 1, if they are the designated physiography, or 0 if they are any other physiography type. For instance, all subbasins within the Piedmont physiography are specified as 1 and all other subbasins are each coded as 0.

In general, the working hypotheses are that there is no difference in the mean values of b, f, and m within one province category vs all other combined, and that each predictor variable influences the b, f, and m exponents systematically as subbasin size changes. To do this, it is necessary to classify the study subbasins according to the characteristics of each predictor variable. For example, to investigate the role of physiography on b, f, and m, study subbasins are grouped as to whether they fall in the Appalachian Plateau, Valley and Ridge, Great Valley, Blue Ridge, Piedmont, or within

Coastal Plain physiographic provinces. The b, f, and m values are described and correlated with each physiographic grouping of subbasins.

The hypotheses models are set as: the mean values of b, f, and m of a specific group are the same as the mean values of the rest of the study area groups. The other hypotheses models are set as b (f , m) = $a_{0.b}(a_{0.f}, a_{0.m}) + a_{1.b}(a_{1.f}, a_{1.m})$ * subbasin size in square miles + $a_{2.b}(a_{2.f}, a_{2.m})$ * predictor variable, where $a_{0.b}(a_{0.f}, a_{0.m})$ are constants, $a_{1.b}(a_{1.f}, a_{1.m})$ are the coefficients for scale factor, and $a_{2.b}(a_{2.f}, a_{2.m})$ are the coefficients for the influences of an individual predictor variable. The null hypotheses are modeled $H_{0..b}$: $a_{2.b} = 0$, $H_{0.f}$: $a_{2\ f} = 0$, $H_{0.m}$: $a_{2\ m} = 0$,and the alternative hypotheses are $H_{1.b}$: $a_2 \neq 0$; $H_{1.f}$: $a_2 \neq 0$; and $H_{1.m}$: $a_2 \neq 0$.

The b, f, and m are analyzed with an interaction term because, in any form of multiple regression, interaction between predictor variables is expected. Where a lower order term, such as scale, is significant and a higher order term like physiography is not significant, the higher order term is removed from the model. Where the higher order term, the interaction term, is significant, then the lower order term is kept even if the lower term is not significant. In this case the hypotheses models are set as b (f , m) = $a_{0.b}(a_{0.f}, a_{0.m}) + a_{1.b}(a_{1.f}, a_{1.m})$ * subbasin size in square miles + $a_{2.b}(a_{2.f}, a_{2.m})$ * predictor variable + $a_{3.b}(a_{3.f}, a_{3.m})$ * interaction between scale and predictor variable, where $a_{0.b}(a_{0.f}, a_{0.m})$ are constants, $a_{1.b}(a_{1.f}, a_{1.m})$ are the coefficients for scale factor, and $a_{2.b}(a_{2.f}, a_{2.m})$ are the coefficients for the influences of an individual predictor variable , $a_{3.b}$, $a_{3.f}$, $a_{3.m}$ are coefficients for individual predictor variable influence. The null hypotheses are $H_{0.b}$: $a_3 = 0$, $H_{0.b}$: $a_3 = 0$, and $H_{0.b}$: $a_3 = 0$, and the alternative hypotheses are $H_{1.b}$: $a_{3.b} \neq 0$, $H_{1.f}$: $a_{3.f} \neq 0$, and $H_{1.m}$: $a_{3.m} \neq 0$.

6.3 The Role of Physiography

The 43 study subbasins extend across six distinct and well known physiographic provinces (Figure 6.6). Two of the study subbasins fall in the Appalachian Plateau province, two in the Valley and Ridge Province; 7 in the Great Valley; 15 in the Blue Ridge; 12 in the Piedmont; and 5 in the Coastal Plain province[4].

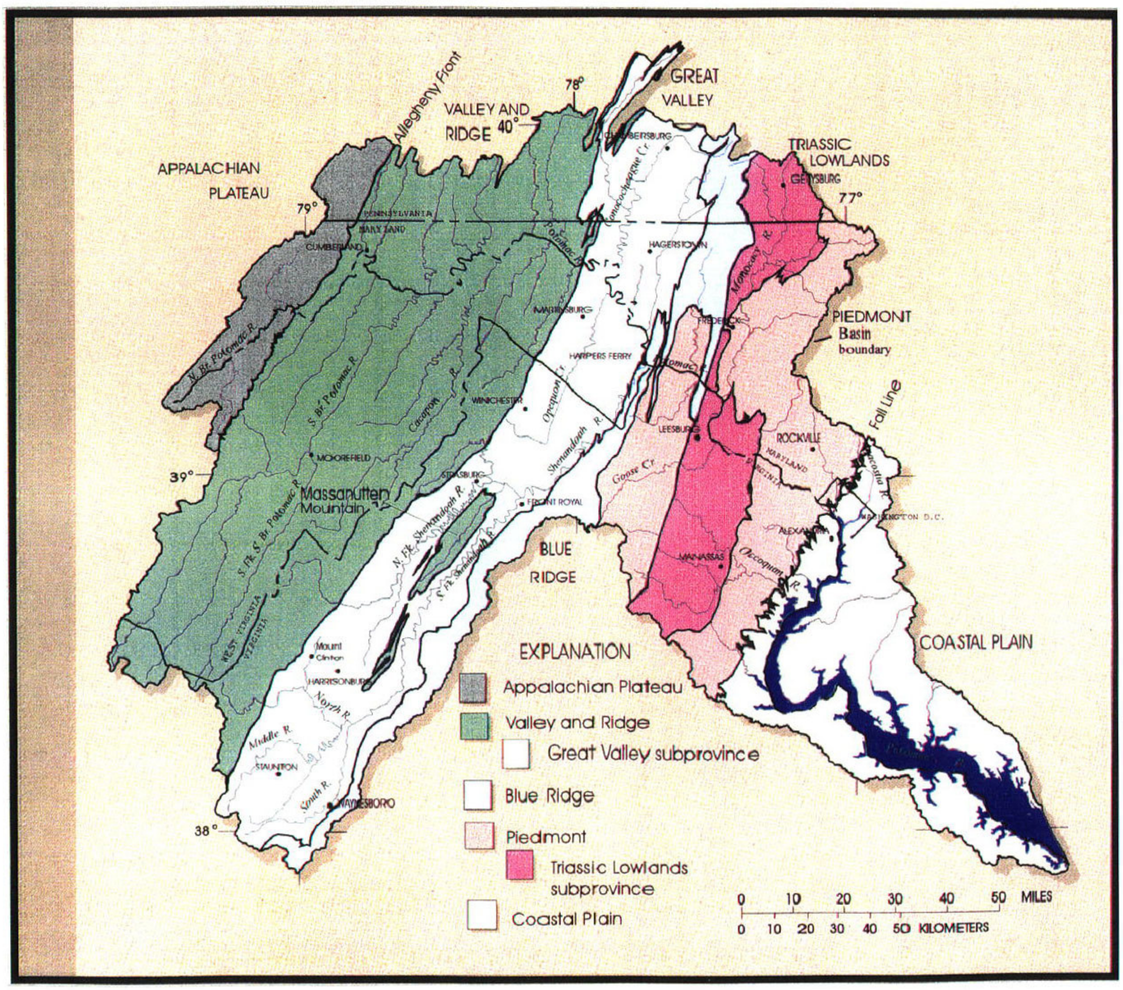
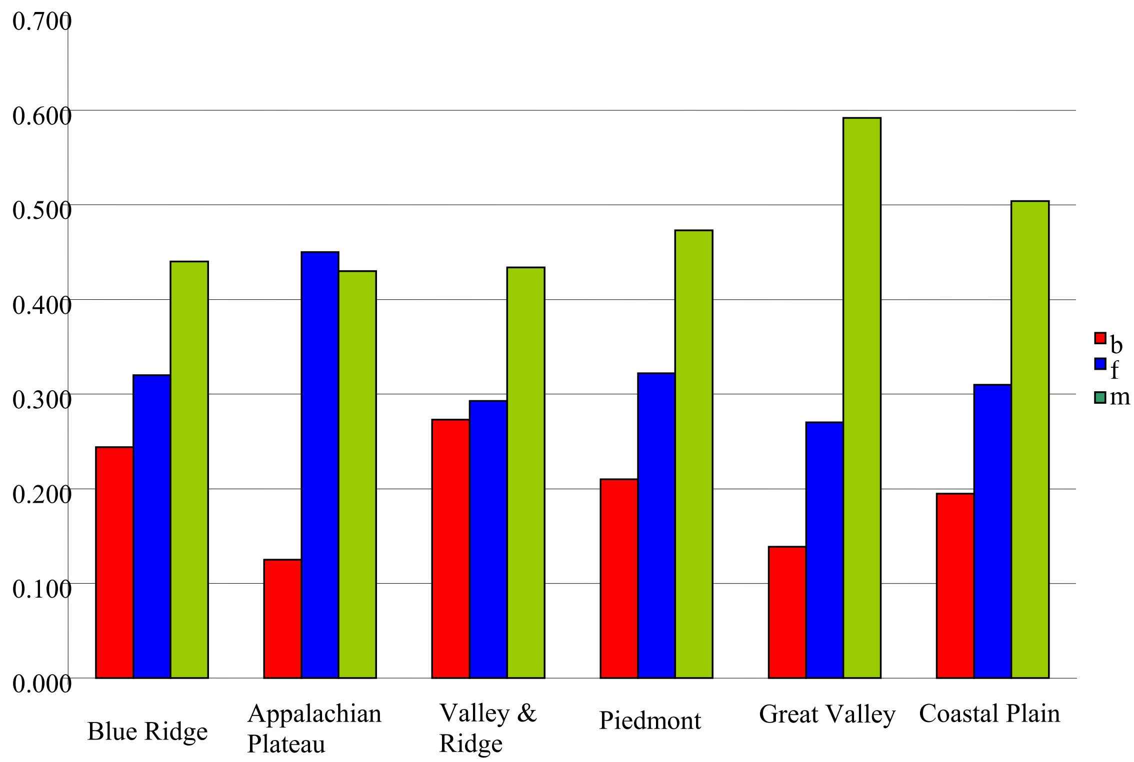


Figure 6.6 Physiographical Provinces of the Study Area
Source: US Geological Survey Water Resources Investigations Report 96-4034

---

[4] As mentioned earlier chapter, the physiography of each subbasin is identified by overlaying subbasin plots on the physiography plots. The study area physiography file in Arc/Info ™ file is acquired from the USGS Geographic Information Scientist and the delineation of each subbasin was delineated from a DEM using ESRI's Arc/Info ™, ERDAS's IMAGINE™, and a couple of commonly used Arc/Info ™ Macro Language routines.



	Blue Ridge	Appalachian Plateau	Valley & Ridge	Piedmont	Great Valley	Coastal Plain
N	15	2	2	12	7	5
Mean b	0.244	0.125	0.273	0.210	0.139	0.195
Mean f	0.320	0.450	0.293	0.322	0.270	0.310
Mean m	0.440	0.430	0.434	0.473	0.592	0.504

Figure 6.7 b, f, and m Average Values by Physiographic Province

6.3.1 Some Statistical Differences in Hydraulic Geometry Parameters Among Physiographic Provinces

The influence of four of the six physiographic provinces to b, f and m values is tested using a t-test for difference of mean values. Two provinces are excluded for the t-test for difference of mean values because these two provinces have a sample size of only two subbasins each.

Using a 0.05 and 0.01 tests, only the Great Valley province is statistically discernable. Comparing subbasins in the Great Valley and non-Great Valley, the mean difference of m are greater than the t-critical value at the 0.05 level (Table 6.2). The null hypothesis (there are no differences in influencing b value and m between Great Valley and non-Great Valley) is rejected for the 0.05 level. Actually, the mean difference of m value in this province is significant at the 0.01 level.

Table 6.2 Differences of Mean b, f, and m within Each Province

	Number of Subbasins	Mean b	Mean b Difference	Mean f	Mean f Difference	Mean m	Mean m Difference
Blue Ridge	15	0.2440		0.3146		0.4425	
Non-Blue Ridge	28	0.1878	0.0562	0.3139	0.0007	0.5020	-0.0595
t-test			1.3196		0.0219		-1.3729
Piedmont	12	0.2096		0.3222		0.4725	
Non-Piedmont	31	0.2066	0.0031	0.3111	0.0111	0.4846	-0.0121
t-test			0.0671		0.3210		-0.2572
Great Valley	7	0.1389		0.2699		0.5918	
Non-Great Valley	36	0.2207	-0.0818	0.3228	-0.0529	0.4598	0.1319
t-test			1.4971		-1.2768		**2.4744**
Coastal Plain	5	0.1950		0.3105		0.5040	
Non-Coastal Plain	38	0.2090	-0.0140	0.3147	-0.0042	0.4783	0.0257
t-test			-0.2163		-0.0860		0.3914

Note: Provinces with less than 5 subbasins (Appalachian Plateau and Valley and Ridge) are excluded for t-test for difference of mean values. The critical value for t with 41 degrees of freedom at 0.01, 2.704; 0.05 level, 2.021; and 0.1 level, 1.684. Statistically significant at the 0.05 level and less are indicated in **Bold**.

Just considering subbasin physiography, everything else being equal, the easiest erosion of bank and bed is expected in the Coastal Plain Province followed by the Great Valley, Piedmont, Valley and Ridge, Appalachian Plateau, and Blue Ridge Provinces (communication with USGS Geologist, Scott Southworth, Nov. 2001). With 1 representing the easiest to be eroded in channel width and depth or greater flow velocity change rate, Table 6.9 shows the comparative erodability of the different physiography provinces.

Table 6.3 Physiography-Based Mean b, f, and m Values and Bank and Bed Erodability

	N	Bank/Bed Erodability for b and f [1]	b	f	Expected Velocity Change[2]	m
Blue Ridge	15	6	0.244	0.320	1	0.440
Appalachian Plateau	2	5	0.125	0.450	2	0.430
Valley and Ridge	2	4	0.273	0.293	3	0.434
Piedmont	12	3	0.210	0.322	4	0.473
Great Valley	7	2	0.139	0.270	5	0.592
Coastal Plain	5	1	0.195	0.310	6	0.500
Mean			0.198	0.328		0.478
Standard Deviation			0.053	0.058		0.057

[1] Bank/bed erodability index is a ranking of all physiographic provinces with respect to each other (communication with USGS geologist, Scott Southworth, Nov.2001). The individual physiographic province is ranked from "easiest" to "hardest" order and they do not constitute magnitude.
[2] The ranking of expected velocity change ranking order is just the inverse of the b and f ranking order based on the equation of continuity.

The expectation is that subbasins in the Coastal Plain Province would have the highest b and f values, and subbasins in the Blue Ridge the lowest b and f values. At the same time, expectation of m would be a reversed order of b and f. The rationale is that if b and f values become bigger because of rapid widening and deepening of the channel, the eroded bank and bed material would result in higher flow resistance. Therefore, flow velocity would be hampered and m becomes smaller in value. As shown in Table 6.3, the mean values of b and f do not correlate closely with the bank and bed erodability indicator which suggests that other physical and environmental controlling factors play more significant roles. The observed orders of the m values are the closest to the expected ranking (R^2 = 0.7714) compared to the orders of the observed b (R^2 = 0.2571) or f (R^2 = 0.4857) values.

The m values somewhat follow the trend of the bank and bed erodabilities, that is, the Coastal Plain and Great Valley subbasins have higher m values reflecting faster stream flow changes with increasing stream discharge. The high m values in high bank and bed erodability provinces indicate that the potential erodability of bank and bed (width and depth) might not have been realized; or that the rate of change in flow velocity was much greater than that of channel width or depth erosion.

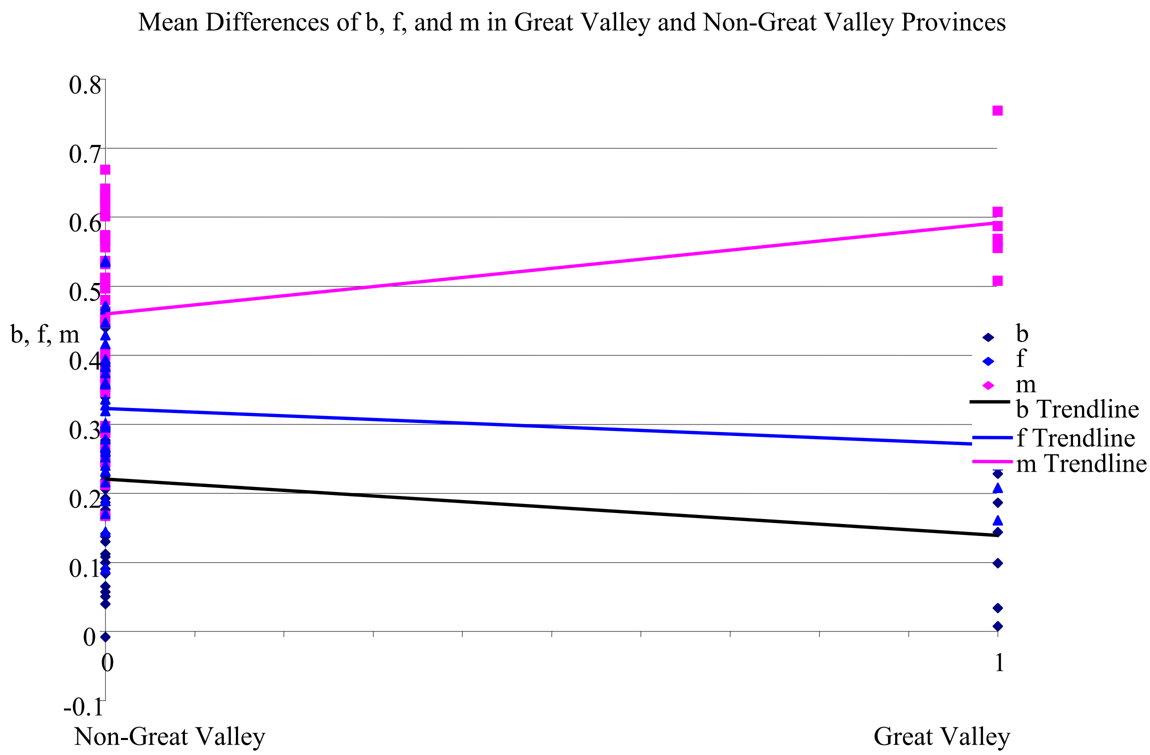
6.3.2 Particular Provinces

The **Appalachian Plateau Province**, characterized by narrow valleys and steep, rugged ridges, is designated as resistant to erosion, and the low mean b value reflects that fact. Two study area subbasins are in this province. Since one subbasin is nested within the other, their b, f, and m values, especially b, are, not unexpectedly, very close. However, the very different f values are explainable by the differences in the slopes of the two subbasins (0.557 vs 0.235).

In the **Valley and Ridge Province**, also with only two subbasins, the physiography results from intensely folded and faulted rocks. The b value (0.273) of this province is much higher than the average for all of the study subbasins. The subbasin (v25) with a higher f value has the steeper slope. For this subbasin, while the f value is much higher, the m value is only half of the overall subbasin average. Even though these two subbasins are in the same province, they display quite different b, f, and m values, especially for m. This suggests that other factor(s) influence b, f, and m values more than the physiography. Also, considering just physiography, the erodability of channels in this province is low (4th out of 6), but the observed b and f values do not reflect the expected erodability, which amplifies the insignificant role of physiography to b, f, and m.

For the **Great Valley Province** (seven study subbasins), which is largely underlain by carbonate bedrock with numerous sinkholes and caverns, the b, f, and m values (Figure 6.8 and Table 6.4) are highly similar to each other (similar standard deviation -Table 6.3). Even the observed b values in this province are the second lowest in contrast with the probable erodability shown in Table 6.3. The differences in mean values of b and m between the Great Valley and all other provinces are discernable. Therefore, subbasins within the Great Valley Province can be expected to have similar b, f, and m values, indicating that physiography is definitely a predictor to b, f, and m.

The f values in this province are the lowest among the six and the slope of the subbasins in this province is least. Therefore, like subbasins in the Appalachian Plateau and Valley and Ridge provinces, it can be said that there is a relationship between slope and f values. As expected, since the mean b value is the lowest, the mean m value within this province is the highest of all the provinces.



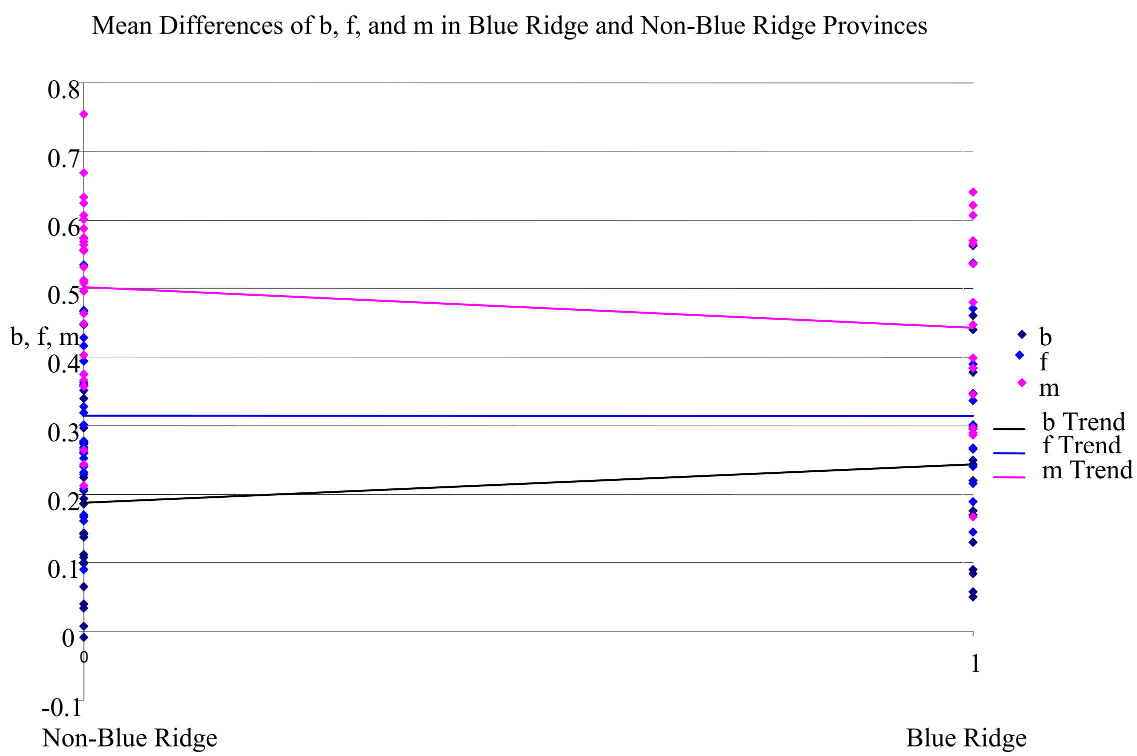


Figure 6.8 Mean Differences of b, f, and m in Great Valley and Non-Great Valley and Blue Ridge and Non-Blue Ridge Provinces

The **Blue Ridge Province**, characterized by steep relief and narrow channels, is represented by fifteen study subbasins. The expected erodability of the Blue Ridge Province is the lowest of all the provinces. However, the mean b and f values for subbasins in this province are higher than the physiography-based mean, and the m values are subsequently lower than the overall average. The differences of b and m (Table 6.2) between the Blue Ridge and the other provinces are high but statistically insignificant at 0.05 level and higher (Figure 6.8) indicating that Blue Ridge is an indiscernible predictor for b, f, and m.

Twelve study subbasins are in the **Piedmont Province**, which is an area of gently rolling hills with low to moderate relief. The average b, f, and m values are similar to the physiography-based mean for the total 43 subbasins. The mean difference tests (Table 6.2) indicate that the differences between Piedmont and non-Piedmont subbasins in b, f, and m are the least indicating that Piedmont is not a discernible predictor for b, f, and m.

Five study subbasins are in the **Coastal Plain Province**, which is underlain by unconsolidated sediments that form a gentle, seaward-sloping plain of low relief. The b and f are similar to the mean values of the study area. While the erodability index suggests that the expected b and f values have potential to be changed most easily in the Coastal Plain, the observed b and f values are not much different from the mean of the total subbasins. Also, the mean difference tests of b, f, and m between Coastal vs. non-Coastal provinces conclude that there is no statistically significant differences between provinces. This suggests that there are other stronger predictor variable(s) than physiography that influence b and f values. The m value is slightly higher in this gentle sloping region which is consistent with findings by other researchers such as Bathurst (1985, 1993).

6.3.3 Physiography in a Scale Context

To estimate the influence of the physiography on b, f, and m in a scale context, the three exponents are modeled as b (f , m) = $a_{0.b}$ ($a_{0.f}$, $a_{0.m}$) + $a_{1.b}$ ($a_{1.f}$, $a_{1.m}$) * $\log_{10}$(size) + $a_{2.b}$ ($a_{2.f}$, $a_{2.m}$) * physiography variable. The interaction between scale and physiography is investigated by adding an interaction term to the model for b (f , m) = $a_{0.b}$ ($a_{0.f}$, $a_{0.m}$) + $a_{1.b}$ ($a_{1.f}$, $a_{1.m}$) * $\log_{10}$(size) + $a_{2.b}$ ($a_{2.f}$, $a_{2.m}$) * physiography variable + $a_{3.b}$ ($a_{3.f}$, $a_{3.m}$) * $\log_{10}$(size) * physiography variable. The null hypotheses ($a_{2.b} = 0$, $a_{2.f} = 0$, $a_{2.m} = 0$, and $a_{3.f} = 0$, $a_{3.m} = 0$) are that there are no discernible influence of physiography nor interaction between subbasin size and physiographic characteristics for the b, f, and m values.

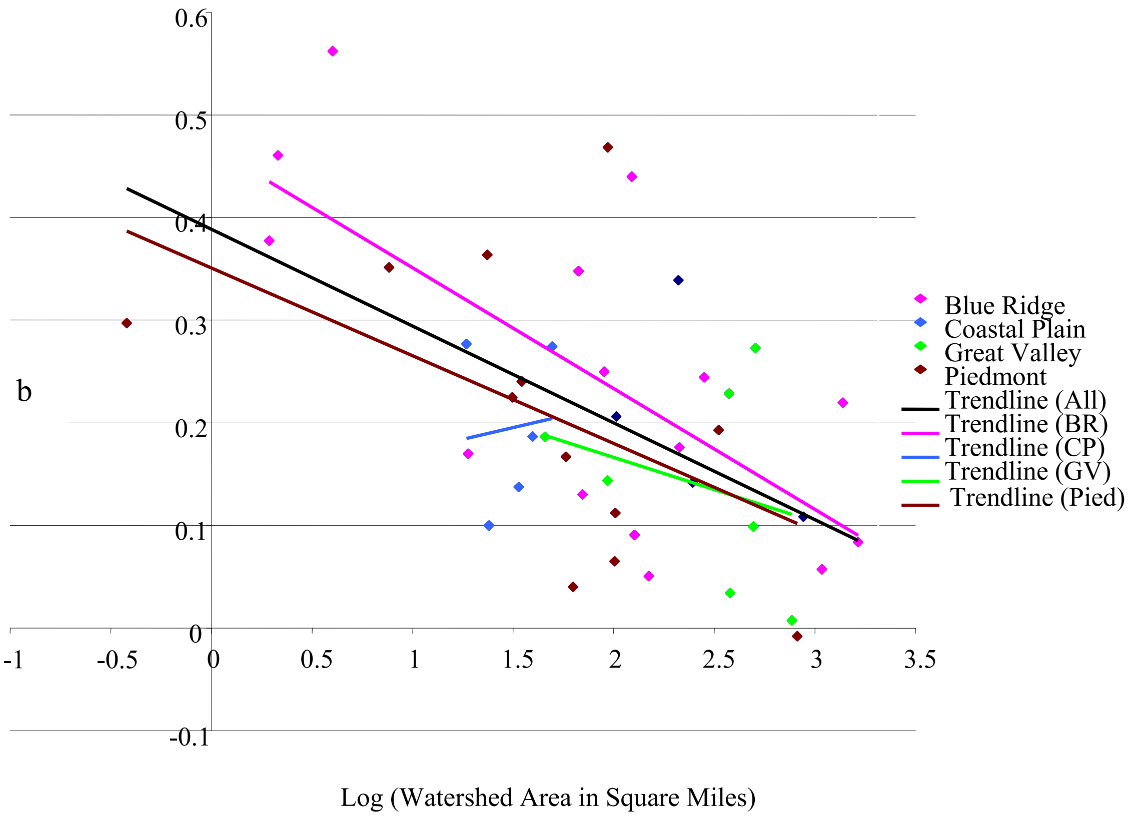
b Exponents

Since the computed value of F for $a_{1.b}$, 16.878 (Table 6.4), exceeds the critical value, I reject the null hypothesis for a_1, and conclude that scale influences the b value at the 0.05 level. However, there is insufficient evidence (F for a_2 is 0.908) to reject the null hypothesis for $a_{2.b}$; it can be concluded that a discernible difference does not exist in the expected response of the contribution of physiography to the b value. Figure 6.8 supports the conclusion that physiography (as measured) does not explain the observed b values in the scale context. The expected visual pattern for the hypothesis is that the b values of each physiographic province would be shown by a set of four parallel lines (two provinces with only two subbasins are excluded) sloping downwards. However, because the correlations for each province separately are weak, there is no clear evidence of parallelism.

By adding the interaction term, R^2 increased from 0.39 to 0.42 but the statistical significances of scale and physiography both decreased such that it is concluded that adding an interaction term does not help to account for b values as shown in Table 6.4. Therefore, it can be said that physiography, as a whole, is not a strong predictor variable influencing the b values.

Table 6.4 b vs. Log Size, Physiography, and Interaction

Dep Var: b	N:43	R^2: 0.3110	
	df	F-ratio	P
Log Size	1	18.512	0.0000
Dep Var: b	N:43	R^2: 0.38770	
	df	F-ratio	P
Log Size	1	16.877	0.0002
Physiography	5	0.9080	0.4867
Dep Var: b	N:43	R^2: 0.41897	
	df	F-ratio	P
Log Size	1	0.0428	0.8357
Physiography	5	0.5168	0.7615
Physiography * Log Size	31	0.3337	0.8887



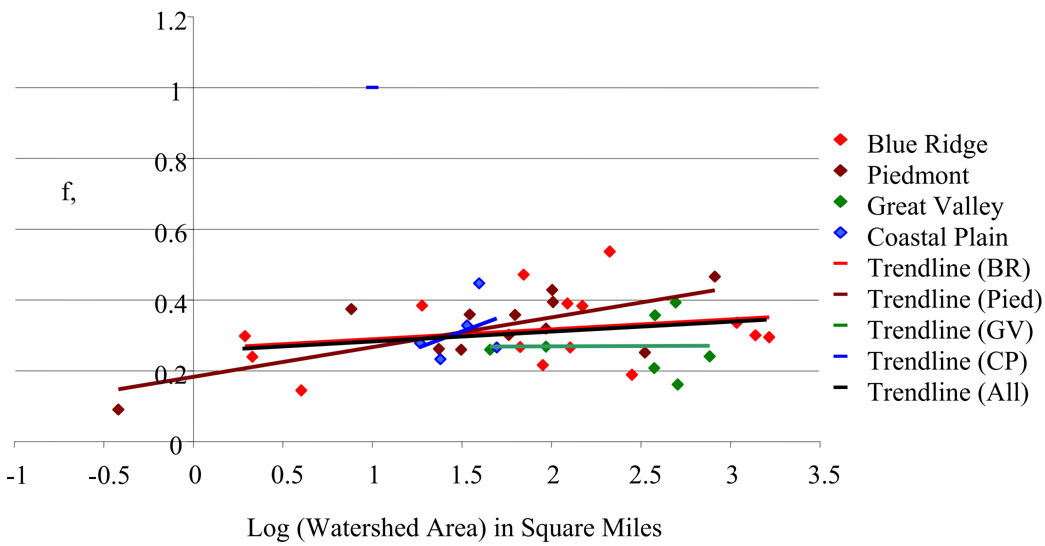
	Blue Ridge	Piedmont	Great Valley	Coastal Plain	Overall
Intercept	0.4688	0.3511	0.2915	0.1274	0.3889
Coefficient	-0.1177	-0.0855	-0.0626	0.0453	-0.0944
R^2	0.4743	0.2476	0.0810	0.0094	0.3111

Figure 6.9 b and Subbasin Log Size in Physiography
Note: Two provinces (Great Valley and Appalachian Plateau Provinces) with only two subbasins each are not graphed.

f Exponents

It is expected that if there is a strong relationship between f and each physiographic province, then the slope of each province will run parallel with the overall f value slope between f and scale. But results, Figure 6.10 and Table 6.5, clearly show that physiography in the scale context does not explain f values at the 0.05 and less level.

Unlike the case of b, the influence of physiography on f is indiscernible in the Great Valley Province (Table 6.2). As discussed in section 6.2, scale influences the f value (0.017 level of statistical significance), but when physiography and interaction terms are included, the physiography's influence on f is of low significance (0.27 level) and the slope of the regression line is 0.04 (Figure 6.10). Adding an interaction term, the R^2 improved from 0.25 to 0.38 but it does not help to explain the role of physiography to the f value.



	Blue Ridge	Coastal Plain	Great Valley	Piedmont	Overall
Intercept	0.2616	0.0278	0.26660	0.18330	0.0233
Coeffici	0.0278	0.1892	0.00137	-0.0840	0.0420
R^2	0.0614	0.1478	0.00006	0.49867	0.0793

Figure 6.10 f and Subbasin in Log Size in Physiography

Table 6.5 f vs. Log Size, Physiography, and Interaction

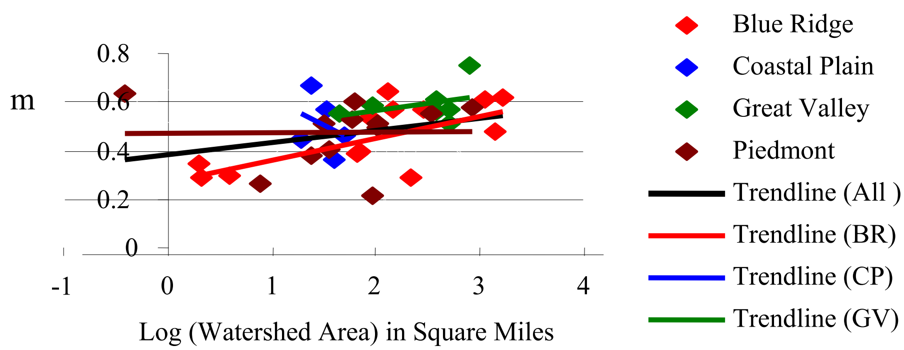
Dep Var: f	N:43		R^2: 0.1090
	df	F-ratio	P
Log Size	1	5.0210	0.0310
Dep Var: f	N:43		R^2: 0.2504
	df	F-ratio	P
Log Size	1	6.2983	0.01672
Physiography	5	1.3570	0.26335
Dep Var: f	N:43		R^2: 0.3843
	df	F-ratio	P
Log Size	1	6.3154	0.0174
Physiography	5	1.0747	0.3934
Physiography * Logs Size	31	1.3479	0.2707

Subbasins v12 (0.471) and v18 (0.537) in the Blue Ridge physiography region have the highest f values among the study area subbasins. These high f value subbasins also have high minimum elevations (365 and 338 meters, respectively) indicating headwater subbasins. These subbasins are another example of the relationship of high f with higher hierarchy of channels. Consequently, the m values of these subbasins are lower than those of the other subbasins. This can be explained by the headwater nature of most of the streams in this province. Mean velocity increases downstream against the intuition that small tributaries flowing on steep slopes must be traveling faster than the low-gradient trunk rivers. These headwater subbasins consequently will have lower m values.

m Exponents

Based on the data (Table 6.6), it can be concluded that scale influence on m is significant at the 0.0908 level; and physiography influences the m value at a significance level of 0.310 which is beyond the statistical significance level for this analysis. Based on the m value analyses data shown in Table 6.6, it is concluded that scale influences m value at the 0.0477 level of significance. However, the influence of physiography is, not as strong as scale's influence, significant at the 0.122 level. Adding an interaction term does help the R^2 (from 0.220 to 0.394) and the statistical significance improved from 0.3100 to 0.1224, as well as, that the m value and physiography improved to 0.0477 from 0.0908 level of significance.

Therefore, it can be said that physiography, as a whole, is an insignificant predictor variable influencing m values with R^2 about 0.400 with statistical significance of 0.05 level. Visual inspection of Figure 6.11 and Table 6.6 indicate that physiography in the scale context does explain m values by showing faint parallel lines by physiography along with the trend line of scale and m relationship. However, the statistical significance is not at the 0.05 level.



	Blue Ridge	Coastal Plain	Great Valley	Piedmont	Overall
Intercept	0.2747	0.8405	0.4417	0.4684	0.3842
Coeffici	0.0879	-0.2254	0.0616	0.0025	0.0504
R^2	0.3191	0.1064	0.1253	0.0002	0.1384

Figure 6.11 m and Subbasin in Log Size in Physiography

Table 6.6 m vs Log Size, Physiography, and Interaction

Dep Var: m	N:43		R^2: 0.0860
	df	F-ratio	P
Log Size	1	3.843	0.0570
Dep Var: m	N:43		R^2: 0.22025
	df	F-ratio	P
Log Size	1	3.01926	0.09083
Physiography	5	1.24251	0.30983
Dep Var: m	N:43		R^2: 0.3939
	df	F-ratio	P
Log Size	1	4.2523	0.0477
Physiography	5	1.9028	0.1224
Physiography * Logs Size	31	1.7766	0.1469

6.3.4 Summary

The conflation of graphical and statistical tools suggest that the b, f, and m values within each distinctive physiographic province are more similar than for the overall means of the 43 subbasins. Comparing the influence of physiography on the three exponents, m is the most apparent (statistical significance level of 0.122 vs 0.393 or 0.762 for f or b) as shown in Table 6.6. This can be also seen in Figure 6.11, from the linear trend line. The mean difference test indicates that the Great Valley physiography influences m at the 0.05 level. However, as Figure 6.9 and statistical analyses (Table 6.4) show, physiography, as a whole, does not strongly influence b, f, and m.

6.4 The Role of Lithology

Physical and geologic characteristics are the primary natural factors affecting the hydrologic properties of ground water and surface water systems and, thus, are the primary factors affecting hydraulic geometry within major river basins. The geology of the Potomac River Basin is complex and diverse, ranging from relatively undisturbed, unconsolidated sediments to intensely deformed crystalline rocks (Milici, 1963; Cleaves, 1968). In recognition of this geologic diversity, the Potomac River Basin lithology has been divided into five major subunits for the purpose of this hydraulic geometry assessment (Figure 6.12).

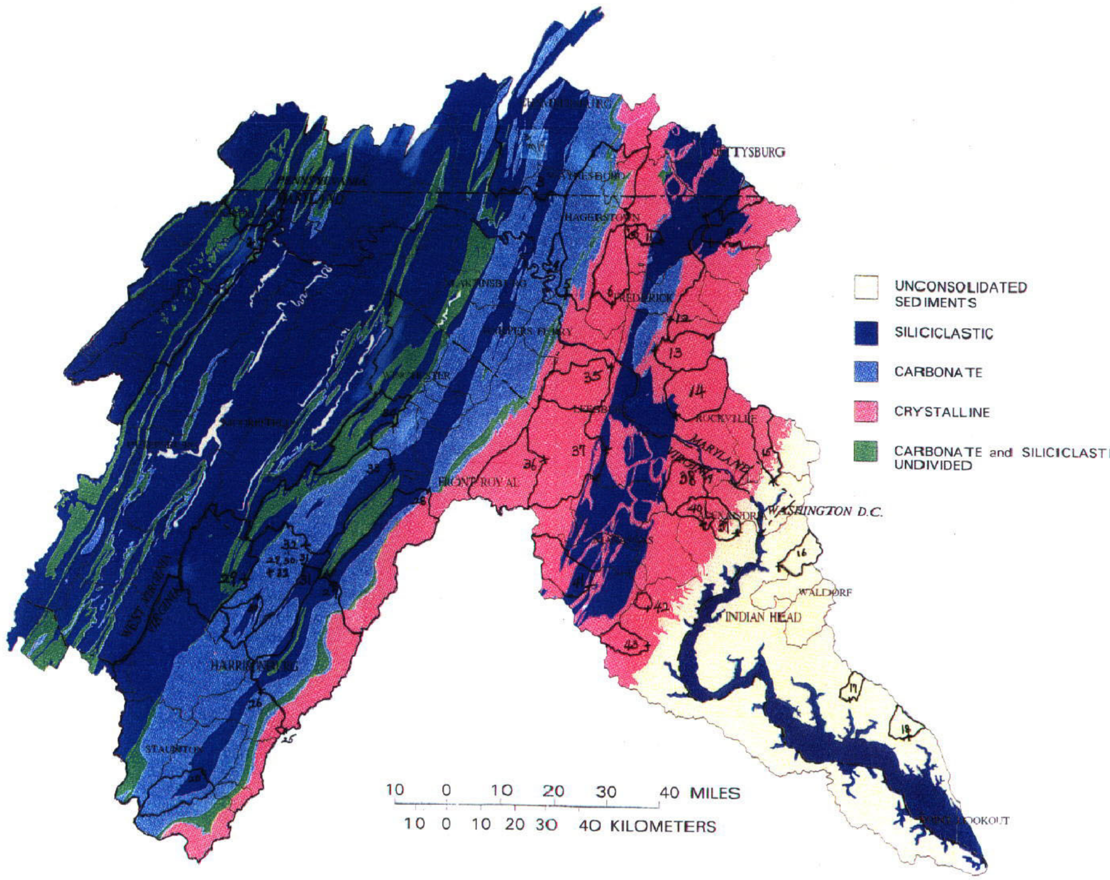
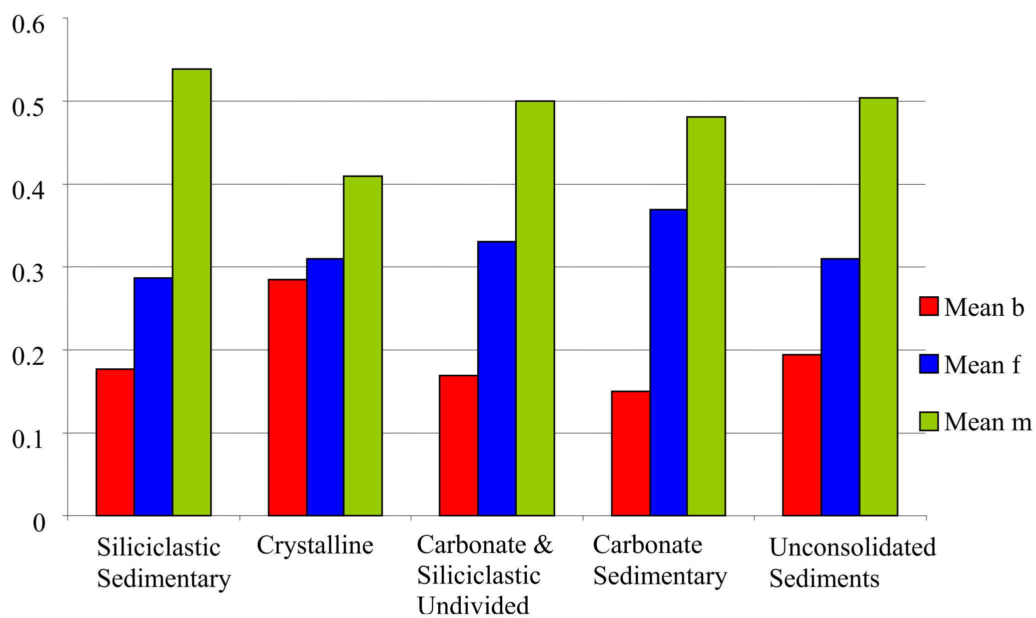


Figure 6.12 Study Area Lithology
Source: US Geological Survey Water Resources Investigations Report 96-4034

The five major rock types present in the study region are: siliciclastic sedimentary (shale and sandstone) – 13 subbasins, crystalline metamorphic and igneous (gneiss, schist, and diabase dikes) – 13 subbasins, undivided carbonate and siliciclastic – 7 subbasins, carbonate sedimentary (limestone and dolomite) – 5 subbasins, and unconsolidated sediments (sand, silt, and clay) – 5 subbasins[5]. The comparative average

[5] As mentioned in an earlier chapter, the lithology of each subbasin is identified by overlaying subbasin plots on the lithology plots. The study area lithology file in Arc/Info ™ file format was acquired from the USGS Geographic Information Scientist and the delineation of each subbasin was delineated from DEM data using ESRI's Arc/Info ™, ERDAS's IMAGINE™, and a couple of commonly used Arc/Info ™Macro Language routines.

values of the b, f, and m for the various lithologies are graphed in Figure 6.13.



N	13	13	7	5	5
Mean b	0.177	0.285	0.169	0.150	0.195
Mean f	0.287	0.310	0.330	0.370	0.310
Mean m	0.538	0.410	0.500	0.480	0.504

Figure 6.13 Average b, f, and m Values in Five Lithology Regions

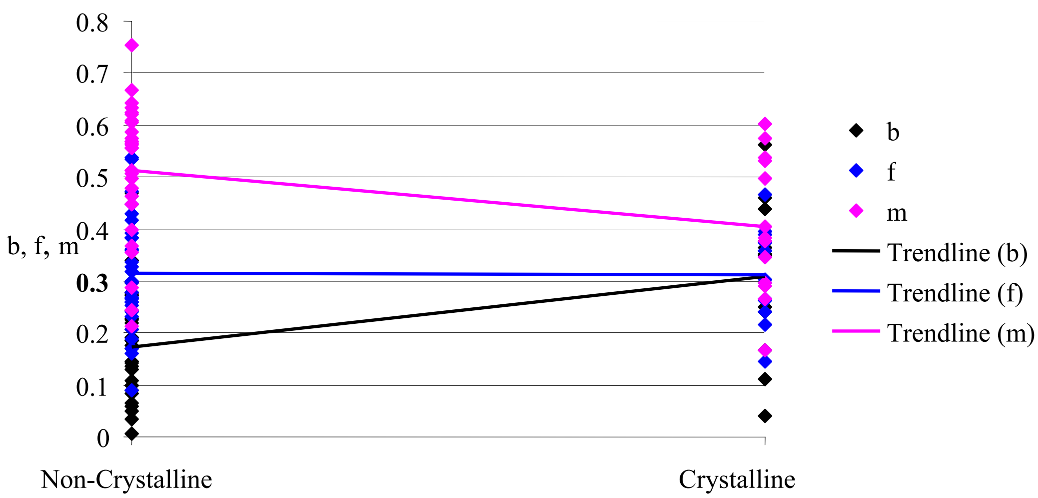
6.4.1 Each Lithology Region's Influence

The influence of lithology on b, f and m values is examined using a t-test for difference of mean values. Using a 0.1 % test, only the Crystalline and Siliciclastic regions are statistically discernable for b and m, and m, respectively[6]. Comparing subbasins in the Crystalline and non- Crystalline regions, the mean differences of b and

[6] The critical value for t with 41 degrees of freedom at the 0.01 level is 2.704; 0.05 is 2.021, at 0.1 level 1.684.

m are greater than the t-critical value at the 0.05 level (Table 6.7). Therefore, the null hypothesis (there is no difference in influencing b and m values between Crystalline and non-Crystalline) is rejected for the 0.05 level and it can be concluded that there is a discernable difference in b and m values between the Crystalline and the other lithology regions.

The mean difference of the m value in the Siliciclastic region is significant at the 0.1 level but not at 0.05 level. As the t-tests and Figure 6.14 indicate, the mean difference between Crystalline and non-Crystalline regions for f, and that of the Siliciclastic and non-Siliciclastic regions for f and m are indiscernible at the 0.05 level.



Mean Differences of b, f, and m in The Siliciclastic and Non-Siliciclastic Regions

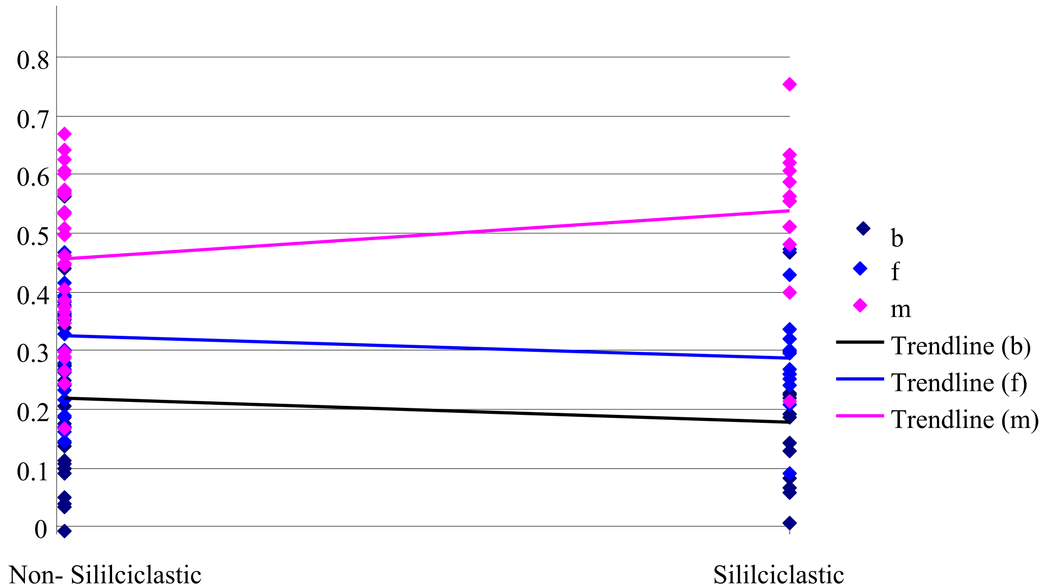


Figure 6.14 Mean Differences of b, f, and m in the Crystalline and Non-Crystalline and Siliciclastic and Non-Siliciclastic Regions

Table 6.7 Differences of Mean b, f, and m within Each Lithology Region

	Number of Subbasins	Mean b	Mean b Difference	Mean f	Mean f Difference	Mean m	Mean m Difference
Crystalline	13	0.2849		0.3132		0.4051	
Non- Crystalline	30	0.1738	0.1111	0.3146	-0.0014	0.5143	-0.1092
t-test			**2.6688**		-0.0421		**-2.5556**
Carbonate	5	0.1504		0.3666		0.4834	
Non- Carbonate	38	0.2149	-0.0645	0.3073	0.0593	0.4810	0.0024
t-test			-1.0105		1.2411		0.0369
Unconsolidated	5	0.1950		0.3105		0.5040	
Non- Unconsolidated	38	0.2090	-0.014	0.3147	-0.0042	0.4783	0.0257
t-test			-0.2163		-0.0860		0.3914
Siliciclastic	13	0.1774		0.2871		0.5377	
Non-Siliciclastic	30	0.2204	-0.0430	0.3259	-0.0388	0.4568	0.0809
t-test			-0.9640		-1.1607		1.8306
Carbonate & Siliciclastic Undivided	5	0.1686		0.3315		0.5000	000
Non-Carbonate & Siliciclastic Undivided	38	0.2149	-0.0463	0.3108	0.0207	0.4776	0.0224
t-test			-0.8313		0.4914		0.3927

Note: The critical value for t with 41 degrees of freedom at the 0.01 level is 2.704; 0.05 is 2.021, at 0.1 level 1.684.Statistically significant at the 0.05 level and less are indicated in **Bold**.

Considering subbasin lithology only, everything else being equal, the easiest erosion of bank and bed is expected in Unconsolidated Sediments followed by Carbonate, Carbonate and Siliciclastic Undivided, Crystalline, and Siliciclastic (communication with USGS Geologist, Scott Southworth, Nov. 2001). Table 6.8 illustrates the comparative erodability among the different lithologies, one being the lithology that is easiest to be eroded, and five being the most resistant. As stated in the Physiography section, the expected m order would be the inverse of order of b and f.

Table 6.8 Lithology-Based Mean b, f, and m Values and Bank and Bed Erodability

	N	Bank/Bed Erodability for b and f	b	f	Expected Velocity Change	m
Siliciclastic	13	5	0.177	0.287	1	0.538
Crystalline	13	4	0.285	0.310	2	0.410
Carbonated & Siliciclastic Undivided	5	3	0.169	0.330	3	0.500
Carbonate	5	2	0.150	0.370	4	0.480
Unconsolidated Sediments	5	1	0.195	0.310	5	0.504
Mean			0.195	0.321		0.486
Standard Deviation			0.047	0.028		0.043

Source: Erodability order by communication with USGS geologist, Scott Southworth, Nov. 2001. b, f, and m values are calculated by the author

The average values of b, f, and m for each lithology type in erodability order do not closely follow the expected bank and bed erodability orders, indicating that other physical and other environmental controlling factors impact b, f, and m more significantly. However, the lowest standard deviations for b, f, and m indicate that, within the Unconsolidated Sediments region, the b, f, and m values are more uniform than they are for many of the other lithology regions.

The thirteen subbasins that fall in **Siliciclastic** region have b values that range widely from 0.008 to 0.469. The average values for b and f are 0.177 and 0.287, which are lower than the average for the entire study area (Table 6.8). The high value of the standard deviation, 0.120, indicates that Siliciclastic lithologies might not be a dominant predictor variable for b. Within the Siliciclastic region, the f values of the 13 subbasins are very similar which indicates that Siliciclastic lithology might play a role in the rate of depth change. Difference of means analysis indicates that t-test of siliciclastic region versus non-siliciclastic region is noticeable (t value of -1.1607) but the difference is statistically insignificant at 0.05 level. That the Siliciclastic area is the least erodable of channel banks and beds is reflected by its having the lowest f values among all the other lithology regions.

The average b value for the thirteen subbasins fall within the **Crystalline** lithology region is 0.285, the highest among all the lithology regions. Seven subbasins out of thirteen, m31 (0.461), m311 (0.562), v19 (0.377), v38 (0.440), v49 (0.364), and v65 (0.352) have significantly high b values which do not follow the erodability order. The b values have a wide range of the set of thirteen subbasins, subbasin m311 has the highest b value in the study area, yet subbasin m34 has the lowest b value, -0.008. The values for b do not support the notion of erodability in this type of lithology, but the average f value (0.310) is small and supports the erodability order.

For the seven subbasins in the **Carbonate and Siliciclastic Undivided** region, average b and f values are 0.169, which is the 2nd lowest followed by the Carbonate region, and 0.332, respectively. The standard deviations of b, f, and m are moderately high. Thus, lithology is not a predominant predictor variable for b, f, and m.

Five study subbasins fall in the **Carbonate** region. Just considering lithology, high rates of change of channel width and depth are expected in this second most easily erodable region. However, the very low (0.150) observed b values do not support the erodability order. As in the Carbonate and Siliciclastic Undivided region, the observation is made that in carbonate region b is small, but f compensates for the small b values.

Considering subbasin lithology only, everything else being equal, the easiest erosion of bank and bed would occur in the **Unconsolidated Sediments** region. For the five subbasins in this region, both the average b and f values, 0.195 and 0.310, respectively, are below the total study area average and the standard deviation of f mean value is the lowest among the other subbasin lithology regions. Therefore, it can be said that the influence of Unconsolidated Sediments on f is obvious. This means that the values of b and f will change (increase) easily in the Unconsolidated Sediments and Carbonates lithology and b and f will change very little in the Siliciclastic region.

6.4.2 Lithology in a Scale Context

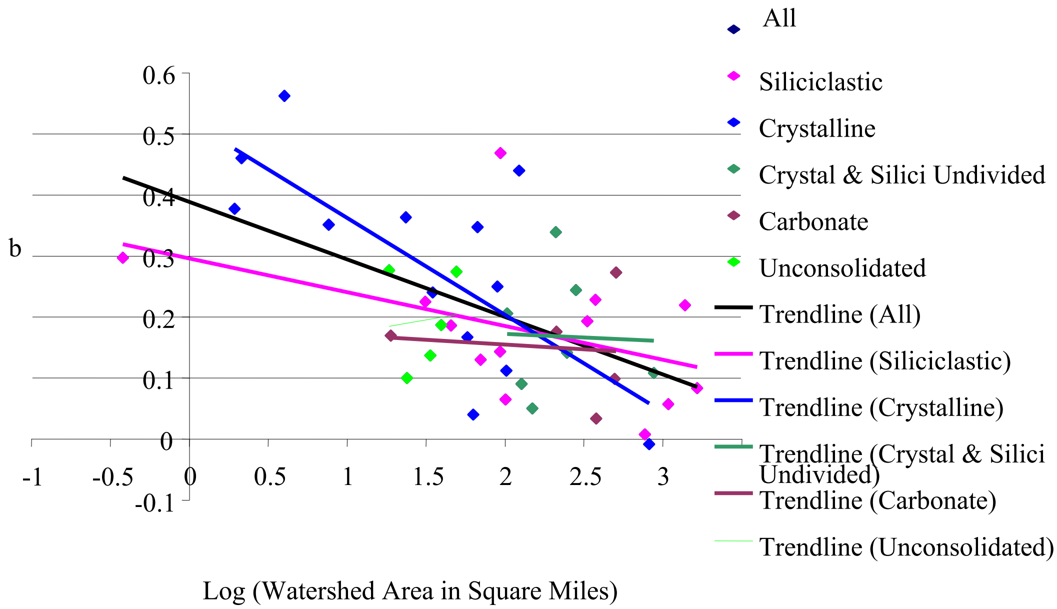
The model for analyzing lithology predictor variables in a scale context is b (f, m) = $a_{0.b}$ ($a_{0.f}$, $a_{0.m}$) + $a_{1.b}$ ($a_{1.f}$, $a_{1.m}$) * $\log_{10}$(size) + $a_{2.b}$ ($a_{2.f}$, $a_{2.m}$)* lithology variable. With the interaction term, the model is b (f, m) = $a_{0.b}$ ($a_{0.f}$, $a_{0.m}$) + $a_{1.b}$ ($a_{1.f}$, $a_{1.m}$) * $\log_{10}$ (size) + $a_{2.b}$ ($a_{2.f}$, $a_{2.m}$)* lithology + $a_{3.b}$ ($a_{3.f}$, $a_{3.m}$)* $\log_{10}$ (size) * lithology. The null hypothesis is that the scale of the subbasins and lithology have no bearing on the b, f, and m values.

b Exponents (Figure 6.15 and Table 6.9)

As expected, the computed F value for a_1, 11.627, exceeds the critical value, which reaffirms the notion that scale influences b values. However, the computed value of F for $a_{2.b}$ (lithology), 0.698, does not exceed the critical value; therefore the $a_{2.b}$ value is not significantly different from 0. Hence, it is concluded that the expected response of the contribution of lithology to b value is almost 0, that is, there is no systematic influence of lithology on b. By adding an interaction term to the model for b, R^2 increased from 0.359 to 0.437, and the statistical significance of lithology to b improved from 0.598 to 0.217. However, overall lithology in the scale context does not statistically account for b values.

Table 6.9 b and Subbasin Log Size and Lithology

Dep Var: b	N:43	R^2: 0.3105	
	df	F-ratio	P
Log Size	1	18.512	0.000
Dep Var: b	N:43	R^2: 0.3589	
	df	F-ratio	P
Log Size	1	11.627	0.0016
Lithology	4	0.6984	0.5979
Dep Var: b	N:43	R^2: 0.4370	
	df	F-ratio	P
Log Size	1	0.2603	0.6133
Lithology	4	1.5291	0.2165
Lithology * Log Size	4	1.1438	0.3532



	Siliciclastic	Crystalline	Cryst & Silic Und.	Carbonate	Uncons	Overall
Intercept	0.2962	0.5215	0.1961	0.1864	0.1274	0.3889
Slope	-0.0554	-0.1588	-0.0117	-0.0156	0.0453	-0.0944
R^2	0.1974	0.5158	0.0013	0.0109	0.0094	0.3110

Figure 6.15 b and Log Size in all Lithology Types

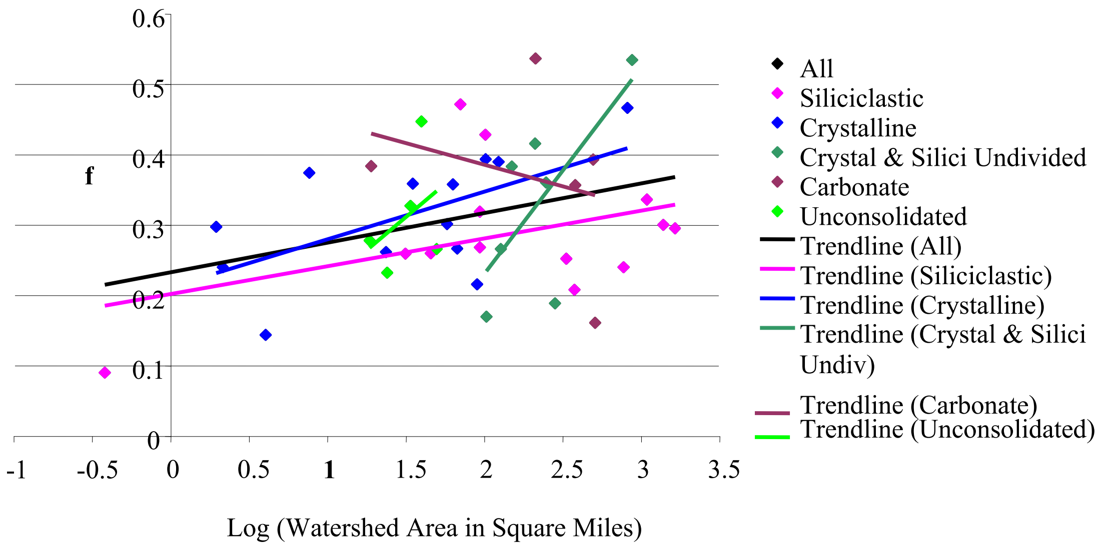
f Exponent (Figure 6.16 and Table 6.10)

Because the computed value of F for $a_{1.f}$, 5.384, exceeds the critical value, 4.08, I reject the null hypothesis for a_1, and conclude that scale influences f value. However, the computed value of F for $a_{2.f}$, 0.7847, does not exceed the critical value, 2.60, which indicates that there is insufficient evidence to reject the null hypothesis for $a_{2.f}$. Hence, it is concluded that a real difference between a_2 and 0 does not exist and the expected response of the contribution of lithology to f value is indiscernible.

Adding the interaction term to the model for f explains more of the variation (R_2 improved from 0.179 to 0.312). However, the model still does not make the lithology statistically significant for f even at the 0.05 level. As Figure 6.16 indicates, lithology as a whole does not explain the f variance well. The overall R^2 is 0.109. The coefficient of f and of lithology regions are a mixture of negative and positive directions.

Table 6.10 f and Subbasin Log Size and Lithology

Dep Var: f	N:43	R^2: 0.109	
	df	F-ratio	P
Log Size	1	5.021	0.0310
Dep Var: f	N:43	R^2: 0.17878	
	df	F-ratio	P
Log Size	1	5.3841	0.0259
Lithology	4	0.7847	0.5425
Dep Var: f	N:43	R^2: 0.31214	
	df	F-ratio	P
Log Size	1	2.7611	0.1061
Lithology	4	1.5995	0.1977
Lithology * Logs Size	4	1.5995	0.1977



	Siliciclastic	Crystalline	Cryst & Silic Und.	Carbonate	Uncons	Overall
Intercept	0.2025	0.2124	-0.3550	0.5085	0.0279	0.2333
Slope	0.0395	0.0677	0.2931	-0.0613	0.1892	0.0420
R^2	0.1617	0.3525	0.4759	0.0751	0.1478	0.1091

Figure 6.16 f and Subbasin Log Size in All Lithology

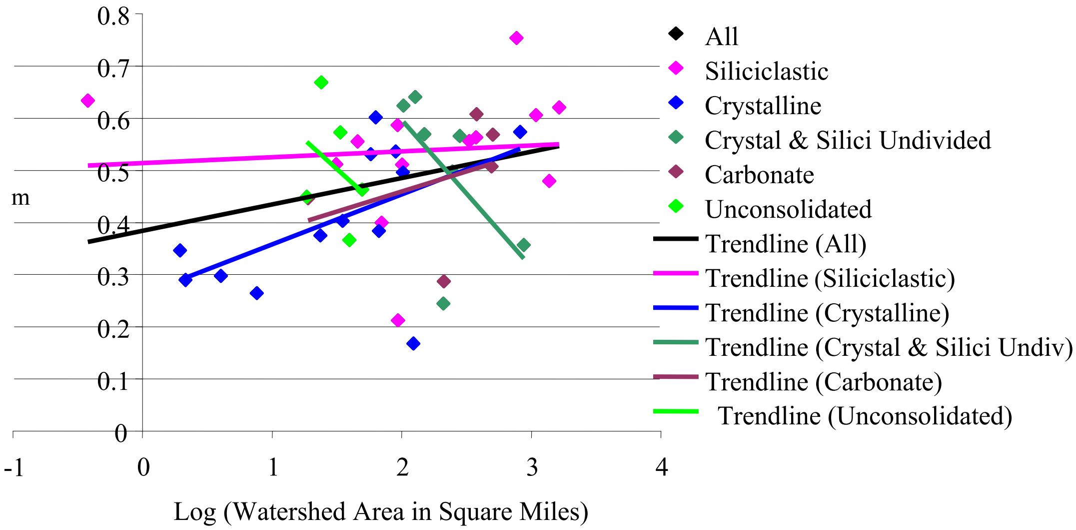
m Exponent (Figure 6.17 and Table 6.11)

Scale does not influence the m value at the 0.05 level of statistical significance, and the computed values of F for $a_{1.m}$ (scale) and $a_{2.m}$ (lithology) do not exceed the critical values at the 0.05 level, and there is insufficient evidence to reject the null hypothesis. Hence, it is concluded that neither scale nor lithology influences m value at the 0.05 level. However, when the interaction term is added to the multiple regression model for m, the influence of lithology on m becomes statistically significant at the 0.086 level. And, the variation is explained better, that is, R^2 improves from 0.188 to 0.316 (Table 6.11).

Table 6.11 m and Subbasin Log Size and Lithology

Dep Var: m	N:43	R^2: 0.0857	
	df	F-ratio	P
Log Size	1	3.843	0.0570
Dep Var: m	N:43	R^2: 0.18840	
	df	F-ratio	P
Log Size	1	1.5215	0.2252
Lithology	4	1.1707	0.3395
Dep Var: m	N:43	R^2: 0.31588	
	df	F-ratio	P
Log Size	1	0.5684	0.4563
Lithology	4	2.2425	0.0857
Lithology * Logs Size	4	1.5373	0.2142

As Figure 6.17 indicates, lithology as a whole does not explain the m variance well. The overall R^2 is 0.0857. The two steep slope lines of Crystalline and Siliciclastic Undivided and Unconsolidated lithology regions are in opposite directions to the rest of lithology region slopes and this fact might negate the overall slope of the lithology in m value.



	Siliciclastic	Crystalline	Cryst & Silic Und.	Carbonate	Unconsol	Overall
Intercept	0.5136	0.2622	1.1608	0.3057	0.8405	0.3842
Slope	0.0112	0.0959	-0.2821	0.0767	-0.2254	0.0504
R^2	0.0070	0.3054	0.3464	0.1350	0.1064	0.0857

Figure 6.17 m and Subbasin Log Size in All Lithology

6.4.3 Summary

Comparing subbasins, there are discernible differences in b and m values in the Crystalline vs. non-Crystalline at the 0.05 level, and m at the 0.1 level in the Siliciclastic vs. non-Siliciclastic regions. And, even though the scale influences b and f values at the 0.05 level, there is insufficient evidence as to lithology's influence in a scale context on b and f values. Adding interaction term between scale and lithology to the multiple regression, the influence of lithology becomes statistically significant at 0.086 level, but it is still below the level of the analysis for this study. The mean b, f, and m values for each lithology do not follow the expected bank and bed erodability orders, indicating that other physical controlling factors impact b, f, and m more significantly. Statistical analyses show lithology, as a whole, does not account for b and f values at the statistically significant level.

6.5 The Role of Landuse

The impacts of landuse type on stream discharge behavior are well documented (Moglen and Beighley, 2000, Moglen and Berger, 1998). In the Potomac River Basin study area, the predominant landuse types, forest, agriculture, and urban areas (Figure 6.18) are investigated for their impacts on the b, f, and m.

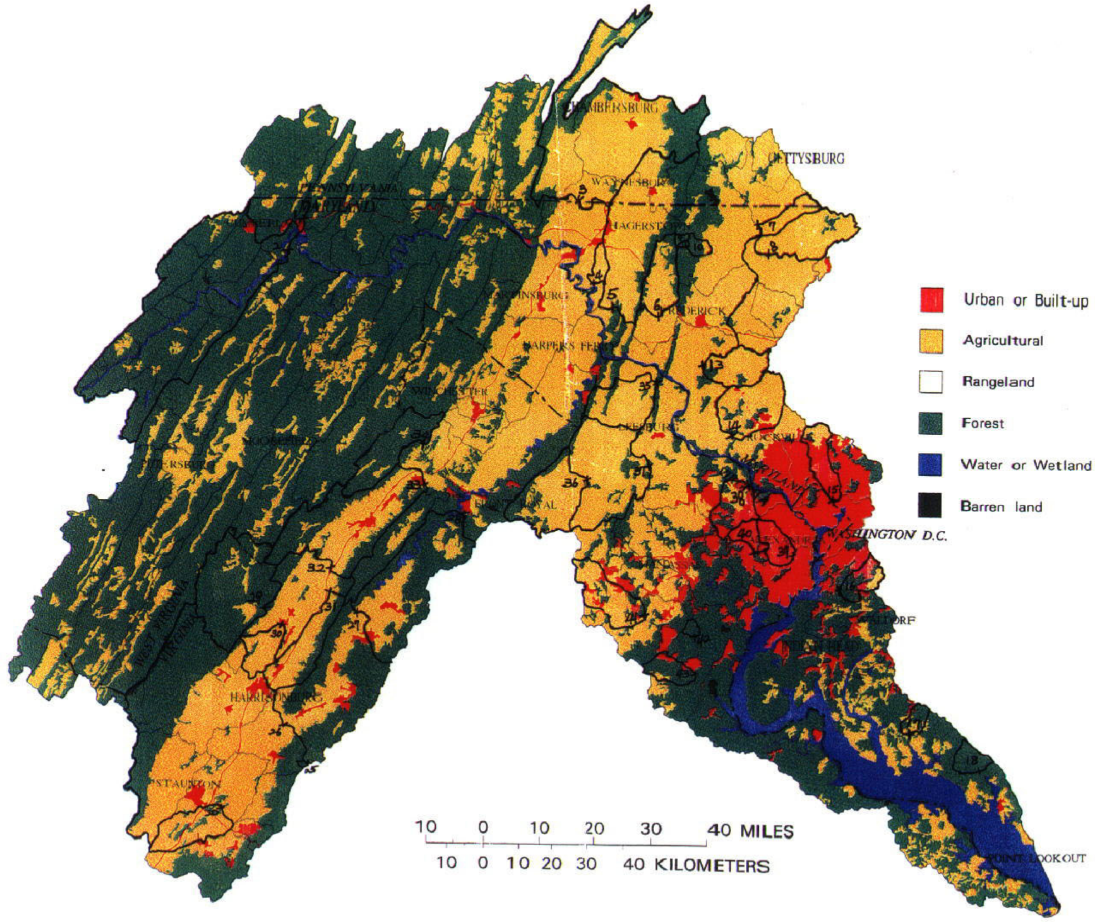


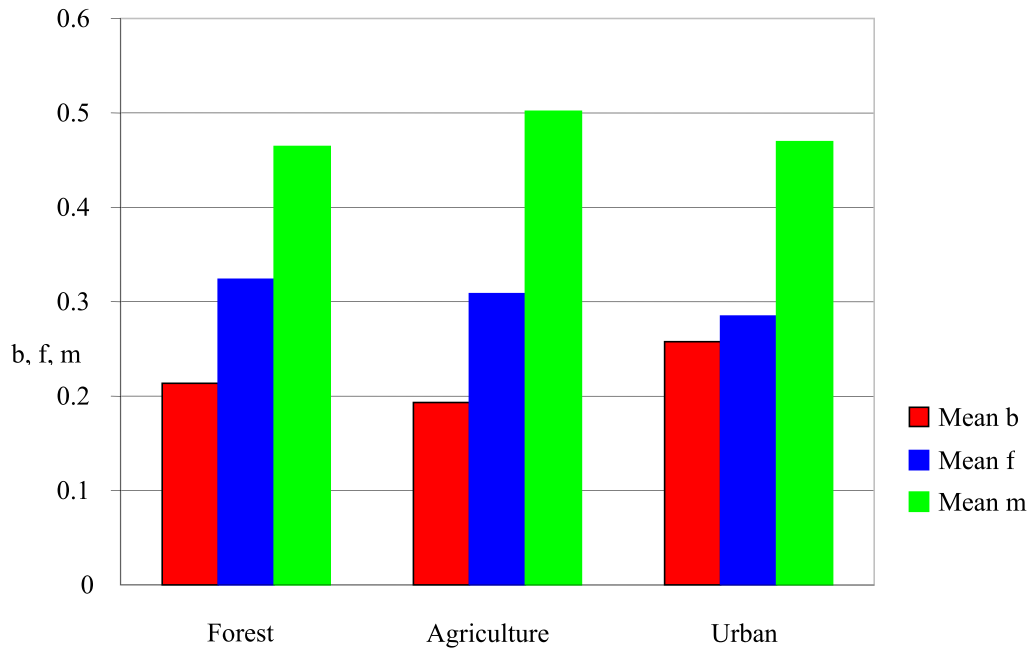
Figure 6.18 Landuse Types of the Study Area
Source: US Geological Survey Water Resources Investigations Report 96-4034

The study subbasins occur in three landuse types: forest (21 subbasins), agriculture (19), and urban (3) [7]. The distribution of b, f, and m average values over forest, agriculture, and urban landuse types do not show clear differences among them

---

[7]As mentioned earlier chapter, the landuse of each subbasin is identified by overlaying subbasin outlines on the landuse plot. The study area landuse file in Arc/Info ™ file is acquired from the USGS Geographic Information Scientist and the delineation of each subbasin was delineated from DEM using ESRI's Arc/Info ™, ERDAS's IMAGINE™, and a couple of commonly used Arc/Info ™Macro Language routines.

(Figure 6.19). The f values of the subbasins in agricultural lands are similar to each other and their standard deviation is 0.088. The subbasins in urban areas have a smaller standard deviation for the mean value, but only 3 subbasins are in this landuse type.



N	21	19	3
Mean b	0.213	0.193	0.258
Mean f	0.324	0.308	0.285
Mean m	0.465	0.501	0.470

Figure 6.19 Average b, f, and m Values in Landuse Types

6.5.1 Each Landuse Type's Influence

The expected correlations between watershed landuse and b, f, and m are that, agricultural areas followed by forest areas would have increased rate of changes in b and

f. The rationale is that in agricultural areas, increased water discharge flows through plowed agricultural fields carrying more suspended and bed load material and has greater erosional impacts on channel beds and banks. On the other hand, in forest landuse areas, increased volumes of discharge occur after ground water saturation: therefore, the discharge would be more or less free of sedimentation compared to agricultural watersheds. That is, it is expected that watersheds in agricultural areas are more susceptible to erosion than those in forest areas. The expected changes in m would be the reverse because the increased bed or suspended load in stream discharge will reduce the flow velocity.

The influence of landuse on b, f and m values is tested using t-test for difference of mean values. Using a 0.1 % test, none of the landuse types is statistically discernable to b, f, and m[8]. However, subbasins in agricultural and forest areas are statistically more significant than any others for m, but not discernible at the 0.1 level (Table 6.12). The m value slopes between agriculture vs. non-agriculture and forest vs. non-forest type of landuse are non- zero (Figure 6.20). Therefore, it is concluded that there is a discernable difference in m values between agriculture and the others and forest vs. non-forest type of landuse, however, the differences are not at the 0.05 level of statistical significance.

---

[8] The critical value for t with 41 degrees of freedom at 0.01 level is 2.704; 0.05, 2.021, and at 0.1 level; 1.684.

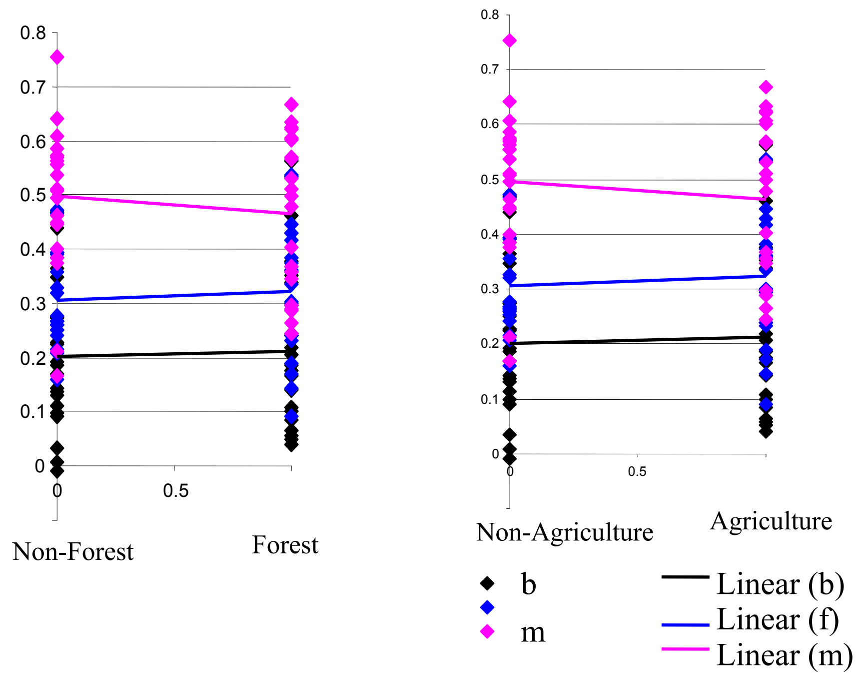


Figure 6.20 Differences of b, f, and m in Forest vs. Non-Forest and Agriculture vs. Non-Agriculture Landuse Types

Table 6.12 Differences of Mean b, f and m within each Landuse Type

	Number of Subbasins	Mean b	Mean b Difference	Mean f	Mean f Difference	Mean m	Mean m Difference
Forest	21	0.2131		0.3237		0.4651	
Non-Forest	22	0.2019	0.0112	0.3051	0.0186	0.4967	0.0316
t-test			0.2690		0.6007		-0.7540
Agriculture	19	0.1930		0.3082		0.5009	
Non-Agriculture	24	0.2188	0.0258	0.3189	0.0107	0.4658	0.0351
t-test			-0.6192		-0.3420		0.8325
Urban	3	0.2584		0.2853		0.4705	
Non-Urban	40	0.2036	0.0548	0.3163	0.0310	0.4821	0.0116
t-test			0.6778		-0.5076		-0.1401

6.5.2 Analyses Using Underlying Rationale

Just considering subbasin landuse type only, all other predictor variables being equal, the increased rate of changes in b and f are expected in agricultural lands followed by forest areas[9]. The rationale is that in agriculture types of landuse, increased water discharge flows through plowed agricultural fields carrying more suspended and bed load material and has greater erosional impacts on channel beds and banks. On the other hand, in forest subbasins, increased volume of discharge occurs after ground water saturation; therefore, the discharge would be more or less free of sedimentation compared to agricultural subbasins. That is, it is expected that subbasins in agricultural areas are more susceptible to erosion than those in forest areas. The expected change in m would be the reverse order of b and m because the increased bed or suspended load in discharge will reduce the flow velocity. Table 6.13 illustrates the comparative change order of b, f, and m between forest and agriculture areas. The average values of b, f, and m for each landuse type and expected change order match, but considering only two types of landuse, it cannot be concluded definitively that b, f, and m values follow landuse.

Table 6.13 Expected Change Orders and Landuse-Based Mean b, f, and m Values

Landuse Type*	N	Expected b and f Change Order	Mean b	Mean f	Expected m Change Order	Mean m
Forest	19	2	0.177	0.287	1	0.538
Agriculture	13	1	0.285	0.310	2	0.410

Note: Landuse type, Urban, has only 3 subbasins, so Urban is excluded in analysis.

[9] The landuse type, Urban, is not included because, only three subbasins fall in this category.

6.5.3 b, f, and m and Landuse in a Scale Context

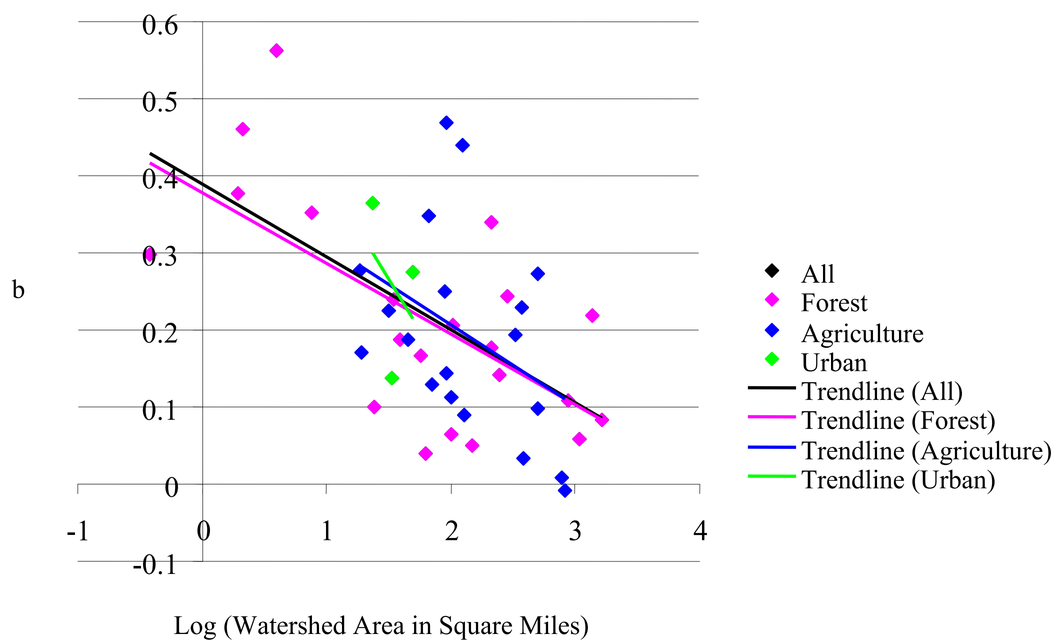
The model for analyzing landuse predictor variables in a scale context is b (f, m) = $a_{0.b}$ ($a_{0.f}$, $a_{0.m}$) + $a_{1.b}$ ($a_{1.f}$, $a_{1.m}$) * $\log_{10}$(size) + $a_{2.b}$ ($a_{2.f}$, $a_{2.m}$)* landuse variable. With the interaction term, the model is b (f, m) = $a_{0.b}$ ($a_{0.f}$, $a_{0.m}$) + $a_{1.b}$ ($a_{1.f}$, $a_{1.m}$) * $\log_{10}$ (size) + $a_{2.b}$ ($a_{2.f}$, $a_{2.m}$)* landuse+ $a_{3.b}$ ($a_{3.f}$, $a_{3.m}$)* $\log_{10}$ (size) * landuse. The null hypothesis is that the scale of the subbasins and landuse have no bearing on the b, f, and m values.

b Exponents

As expected, the computed F value for $a_{1.b}$, 16.842, exceeds the critical value, which reaffirms the notion that scale influences b values. However, the computed value of F for $a_{2.b}$ (landuse), 0.068, does not exceed the critical value, and the $a_{2.b}$ value is not significantly different from 0. Hence, it is concluded that there is no systematic influence of landuse on b. By adding an interaction term to the model for b, R^2 increased from 0.313 to 0.318, and the statistical significance of landuse to b improved from 0.934 to 0.903. Figure 6.21 and Table 6.14 clearly show that landuse in the scale context does not explain b values.

Table 6.14 b, Subbasin Log Size, and Landuse

Dep Var: b	N:43		R^2: 0.3110
	df	F-ratio	P
Log Size	1	18.512	0.000
Dep Var: b	N:43		R^2: 0.3129
	df	F-ratio	P
Log Size	1	16.842	0.0020
Landuse	2	0.0679	0.9344
Dep Var: b	N:43		R^2: 0.3157
	df	F-ratio	P
Log Size	1	0.7900	0.3799
Landuse	2	0.1021	0.9032
Landuse * Log Size	2	0.0766	0.9264



	Forest	Agriculture	Urban	Overall
Intercept	0.3786	0.4176	0.6664	0.3889
Coefficient	-0.0920	-0.1058	-0.2665	-0.0944
R^2	0.4191	0.1702	0.1424	0.31107

Figure 6.21 b and Log Size in All Landuse Types

f Exponent

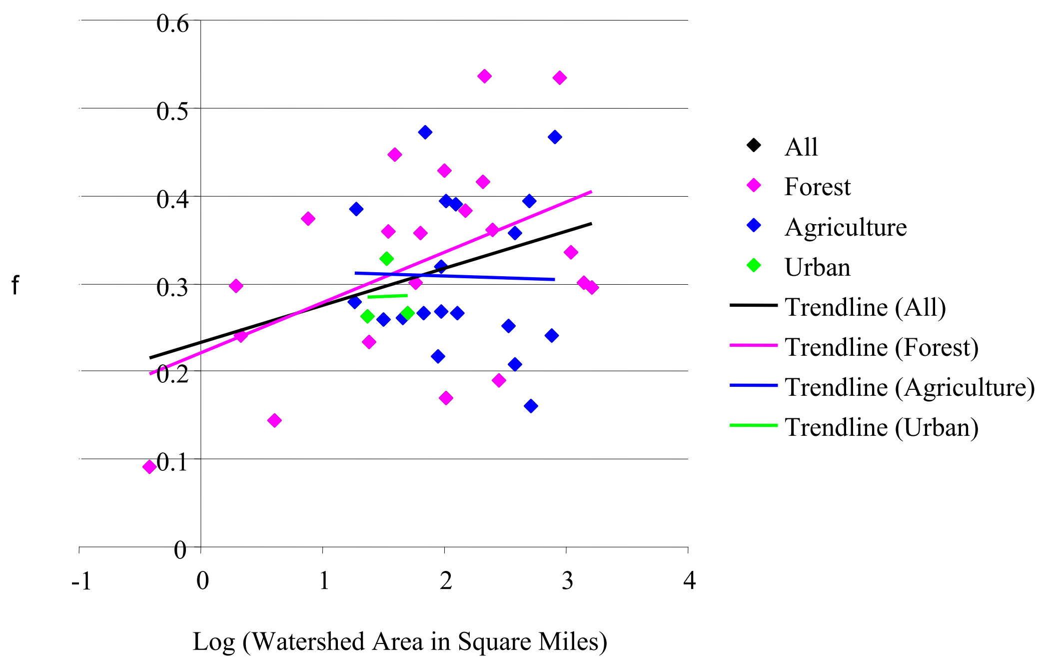
Because the computed value of F for $a_{1.f}$, 5.33, exceeds the critical value, the null hypothesis for $a_{1.f}$ is rejected, and it is concluded that scale influences f values at the 0.05 level of statistical significance. However, the computed value of F for $a_{2.f}$, does not exceed the critical value, which indicates that there is insufficient evidence to reject the null hypothesis for $a_{2.f}$. Hence, it is concluded that a real difference between $a_{2.f}$ and 0 does not exist and the expected response of the contribution of landuse to f value is indiscernible.

Adding the interaction term to the model, the model explains more of the variation (R^2 improved from 0.131 to 0.164); however, it still does not make the landuse statistically significant for f at the 0.05 level.

Table 6.15 f, Subbasin Log Size, and Landuse

Dep Var: f	N:43	R^2: 0.1090	
	df	F-ratio	P
Log Size	1	5.021	0.031
Dep Var: f	N:43	R^2: 0.1306	
	df	F-ratio	P
Log Size	1	5.3256	0.0264
Landuse	2	0.4824	0.6210
Dep Var: f	N:43	R^2: 0.1640	
	df	F-ratio	P
Log Size	1	0.0210	0.8855
Landuse	2	0.3891	0.6804
Landuse * Log Size	2	0.7395	0.4843

As Figure 6.22 indicates, landuse as a whole does not explain the f variance well. The overall R^2 is 0.109. The slopes of landuse types are a mixture of negative and positive directions.



	Forest	Agriculture	Urban	Overall
Intercept	0.2213	0.3167	0.2699	0.2333
Coefficient	0.0569	-0.0040	0.0101	0.0420
R^2	0.2318	0.0897	0.0019	0.1091

Figure 6.22 f and Subbasin Log Size in All Landuse Types

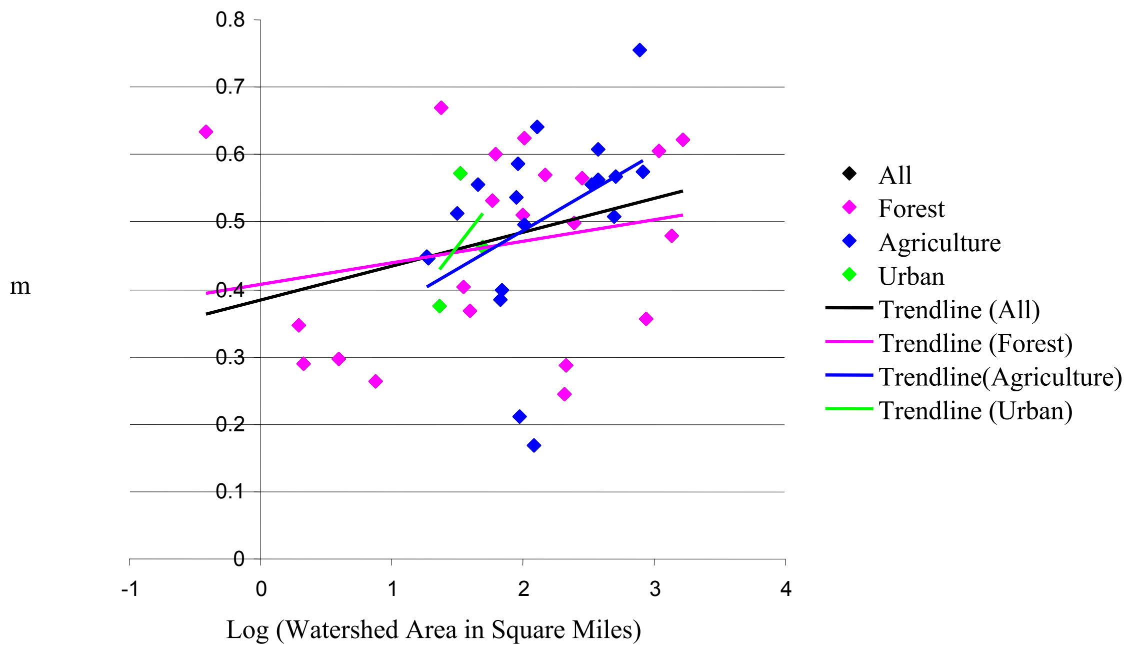
m Exponent

The computed values of F for $a_{1.m}$ (scale) and $a_{2.m}$ (landuse) do not exceed the critical values at 0.05 levels. However, only a_1 values exceed the critical value at 0.1 level. Hence, while it is concluded that neither scale nor landuse influences the m value at 0.05 level, but it can be said that scale influences m value at 0.1 level. When the interaction term is added to the model, the role of the landuse to m becomes statistically significant at the 0.573 level, but not in a meaningful level, and the variation is explained better (R^2 improves from 0.090 to 0.128). This is shown in Table 6.16.

Table 6.16 m and Subbasin Log Size and Landuse

Dep Var: m	N:43	R^2: 0.086	
	df	F-ratio	P
Log Size	1	3.843	0.057
Dep Var: m	N:43	R^2: 0.0910	
	df	F-ratio	P
Log Size	1	3.1846	0.0821
Landuse	2	0.1128	0.8936
Dep Var: m	N:43	R^2: 0.1277	
	df	F-ratio	P
Log Size	1	0.4642	0.4999
Landuse	2	0.5651	0.5731
Landuse * Log Size	2	0.7787	0.4664

As Figure 6.23 indicates, landuse as a whole does not explain the m variance well. The overall R^2 is 0.0857.



	Forest	Agriculture	Urban	Overall
Intercept	0.4074	0.2566	0.0694	0.3842
Coefficient	0.0321	0.1151	0.2620	0.0505
R^2	0.0510	0.1811	0.1823	0.0857

Figure 6.23 m and Subbasin Log Size in All Landuse

6.5.4 Summary

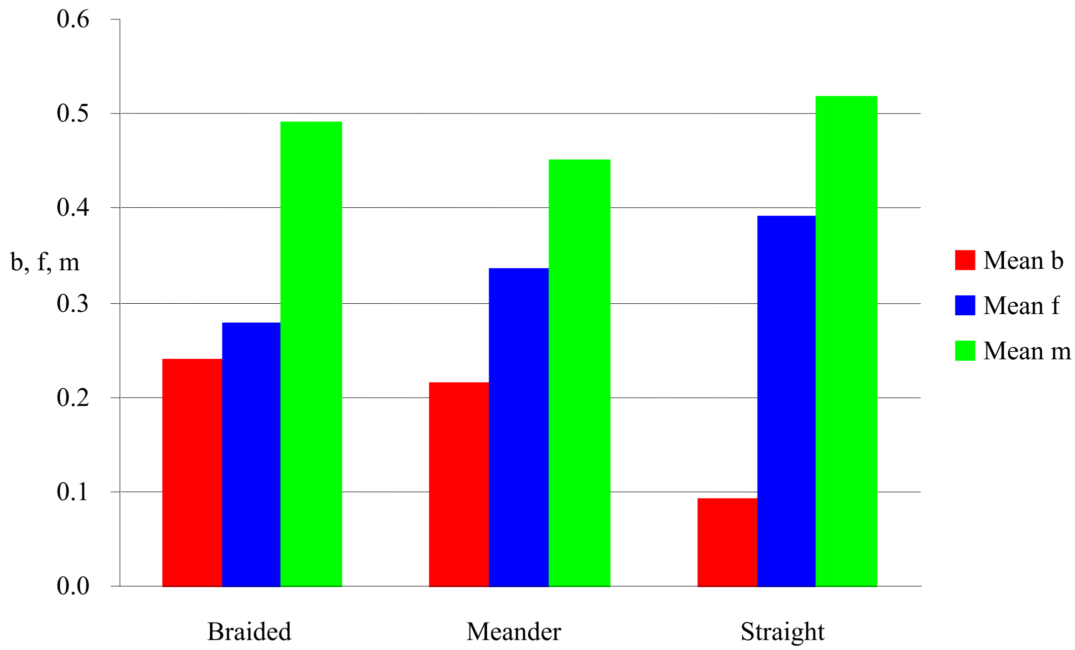
As expected, scale influences b and f values, but there is not sufficient evidence as to its influence on the m values. Disregarding scale, the subbasins in forest vs. non-forest and agriculture vs. non-agriculture landuse types show differences of mean in m value but the difference of means are statistically insignificant at the 0.05 level. Hence, landuse, as a whole, does not show any systematic trend in m values.

6.6 The Role of Channel Pattern

The channel pattern of a stream, whether straight, braided, or meandering, produces characteristic cross-sections. Because channel morphology is a major factor in determining the hydraulic geometry of a cross-section, it seems probable that there is a relationship between the hydraulic geometry exponents and channel pattern. Knighton and Rhodes (1977) stated that channel pattern has an important influence on the hydraulic geometry of rivers, but the absence of adequate data has hindered definitive conclusions. The variation is apparently not random but systematically related to channel pattern, straight reaches being distinguishable from both meander and braided reaches in terms of the rates of change of width.

Twenty-two channels in the Potomac River Basin study area are categorized as braided, 14 as meander, and 7 as straight. The channel pattern categorization is based on the criteria described in Chapter 5. The comparative b, f, and m average values for the various channel patterns are graphed in Figure 6.24.

Comparing the average values of b, f, and m for each channel pattern, there are significant differences among the three channel pattern types (Figure 6.24). The mean b value of the straight channels is 0.092, while both the meander and braided channels' b values are 0.215 and 0.239, respectively.



N	22	14	7
Mean b	0.239	0.215	0.092
Mean f	0.277	0.335	0.391
Mean m	0.490	0.450	0.517

Figure 6.24 Average b, f, and m Values in All Channel Patterns

6.6.1 Each Channel Pattern's Influence

The influence of channel pattern on b, f, and m values is examined using a t-test for difference of mean values. Using a 0.05% test, straight channel pattern is statistically discernable for b. The straight channel's influence on b is statistically significant at the 0.025 level (Table 6.17 and Figure 6.25). Using a 0.2% test, braided channel becomes statistically discernible for b and f, and straight channel for b. Therefore, the null hypothesis is rejected for braided for b, f, and m and straight channel for b and f at the 0.2

level, and it is concluded that there are discernable differences in b and f in braided channels and for b and f in straight channels.

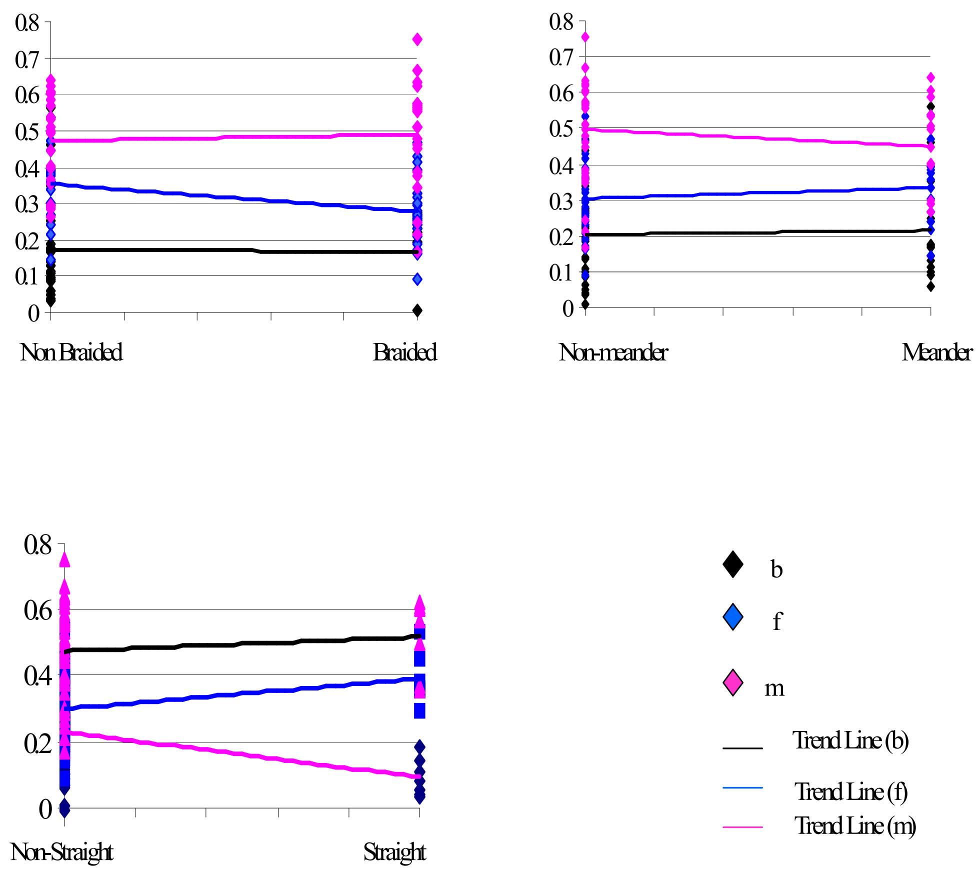


Figure 6.25 Mean Differences of b, f, and m in the Braided vs. Non- Braided, Meander v Non-Meander, and Straight vs. Non-Straight Channels

Table 6.17 Differences of Mean b, f, and m within each Channel Pattern Type

	Number of Subbasins	Mean	Mean b Difference	Mean	Mean f Difference	Mean	Mean m Difference
Braided	21	0.2392		0.2766		0.4900	
Non-Braided	22	0.1741	0.0651	0.3535	0.0769	0.4721	0.0179
t-test			1.6191		-1.5589		0.1868
Meander	19	0.2150		0.3348		0.4496	
Non-Meander	24	0.2037	0.0113	0.3042	0.0306	0.4966	0.0470
t-test			0.2566		0.9294		-1.0568
Straight	7	0.0922		0.3909		0.5172	
Non- Straight	36	0.2298	0.1376	0.2993	0.0916	0.4743	0.0429
t-test			**-2.6528**		1.3095		0.3250

Note: Critical value at the 0.01 level is 2.704; 0.025 level, 2.423; 0.05 level, 2.021, and 0.1 level 1.684. Statistically significant at the 0.025 and less are indicated in **Bold**.

As expected, straight channels, which are narrow and deep in nature, have the lowest b values with the highest m values, because with a low b value, f and m have to be higher in order for the summation of the b, f, and m to become unit 1. The observed mean b value in straight channels, 0.09, is not as dramatically low as Knighton's (1975) finding, 0.03, but the observed mean b values in both meandering and braided channels are essentially in agreement with the Knighton's (1975) finding of 0.24.

Braided channels are typically broad and shallow. Characteristics are usually unstable banks and steep slopes with variations in flow. Braided channels are often, but not always, associated with sandy or friable bank materials. Therefore, higher m values are expected for braided channels than those of meander channels, and the observed mean m value are in agreement with the expected m.

Braided channels have the widest range of maximum and minimum values of b, f, and m and have the largest b values, as expected, because of usually unstable banks, shallow channels with high slope, among the three channel pattern types. Slope also varied with channel pattern. Braided reaches had consistently steeper slopes than undivided channels, which may account for their higher mean flow velocities.

Meandering channels seem to be associated with relatively low b values, although not as low as those for straight channels. The mean m value appears to be smallest among the three channel patterns.

Comparing straight, meander, and braided channels, the straight channels have the smallest range of maximum and minimum values for all b, f, and m, which indicate that straight channels have very similar b, f, and m values among themselves. And, the mean f value for braided channels has also a very small standard deviation meaning the rates of depth changes with discharge are similar within braided channels.

6.6.2 Channel Pattern in a Scale Context

The role of the channel pattern on the subbasin in a scale context is b (f, m) = $a_{0.b}$ ($a_{0.f}$, $a_{0.m}$) + $a_{1.b}$ ($a_{1.f}$, $a_{1.m}$)* $\log_{10}$(size) + $a_{2.b}$ ($a_{2.f}$, $a_{2.m}$)* channel pattern variable. The null hypothesis is that the scale of the subbasins and channel pattern characteristics have no bearing on the b (f, m) values.

b Exponents (Figure 6.26 and Table 6.18)

As expected, the channel pattern and b is significant at the 0.05 level in scale context. The computed values of $a_{1.b}$ and $a_{2.b}$ 14.886 and 2.47, exceed the critical values for the levels of α = 0.05 and α = 0.10, respectively. This statistical discernability of scale affirms the notion that scale influences b values and the role of channel pattern vis-à-vis b values (Table 6.18). The null hypotheses for $a_{1.b}$ and $a_{2.b}$ are rejected and it is concluded that not only scale, but also channel pattern, influences b values.

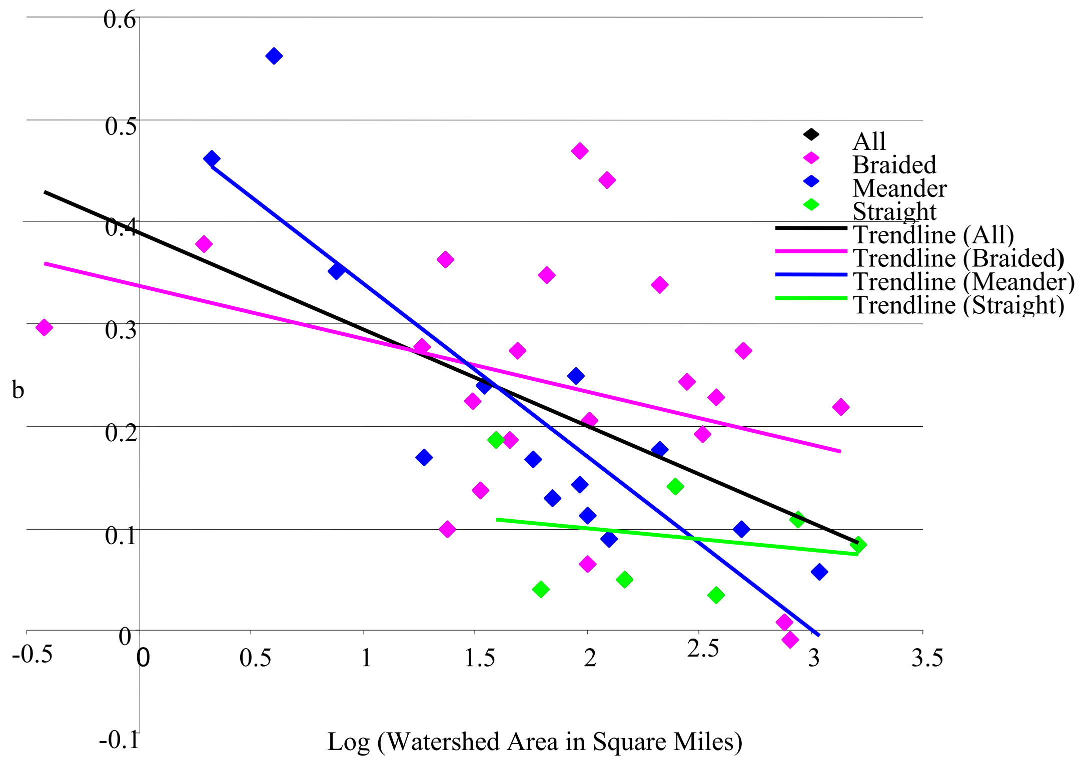
Specifically, the meander channels clearly show that channel pattern does explain the b value in a scale context, as revealed by an R^2 of 0.758 (Figure 6.26). By adding an interaction term to the model for b, R^2 increased from 0.388 to 0.493, and the statistical significance of channel pattern for b improved from 0.098 to 0.065.

In general, as subbasin size increases, the b value decreases, and especially, it is noticeable in the meander channels where the slope is the steepest among the all other channel patterns. In straight channels, the role of scale appears to be minimal (Figure 6.26).

Table 6.18 b, Subbasin Log Size, and Channel Pattern

Dep Var: b	N:43	R^2: 0.3105	
	df	F-ratio	P
Log Size	1	18.512	**0.000**
Dep Var: b	N:43	R^2: 0.153	
	df	F-ratio	P
Channel Pattern	2	3.615	**0.0360**
Dep Var: b	N:43	R^2: 0.3883	
	df	F-ratio	P
Log Size	1	14.886	**0.0004**
Channel Pattern	2	2.4708	**0.0977**
Dep Var: b	N:43	R^2: 0.4927	
	df	F-ratio	P
Log Size	1	8.2117	**0.0068**
Channel Pattern	2	2.9490	**0.0648**
Channel Pattern * Log Size	2	3.8169	**0.0311**

Note: Statistical significance at the 0.1 level is in **Bold**.



	Braided	Meander	Straight	Overall
Intercept	0.3368	0.5093	0.1433	0.3889
Coefficient	-0.0515	-0.1693	-0.0214	-0.0944
R^2	0.1171	0.7584	0.0481	0.3110

Figure 6.26 b and Subbasin Log Size in all Channel Pattern Types

f Exponents (Figure 6.27 and Table 6.19)

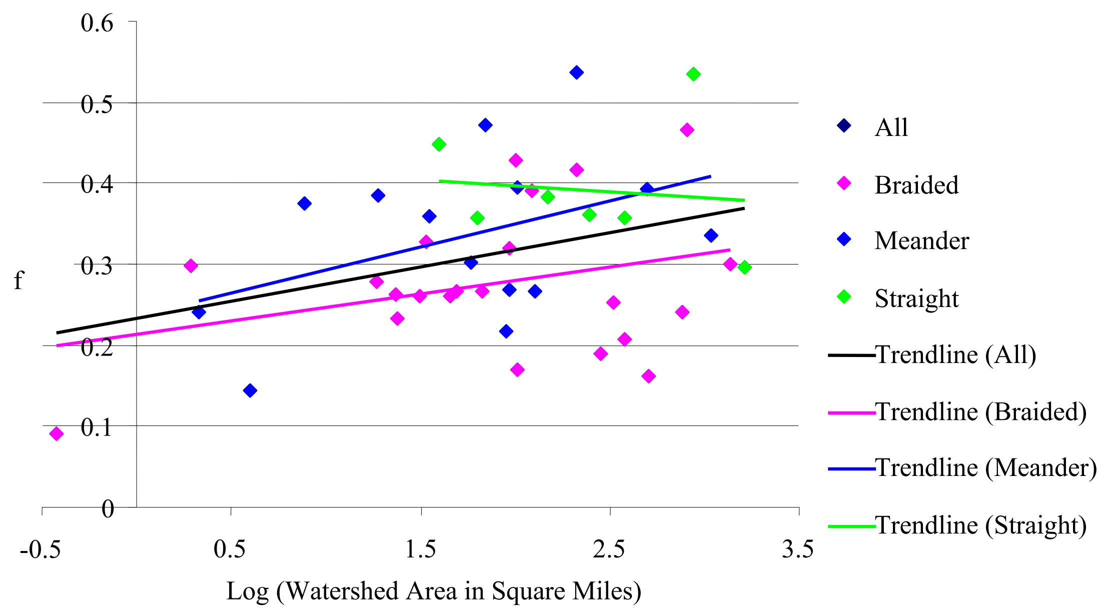
The computed values for $a_{1.f}$, 4.0059, and $a_{2.f}$, 3.9342, exceed the critical value at the $\alpha = 0.1$ and $\alpha = 0.05$ level, respectively. Hence, the null hypotheses for $a_{1.f}$ and $a_{2.f}$, are rejected and it is concluded that geographic scale and channel pattern both influence the f value at the 0.1 and 0.05 levels, respectively.

The relationship between the channel pattern and f in the scale context is not strong (R^2 = 0.259), but clearly the role of channel pattern on f is evidenced on R^2 of 0.259 from 0.109 with just f and log size relationship. The R^2 for each channel pattern and f value in a scale context is lower compared to the mean differences of Straight vs. Non-Straight and Braided vs. Non-Braided (Figure 6.25). This result can be explained by the fact that regression slope lines between channel pattern types and f values are in opposite directions among the three channel pattern types and the f values are scattered in the scale domain of braided and straight channels.

Table 6.19 f, Subbasin Log Size, and Channel Pattern

Dep Var: f	N:43	R^2: 0.1090	
	df	F-ratio	P
Log Size	1	5.021	**0.0310**
Dep Var: f	N:43	R^2: 0.1830	
	df	F-ratio	P
Channel Pattern	2	4.466	**0.0180**
Dep Var: f	N:43	R^2: 0.2587	
	df	F-ratio	P
Log Size	1	4.0059	**0.0523**
Channel Pattern	2	3.9342	**0.0278**
Dep Var: f	N:43	R^2: 0.2789	
	df	F-ratio	P
Log Size	1	1.0007	0.3237
Channel Pattern	2	0.8356	0.4416
Channel Pattern * Log Size	2	0.5197	0.5990

Note: Statistical Significance at the 0.1 level is in **Bold**.



	Braided	Meander	Straight	Overall
Intercept	0.2139	0.2355	0.4253	0.2333
Coefficient	0.0331	0.0571	-0.0144	0.0420
R^2	0.0943	0.1745	0.0118	0.1091

Figure 6.27 f and Subbasin Log Size in all Channel Pattern Types

In spite of a negative influence of straight channels on f, the overall trend is that as the subbasin size increases, the f values increase. Specifically, in meander channels the regression slope line of the f and subbasin size is the steepest (0.057).

m Exponents (Figure 6.28 and Table 6.20)

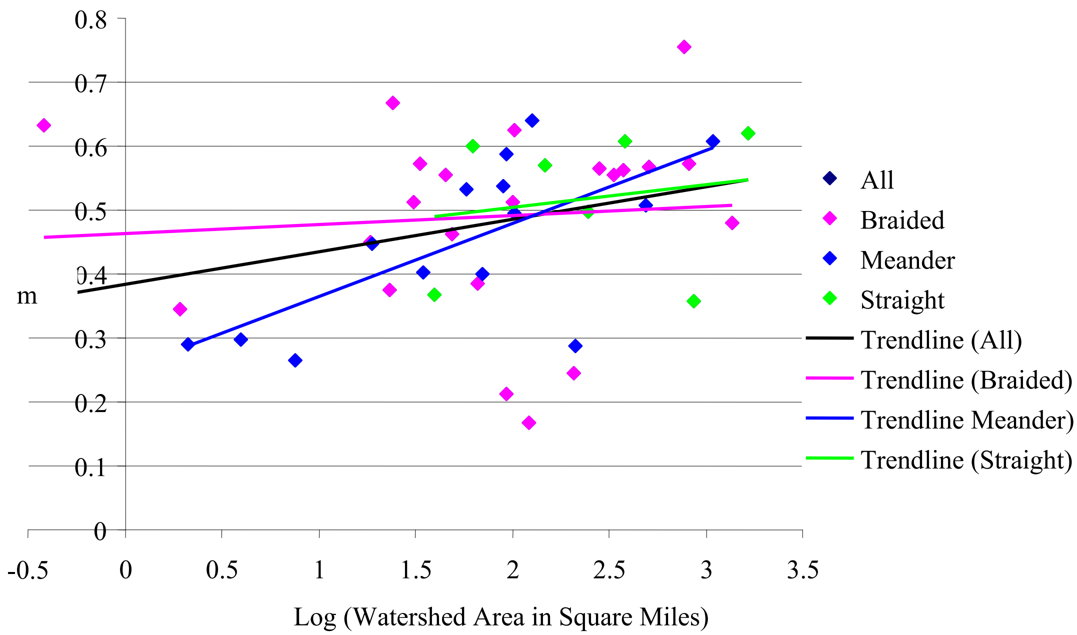
Since the computed a_1 value, 2.938, exceeds the critical value at the $\alpha = 0.1$ level, the null hypothesis is rejected, and it is concluded that scale influences m values with a statistical significance of 90% (Table 6.20). However, the computed value for $a_{2.m,}$ 0.296, does not exceed the critical value at the $\alpha = 0.1$ level, which indicates that there is insufficient evidence to reject the null hypothesis.

By adding the interaction term, the role of the channel pattern improves statistical significance at the 0.2 level but even with the interaction term, it is concluded that the response of the contribution of channel pattern to m value is indiscernible at 0.05 level.

Table 6.20 m, Subbasin Log Size, and Channel Pattern

Dep Var: m	N:43	R^2: 0.0857	
	df	F-ratio	P
Log Size	1	3.843	**0.0570**
Dep Var: m	N:43	R^2: 0.032	
	df	F-ratio	P
Channel Pattern	2	0.651	0.5270
Dep Var: m	N:43	R^2: 0.0994	
	df	F-ratio	P
Log Size	1	2.9375	**0.0945**
Channel Pattern	2	0.2959	0.7455
Dep Var: m	N:43	R^2: 0.1636	
	df	F-ratio	P
Log Size	1	2.1921	0.1472
Channel Pattern	2	1.6955	0.1975
Channel Pattern * Log Size	2	1.4217	0.2542

Note: Statistical Significance at the 0.1 level is in **Bold**.



	Braided	Meander	Straight	Overall
Intercept	0.4632	0.2507	0.4332	0.3842
Coefficient	0.0141	0.1144	0.0352	0.0505
R^2	0.0063	0.4596	0.0328	0.0857

Figure 6.28 m and Subbasin Log Size in All Channel Pattern Types

6.6.3 Summary

At the 0.1 level, there are no discernable differences in the b, f, and m values between braided and non-braided channels, and for b and f values in straight versus non-straight channels. Also, as expected, the straight channels have the smallest mean b value (0.092), but the highest m value (0.517). Braided channels have the highest mean b values, higher than meander channels.

As expected, the scale influences on band f values are evident. The channel pattern's influence on f is statistically significant at 0.05 level, respectively. However, the channel pattern's influence on m is indiscernible. It is expected that channel pattern would influence width and depth change rate rather than velocity of flow change rate. Specially, the channel patterns' influence on the f value with a statistical significance level of 0.0278 is notable.

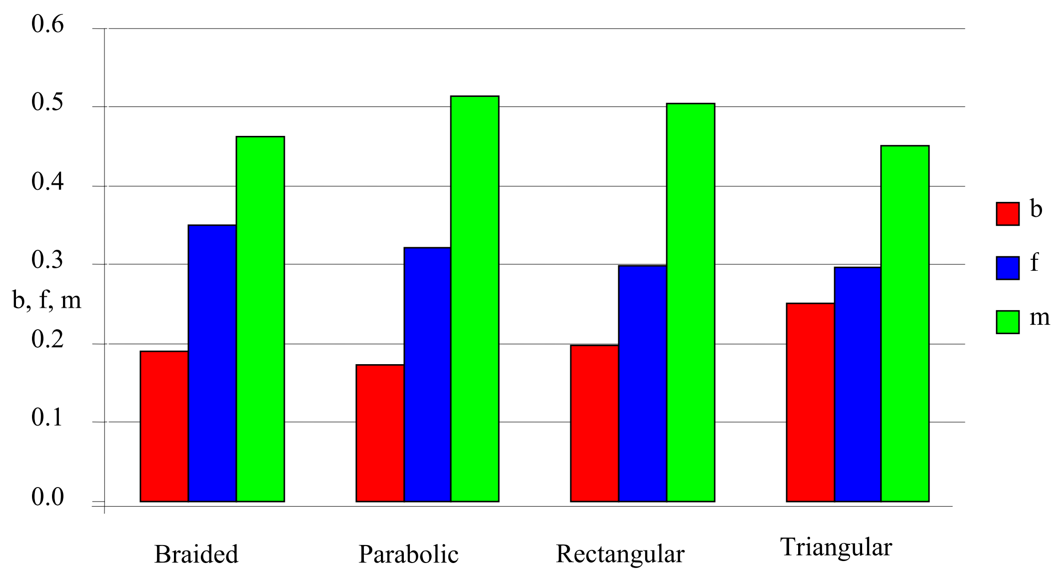
6.7 The Role of Channel Shape

Considering only channel shape, it is expected, based on Rhodes' (1977) research, that rectangular channels will have the lowest b values, parabolic channels will have $b = f/2$, triangular channels will have $b = f$, and braided channels will have $b > f$. Differences in channel shape can vary between rectangular ($b/f \approx 0$) and triangular ($b/f \approx 1$). Changes in width and depth with increasing discharge may occur either by erosion of banks and beds or by progressive filling of a stable channel. Therefore, the b to f ratio gives an indication of the change in shape of the channel cross-section with changing discharge.

Intrinsically, it can be assumed that the b, f, and m values for shallow wide channels would be different with increasing discharge than would the hydraulic geometry exponents for deep narrow channels. These differences in channel shape cause different friction characteristics which promote m/f differences. Therefore, it is reasonable to hypothesize that the shape of the channel cross-section causes different rates of b and f.

For this research, channel shape was categorized first by visual inspection using channel depth and width profile diagrams. Channel profiles were created for each survey to classify the channels into rectangular, triangular, parabolic, and braided chanel shapes. The visual inspection was based on Ferguson's four channel shapes, however his categorization criteria (ratio of b and f) were not used to classify the channels in this study. Using File Maker Pro™, a macro program was written to calculate cumulative width, area, and distance from the mid-point for each segment. In order to draw the channel profile, the depth values were expressed as a negative value.

The channel cross-section profile is drawn for each survey measurements in a given subbasin. The study subbasins are categorized as having 10 braided, 7 parabolic, 14 rectangular, and 12 triangular channels, using a channel shape classification based on criteria described in the Chapter 5. The comparative b, f, and m average values for the various channel shapes are graphed in Figure 6.29.



N	10	7	14	12
b	0.190	0.174	0.199	0.251
f	0.351	0.322	0.299	0.297
m	0.462	0.514	0.504	0.452

Figure 6.29 Average b, f, and m Values by Channel Shape

6.7.1 Each Channel Shape's Influence (Figure 6.30 and Table 6.21)

The influence of channel shape on b, f and m values is examined using a t-test for difference of mean values. Comparing Braided vs. non- Braided and Triangular vs. non-Triangular channels, the mean differences of f and b, respectively, are not greater than the t-critical value at the 0.05 level. Therefore, the null hypothesis (there is no difference in influencing f values between Braided and non-Braided and b values between Triangular and non-Triangular channels) cannot be rejected for the 0.05 level, and it can be concluded that there is an indiscernable difference in f values between the Braided and the other channel shapes as well as Triangular and other channels in regard to b values.

The mean difference of the b value in the Parabolic and all other channels is insignificant at the 0.1 level. Also, the differences in the mean f and m values between Rectangular and other channels as well as Triangular vs. non-Triangular channels are insignificant at the 0.1 level.

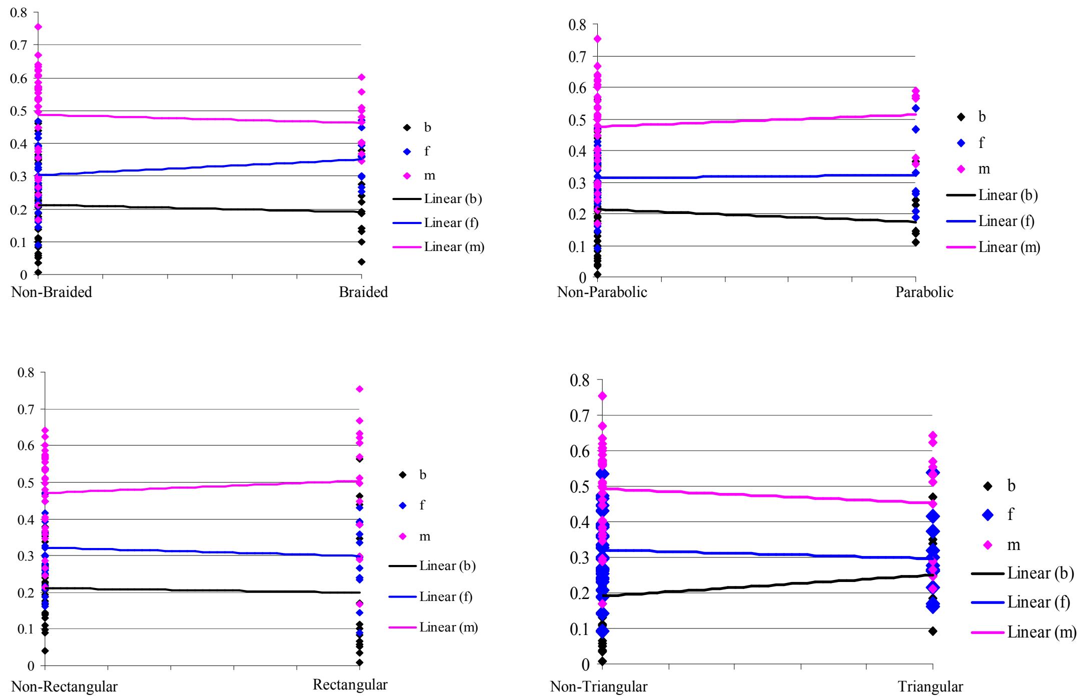


Figure 6.30 Mean Differences of b, f, and m in All Channel Shapes

Table 6.21 Differences of Observed Mean b, f, and m in One Type vs. All Other Channel Shapes

	Number of Subbasins	Mean b	Mean b Difference	Mean f	Mean f Difference	Mean m	Mean m Difference
Braided	10	0.1902		0.3510		0.4621	
Non-Braided	33	0.2126	0.0224	0.3031	0.0479	0.4871	0.0250
t-test			-0.4582		1.3184		-0.5014
Parabolic	7	0.1740		0.3224		0.5136	
Non-Parabolic	36	0.2139	0.0399	0.3130	0.0094	0.4750	0.0386
t-test			-0.7151		0.2336		0.6786
Rectangular	14	0.1991		0.2989		0.5038	
Non-Rectangular	29	0.2114	0.0123	0.3216	0.0227	0.4704	0.0334
t-test			-0.2767		-0.6849		0.7467
Triangular	12	0.2508		0.2967		0.4521	
Non-Triangular	31	0.1906	0.0602	0.3209	0.0242	0.4926	0.0405
t-test			1.3321		-0.7011		-0.8672

Note: Critical value at the 0.01 level is 2.704; 0.025 level, 2.423; 0.05 level, 2.021, and 0.1 level 1.684. None of the t-test result is statistically significant.

Table 6.22 Differences of Expected and Observed Mean b, f, and m within Each Channel Shape Type

	Number of Subbasins	Expected Change Rate (b, f)	Observed Mean b	Observed Mean f	Observed Mean m
Braided	10	b > f	0.1902	0.3510	0.4621
Triangular	12	b = f	0.2508	0.2967	0.4521
Parabolic	7	b = f/2	0.1740	0.3224	0.5136
Rectangular	14	b = lowest	0.1991	0.2989	0.5038

Source: Expected b and f change rates are from Rhodes (1977). The observed mean b, f, and m values are derived by the author.

The observed values and the comparative values of each b and f for channel shape type do not closely follow the expected order of b value changes. The relationship between channel shape and b and f indicates that other physical and other environmental controlling factors impact b and f more significantly. The biggest discrepancy is the mean b value of the braided channels. It is expected to have the highest mean b value, but the observed b value is the second lowest which causes b < f rather than b > f. Triangular channels have the highest mean b value which match the expected relationship (b = f) between b and f. Also, the parabolic channels match the expected relationship (b = f/2).

Contrary to expectation, parabolic channels have the lowest b value and rectangular and triangular channel shapes have higher b values than braided channels. The reason that subbasins with rectangular channels have a higher b average value is that subbasin m311 which has the highest b value (0.562) in the study area, as well as subbasin m31 (0.461), are classified as having rectangular channels. Excluding these subbasins, rectangular subbasins have an average b value of 0.146 which is the lowest b value among all channel shapes. However, as shown in Figure 6.31 and Figure 6.32, these subbasin channels are clearly rectangular in shape and the widths of the channels change from 0.7 – 18.6 and 1.5 – 31.5 feet in m31 and m311, respectively, and still maintain rectangular shapes. Therefore, m311 and m31 cannot be discarded as rectangular shape channel and it can be concluded that the b is influenced by factors other than by channel shape.

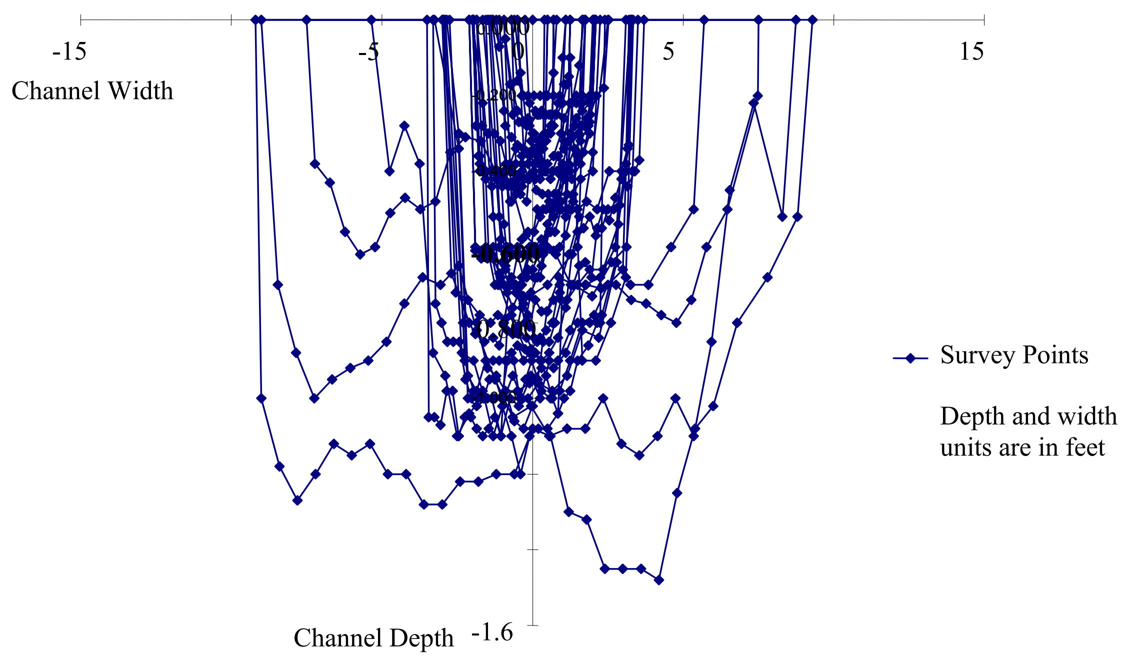


Figure 6.31 Channel Shape of Subbasin m31
Source: Selected 1985 – 1994 USGS Hydrographic Survey Data

Comparing all channel shapes, **braided** channels have b, f, and m values that are very similar to each other. This indicates that b, f, and m values can be estimated without a large variance in braided channel shaped subbasins.

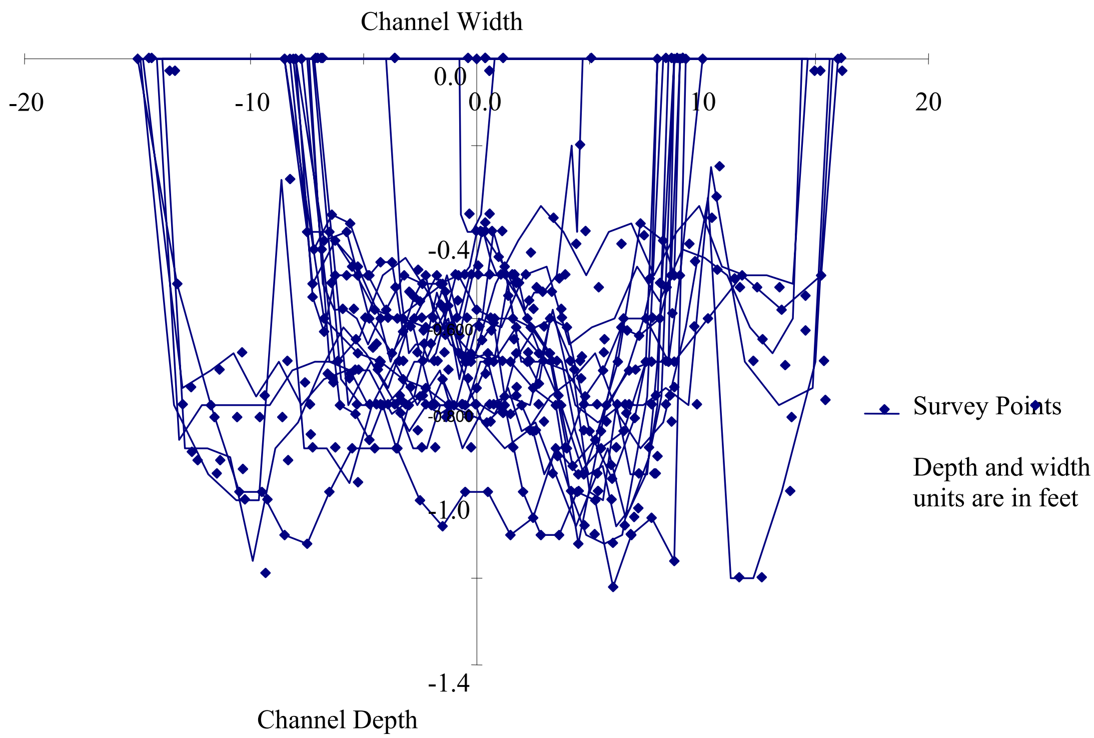


Figure 6.32 Channel Shape of Subbasin m311
Source: Selected 1985 – 1991 USGS Hydrographic Survey Data

6.7.2 Channel Shape in Scale Context

As discussed in 6.1, examination of b, f, and m exponents with subbasin size indicated that there is a systematic change in b, f, and m values with subbasin size. The role of the channel shape in a scale context, b (f and m) is examined by setting the model $b\ (f, m) = a_{0.b}\ (a_{0.f}, a_{0.m}) + a_{1.b}\ (a_{1.f}, a_{1.m}) * \text{scale} + a_{2.b}\ (a_{2.f}, a_{2.m}) * \text{channel shape} + a_{3.b}\ (a_{3.f}, a_{3.m}) * \text{channel shape} * \text{scale variable}$.

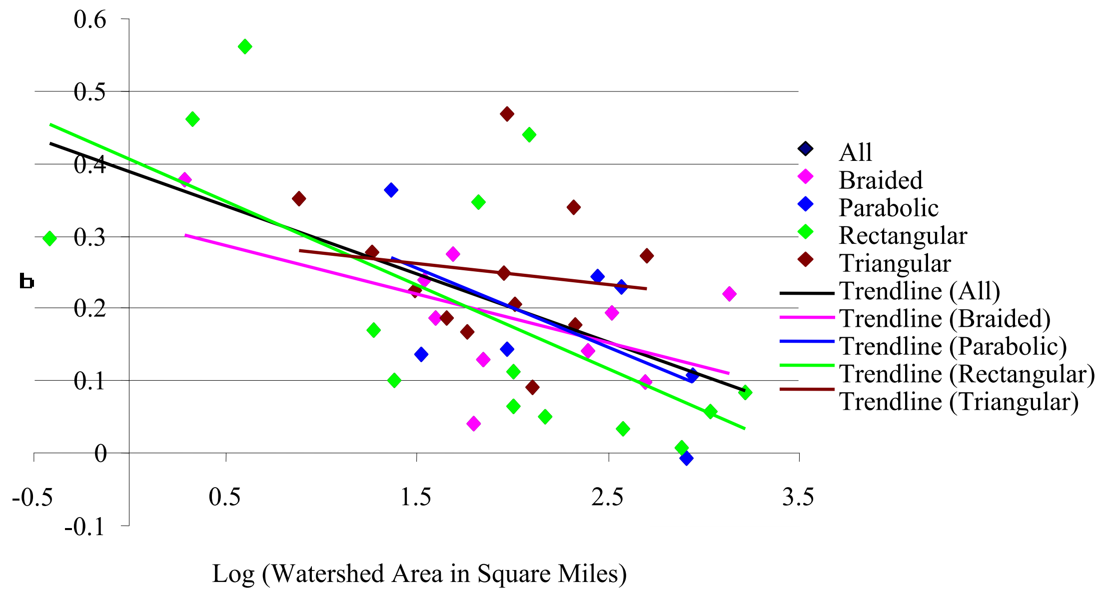
b Exponents (Figure 6.33 and Table 6.23)

The computed value of $a_{1.b}$, 17.448, exceeds the critical values for level at $\alpha = .0002$, the null hypothesis for $a_{1.b}$ is rejected and it is concluded that scale influences b, but $a_{2.b}$, 0.676, does not exceed critical value at the 0.1 level. Therefore, it is concluded that channel shape is an insignificant variable influencing b at the 0.1 level.

Table 6.23 b and Subbasin Log Size and Channel Shape

Dep Var: b	N:43	R^2: 0.3105	
	df	F-ratio	P
Log Size	1	18.512	**0.000**
Dep Var: b	N:43	R^2: 0.3454	
	df	F-ratio	P
Log Size	1	17.4477	**0.0002**
Channel Shape	3	0.6763	0.5719
Dep Var: b	N:43	R^2: 0.3755	
	df	F-ratio	P
Log Size	1	7.3755	0.0102
Channel Shape	3	0.2800	0.8409
Channel Shape * Log Size	3	0.5609	0.6444

Note: Statisitcally significant at the 0.1 level or less are indicated in **Bold.**



	Braided	Parabolic	Rectangular	Triangular	Overall
Intercept	0.3201	0.4198	0.4049	0.3061	0.3889
Coefficient	-0.0666	-0.1093	-0.1153	-0.0295	-0.0944
R^2	0.3039	0.3480	0.4352	0.0213	0.3110

Figure 6.33 b and Subbasin Log Size in Channel Shape

In general, as subbasin size increases, the b value decreases. However, in triangular shape channels, when the subbasins exceed 100 square miles in area, there is a discontinuity in the downward slope line. Even though the sample size is small (12), could it be an example of representative elementary area (REA) phenomenon, which is defined as a critical area at which implicit continuum assumptions may be used without knowledge of patterns of parameter values although some knowledge of the underlying distributions may still be necessary? The implicit notion of the REA is that at scales smaller than the REA the actual parameters of variability are important in determining the hydrological response and at larger scales a statistical description of spatial variability should suffice. Even though, REA in the literature has been historically much smaller (1 – 5 km^2) than 100 square miles in size, as Bloschl et al. (1995) and Beven (1995) suggested, it is conceivable that the concept is feasible for larger basins, as it seems likely that the appropriate size of an area might vary between watershed environments and processes. The REA might be at 100 square miles for the at-a-station hydraulic geometry in the study area? It needs to be further investigated, but it is out of scope in this research.

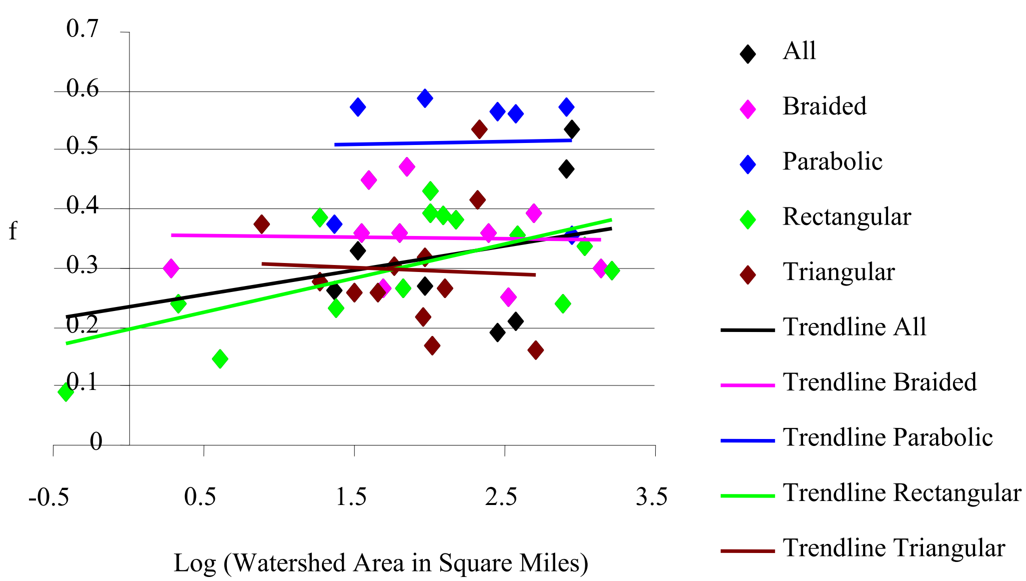
f Exponent (Figure 6.33 and Table 6.24)

The computed value of $a_{1.f}$, 4.456, exceeds the critical values for level at $\alpha = 0.05$, but $a_{2.f}$, 0.5839, does not exceed the critical value of the 0.1 level. Therefore, the null hypothesis for $a_{1.f}$ is rejected and it is concluded that scale influences f, but the channel shape is an insignificant variable to influence f at the 0.1 level. By adding an interaction term, R^2 improved and the role of channel shape became more significant but still not significant at $\alpha = 0.1$ level.

Table 6.24 f and Subbasin Log Size and Channel Shape

Dep Var: f	N:43	R^2: 0.1090	
	df	F-ratio	P
Log Size	1	5.021	**0.0310**
Dep Var: f	N:43	R^2: 0.1484	
	df	F-ratio	P
Log Size	1	4.4564	**0.0414**
Channel Shape	3	0.5839	0.6292
Dep Var: f	N:43	R^2: 0.2198	
	df	F-ratio	P
Log Size	1	2.1690	0.1498
Channel Shape	3	1.3180	0.2841
Channel Shape * Log Size	3	1.0688	0.3748

Note: Statisitcally significant at the 0.1 level or less are indicated in **Bold.**



	Braided	Parabolic	Rectangular	Triangular	Overall
Intercept	0.3580	0.4198	0.1957	0.3128	0.2333
Coefficient	-0.0037	-0.1093	0.0578	-0.0086	0.0420
R^2	0.0016	0.2357	0.3667	0.0016	0.1091

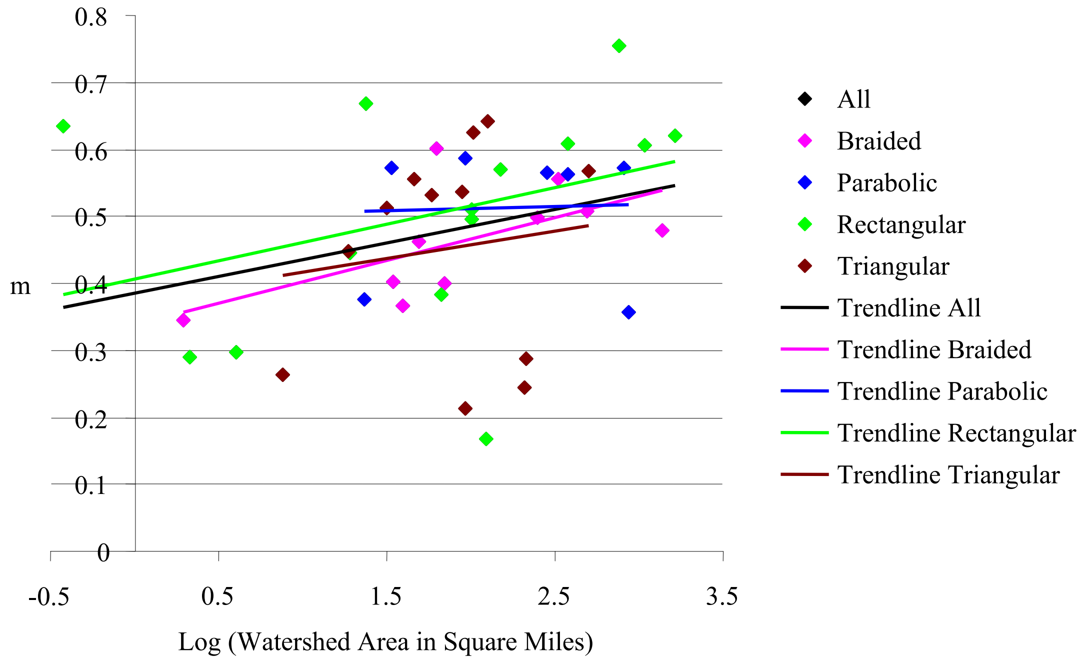
Figure 6.34 f and Subbasin Log Size in Channel Shape

m Exponent (Figure 6.35 and Table 6.25)

The computed value of $a_{1.m}$, 3.609, exceeds the critical values for level at α = 0.050, the null hypothesis for a_1 is rejected and it is concluded that scale influences m, but for $a_{2.m}$, 0.488 does not exceed critical value at the 0.1 level. Therefore, it is concluded that channel shape is an insignificant variable to influence m.

Table 6.25 m and Subbasin Log Size and Channel Shape

Dep Var: m	N:43	R^2: 0.086	
	df	F-ratio	P
Log Size	1	3.843	0.057
Dep Var: m	N:43	R^2: 0.1196	
	df	F-ratio	P
Log Size	1	3.6089	0.0651
Channel Shape	3	0.4882	0.6925
Dep Var: m	N:43	R^2: 0.1276	
	df	F-ratio	P
Log Size	1	1.3889	0.2466
Channel Shape	3	0.1674	0.9177
Channel Shape * Log Size	3	0.1063	0.9558



	Braided	Parabolic	Rectangular	Triangular	Overall
Intercept	0.3376	0.4991	0.4056	0.3744	0.3842
Coefficient	0.0638	0.0064	0.0550	0.0415	0.0505
R^2	0.3720	0.0016	0.1210	0.0175	0.0857

Figure 6.35 m and Log Size in Channel Shape Type

In general, as subbasin size increases, the m value increases as well (Figure 6.34). However, in subbasins larger than 100 square miles, the slope line is broken as has been shown in the b case. Since b and m are complementary and the correlation between b and m is strong, it is expected. The channel shape's role to m is insignificant; however, the braided channels have the highest R^2, 0.372, among all channel shapes.

6.7.3 Summary

In general, as subbasin size increases, the b value decreases, and f and m values increase. But there seems to be a break in size and b, f, and m trend lines around 100 square miles. The role of the channel shape is insignificant for b, f, and m, but the b values for rectangular and parabolic channels have higher R^2, 0.435 and 0.348, respectively. The rectangular channels are the highest R^2, 0.367, for the f values and, the braided channels ($R^2 = 0.372$) for the m values.

It is expected to find that channel shape does not strongly effect b, f, and m. That is, channel shape can be changed so easily and each hydrographic survey is a snapshot of the channel profile at a given time. Even though the number and duration of hydrographic surveys used in this study are high and span a long time frame (around 10 years), the hydrographic surveys are conducted without consideration of the channel's resumption to its normal shape. Therefore, the hydrographic survey might have conducted in various stages of return to normal channel shape from extreme conditions. Therefore, channel shape seems to be a clear-cut variable in a theoretical sense, but it is an obscure, hard to deal with indicator for investigating b, f, and m, unless the surveys are very controlled with consideration of the normalcy of the channel shape.

6.8 The Role of Channel Bed Material

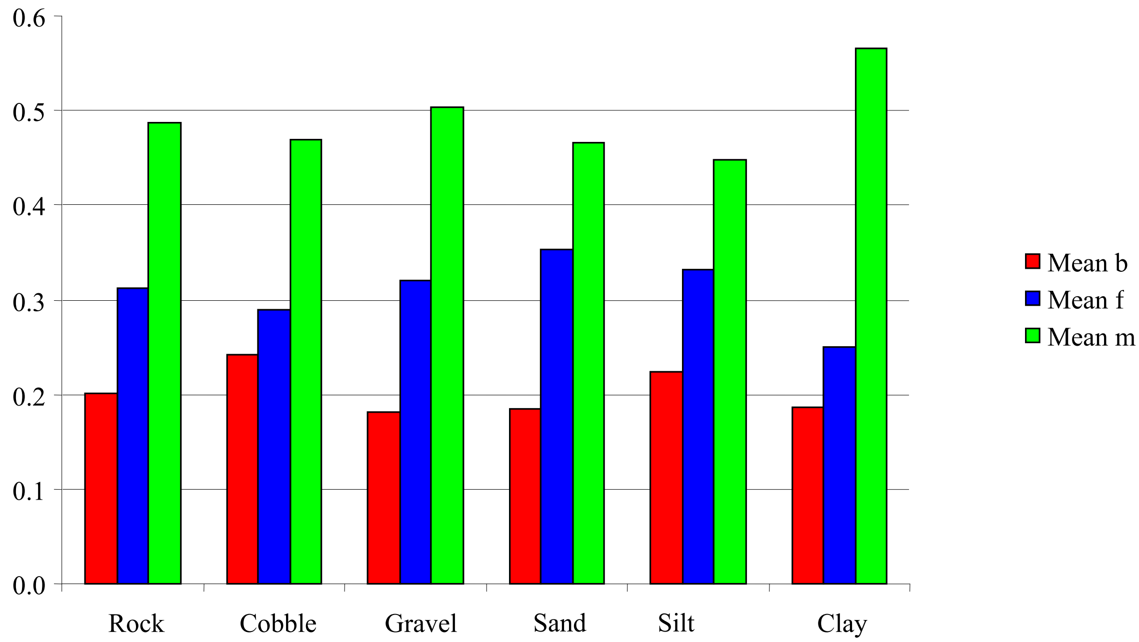
The main stem Potomac River and major tributaries generally have bedrock bottoms, with alluvial sediments in depositional areas. The study area stream-bottom materials range from bedrock to small cobbles and gravel in upstream areas, and from gravel, sand, and silt to eroded fine sediments in Coastal Plain streams.

From a rational point of view, the size and pattern/shape of a river channel at a particular point must represent a balance between erosive forces associated with water flow and with resistive forces associated with bed material size, bed structure, and bank cohesion. Variations in flow resistive forces produce not only different flow resistance magnitudes but also different rates of change of flow resistance at a site, therefore, different rates of changes in m.

Bathurst (1993) stated that at-a-station hydraulic geometry exponents differ among the different channel types and he approximated that for sand-bed channels, $m < 0.40$; for gravel-bed rivers, m = 0.35 – 0.45; for boulder-bed rivers, m = 0.45 - 0.55; and for steep pool/fall streams and pool-riffle sequence, $m > 0.55$. This pattern suggests an increase in the variation of flow resistance as the bed material size increases.

The six major channel bed material types present in the study region are: rock, cobble, gravel, sand, silt, and clay. Twenty two subbasins have rock channels; 17 cobble; 27 gravel; 16 sand; 2 silt, and 2 clay bed channels[10]. The comparison of the b, f, and m average values for the various bed materials are graphed in Figure 6.36.

[10] The channel bed material of each subbasin is identified by visual inspection by the author's field trip and the USGS field notebook. In the case of multiple bed material subbasins, each type of bed material is counted as a separate subbasin, therefore the subbasin sample size increased to 86 subbasins.



	Rock	Cobble	Gravel	Sand	Silt	Clay
N	22	17	27	16	2	2
Mean b	0.2014	0.2421	0.1813	0.1844	0.2234	0.1871
Mean f	0.3125	0.2899	0.3202	0.3536	0.3313	0.2495
Mean m	0.4873	0.4692	0.5032	0.4667	0.4478	0.5657

Figure 6.36 Average b, f, and m Values by Bed Material

6.8.1 Each Bed Material Type's Influence

The influence of bed material on b, f and m values is examined using a t-test for difference of mean values. Using a 0.05 % test, sand for f is statistically discernable; for a 0.1% test, gravel is statistically discernable for b (Table 6.26)[11]. Comparing subbasins with sand and non-sand channel beds, the mean difference of f is greater than the t-critical value at the 0.05 level (Table 6.26). Therefore, it can be concluded that there is a

[11] The critical value for t with 84 sample size at 0.02 is 2.374, at 0.05 level 1.990, and 0.1 level 1.665, 0.2 level, 1.293; and 0.5 level, 0.678.

discernable difference in f values between the sand and the other bed material channels at 0.025 level. The mean difference of the b value in the gravel beds is bigger compared with other bed material types, but not significant at the 0.05 level.

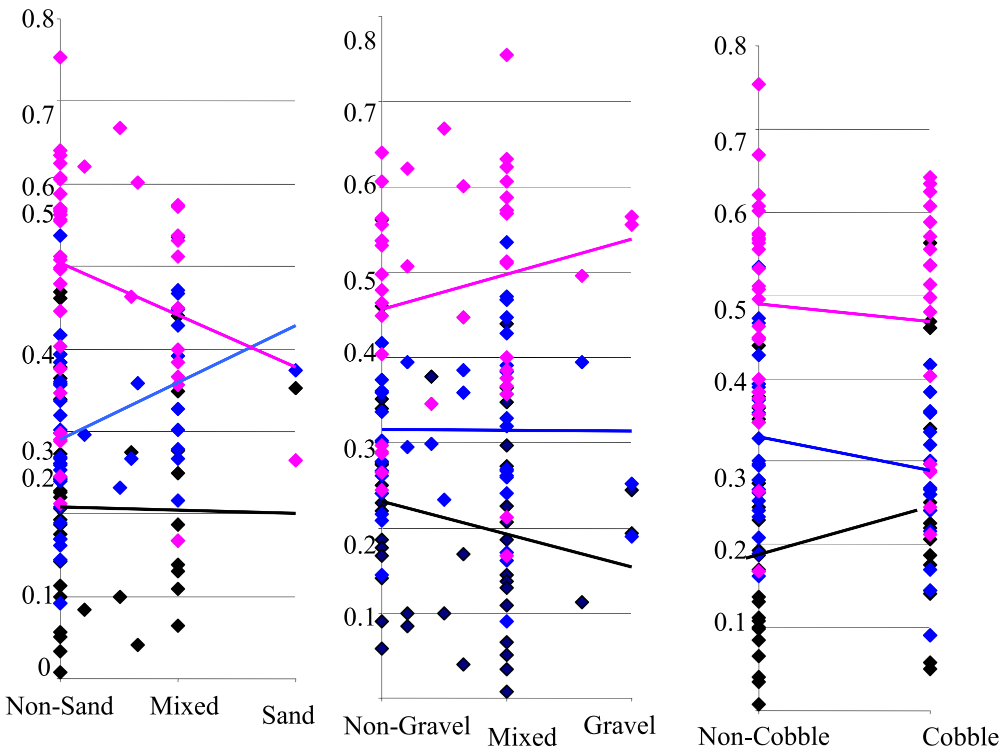


Figure 6.37 Mean Differences between Sand, Gravel, and Cobble vs. Other Bed Material

Table 6.26 Differences of Mean b, f, and m within Each Bed Material

	Number of Subbasins	Mean b	Mean b Difference	Mean f	Mean f Difference	Mean m	Mean m Difference
Rock	22	0.2014		0.3125		0.4873	
Non-Rock	21	0.2137	0.0123	0.3160	0.0035	0.4750	0.0123
t-test			-0.2977		-0.1135		0.3973
Cobble	17	0.2421		0.2899		0.4692	
Non-Cobble	26	0.1847	0.0574	0.3300	0.0401	0.4891	0.0199
t-test			1.3837		-1.2830		-0.4618
Gravel	27	0.1813		0.3202		0.5032	
Non-Gravel	16	0.2514	0.0701	0.3041	0.0161	0.4443	0.0589
t-test			**-1.6895**		0.4995		1.3774
Sand	16	0.1844		0.3536		0.4667	
Non-Sand	27	0.221	0.0366	0.2908	0.0628	0.4899	0.0232
t-test			-0.8611		**2.0425**		-0.5337
Silt	2	0.2234		0.3313		0.4478	
Non-Silt	41	0.2066	0.0168	0.3133	0.018	0.482	0.0342
t-test			0.1707		0.2421		-0.3425
Clay	2	0.1871		0.2495		0.5657	
Non-Clay	41	0.2084	0.0021	0.3173	0.0678	0.4817	0.084
t-test			-0.2169		-0.9264		0.8455

Note: Statistically significant at the 0.05 level is highlighted in underlined **b**old, and the 0.1 level and less in **b**old.

Considering channel bed material only, everything else being equal, the expected order of b and f change is sand, gravel, cobble, and rock in the order of easiest to hardest to erode. It is also expected that, unlike bank material, bed material would influence f more than b. Table 6.27 illustrates the comparative erodability among the different lithologies, one being the lithology that is easiest to be changed, and five being the most resistant. As stated in the Physiography section, the expected m order would be the inverse of order of b and f.

Table 6.27 Bed Material Based Mean b, f, and m Values and Expected b, f, and m Changes

	N	Expected Order of b and f Changes	Observed b	Observed f	Expected Order of m Changes	Observed m
Rock	22	4	0.2014	0.3125	1	0.4873
Cobble	17	3	0.2421	0.2899	2	0.4692
Gravel	27	2	0.1813	0.3202	3	0.5032
Sand	16	1	0.1844	0.3536	4	0.4667

Source: Inferred from Bathurst’s (1993) finding.

In general, an increase in stream discharge or channel depth results in a decrease in the bed materials’ relative roughness and, thus, in the resistance resulting in higher m values. For sand-bed channels, however, the accompanying increase in stream power with increased water discharge can also produce a change in bed form, from plane bed to ripples to dunes. The mean m value of the 16 sand bed channel profiles illustrates this point by having low m values compared to the other channel bed types.

The effect of decreasing channel bed relative roughness is, therefore, partly offset by the effect of increasing bedform drag, producing a relatively restrained rate of increase of flow velocity with higher discharge (Richards, 1982). The channel profile of m48 shows that the bedform is not smooth. However, the high flow submerged these riffle or sand dune bedforms, with resultant m values as high as 0.668. The other example is the v38 channel profile case. Here the flow is low and the uneven bedform has caused high bedform drag which caused the mean m value to be as low as 0.1676.

In gravel-bed (containing both gravel and cobble and gravel and rock) channels, drops in flow resistance are achieved by the drowning of roughness elements as discharge rises, therefore causing high m values in all gravel channels. Subbasins v52 and v19 both had low flows during the study period, and exhibit low m values, 0.212 and 0.346, respectively. On the other hand, in gravel-bed channels not much bedform development is expected, therefore, the b values are low and the flow velocity increases at a faster rate (Table 6.27).

In rock-bed channels, the rate of increase in m is larger than for cobble channels because of greater contrasts between low- and high-flow conditions. At low flows, the rocks protrude through the flow, rock form drag is high, and only the low velocity zone between the rocks is subject to bedform changes. As discharge increases, the rock bed channels are expected to have the highest m values among the different bed material types because of drowning rough bed material and smoothing the roughness. As expected, the exponent m increases in value, moving up the network from sand bed channels, via gravel, cobble and boulder bed channels (Bathurst, 1993) except the gravel bed (Table 27). The gravel beds have the highest m value, 0.5032, which is higher than cobble and rock bed channels. Excluding the two lowest m value subbasins, m31 and m311, the rock channel beds would have the highest mean m value and follow the expectation of being high m value channels. The m31 and m311 subbasins have meander channel patterns which are expected to have high b and low m values. With highest b values of the study area, the stream power must have been consumed by making rapid changes of channel width, resulting in low m values. Also, it can be explained that these two subbasins did not reach high flows which would drown out the ripple and ponding effects.

6.8.2 b, f, and m and Channel Bed Material in Scale Context

The influencing role of the channel bed material to b, f, and m in a scale context is investigated by setting the model, b (f, m) = $a_{0.b}$ ($a_{0.f}$, $a_{0.m}$) + $a_{1.b}$ ($a_{1.f}$, $a_{1.m}$)* $\log_{10}$ (size) + $a_{2.b}$ ($a_{2.f}$, $a_{2.m}$)* channel bed material variable. The null hypothesis is that the geographical scale of the subbasins and channel bed material have no bearing on the b, f, and m values.

b Exponents (Figure 6.38 and Table 6.28)

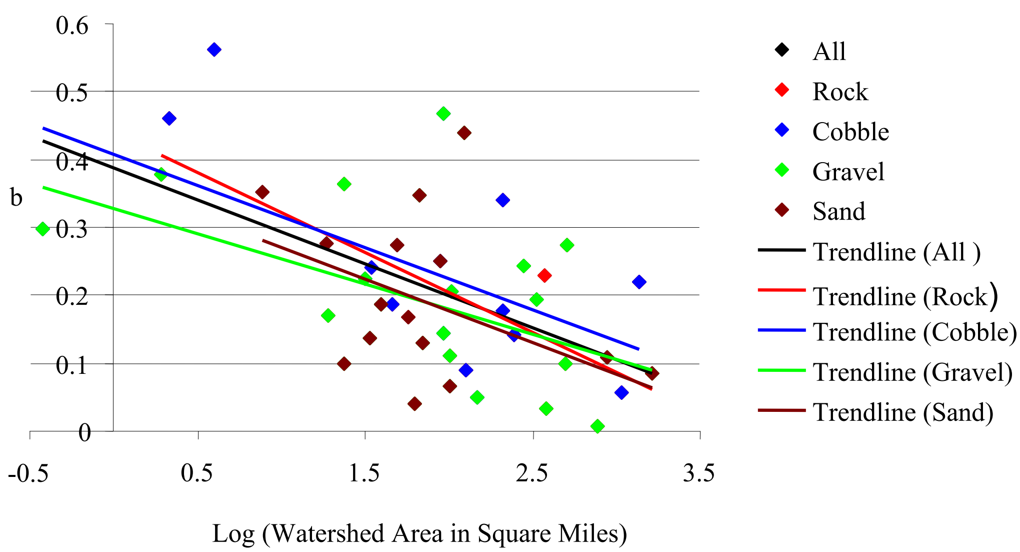
As expected, the computed value of $a_{1.b}$, -4.440, exceeds the critical values for level at $\alpha = 0.00007$, but $a_{2.b}$, -1.1037, does not exceed the critical value even at the 0.1 level. Therefore it is concluded that channel bed material is an insignificant variable to influence b at the 0.1 level. Adding an interaction term to the model, R^2 increases very little, but the bed material's role on b becomes less significant. Therefore, it is concluded that the role of the channel bed materials is an insignificant influence on b values.

Table 6.28 b and Subbasin Log Size and Bed Material

Dep Var: b	N:43		R^2: 0.3110
	df	F-ratio	P
Log Size	1	18.512	**0.000**

Dep Var: b	N:43		R^2: 0.3309
	df	t-value	P
Log Size	1	-4.4400	**0.0001**
Bed Material	5	-1.1037	0.2763

Dep Var: b	N:43		R^2: 0.3399
	df	t-value	P
Log Size	1	-2.3322	**0.0249**
Bed Material	5	-1.0682	0.2920
Bed Material * Log Size	5	0.7311	0.4691



	Rock	Cobble	Gravel	Sand	Silt*	Clay*	Overall
N	22	17	27	16	2	2	86
Intercept	0.4391	0.4071	0.3274	0.3617	-14.8718	-0.6665	0.2333
Coefficient	-0.4173	-0.0917	-0.0743	-0.0924	11.518	0.5553	-0.0944
R^2	0.4833	0.3312	0.2015	0.2087	1.0000	1.0000	0.3111

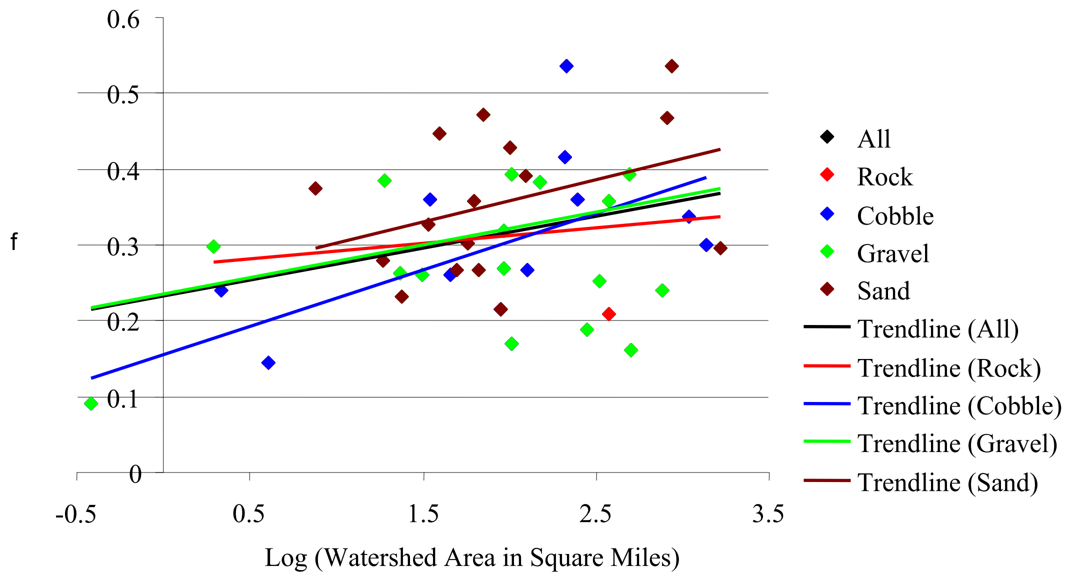
Figure 6.38 b and Subbasin Log Size in all Channel Bed Materials
Note: Since silt and clay have only 2 subbasins each, they are excluded from the analyses.

f Exponents (Figure 6.39 and Table 6.29)

The computed value of $a_{1.f}$, 2.416, exceeds the critical values for α = 0.021, but $a_{2.f}$, -1.212, does not exceed the critical value at the 0.1 level. Therefore, it is concluded that channel bed material is an insignificant variable to influence f. Adding an interaction term to the model, the R^2 increased but the influencing role of bed material on f worsened from a 0.233 level to a 0.592 level. Even though there is a correlation between f and sand bed channels at the 0.05 level, the overall influencing role of bed materials on f is statistically indiscernible.

Table 6.29 f and Subbasin Log Size and Bed Material

Dep Var: f	N:43	R^2: 0.1090	
	df	F-ratio	P
Log Size	1	5.021	**0.0310**
Dep Var: f	N:43	R^2: 0.1407	
	df	t	P
Log Size	1	2.4160	**0.0204**
Bed Material	4	-1.2118	0.2327
Dep Var: f	N:43	R^2: 0.9595	
	df	t	P
Log Size	1	1.4112	0.1661
Bed Material	4	0.5409	0.5917
Bed Material * Log Size	4	-1.0029	0.3221



	Rock	Cobble	Gravel	Sand	Silt*	Clay*	Overall
Intercept	0.2716	0.1560	0.2358	0.2464	-14.1390	0.6212	0.2333
Coefficient	0.0201	0.0744	0.0429	0.0559	11.3777	-0.1214	0.0420
R^2	0.0374	0.3982	0.1035	0.1346	1.0000	0.2582	0.1091

Figure 6.39 f and Subbasin Log Size in all Channel Bed Material Types
Note: Since silt and clay have only 2 subbasins each, they are excluded from the analyses.

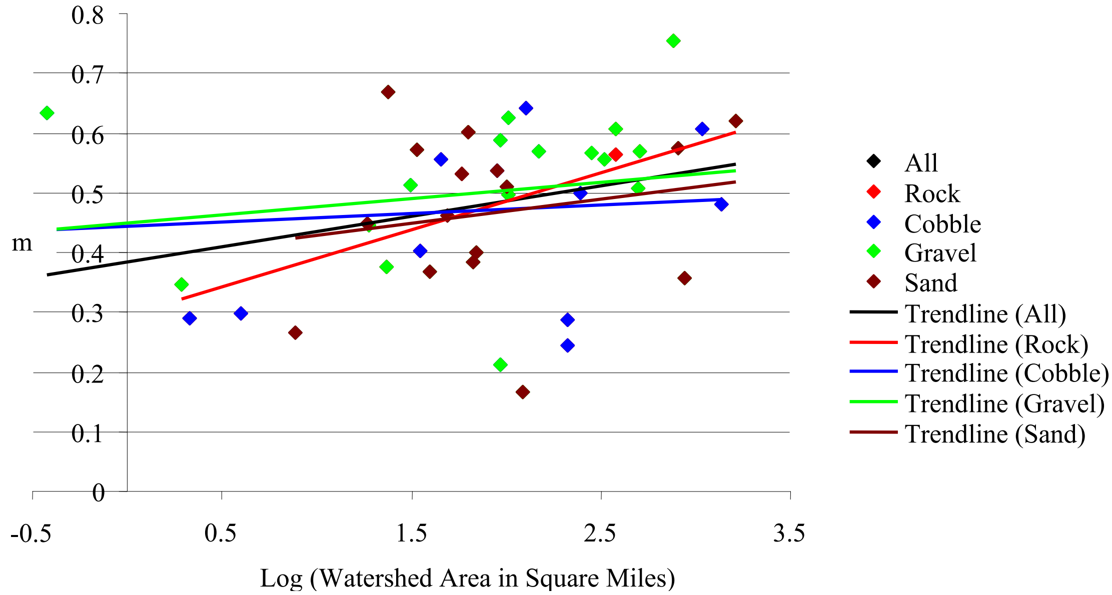
m Exponents (Figure 6.40 and Table 6.30)

The computed value of $a_{1.m}$, 1.900, exceeds the critical values for level at α = 0.0646, but $a_{2.m}$, 0.0096, does not exceed the critical value at the 0.1 level. Therefore, it is concluded that the null hypothesis for $a_{1.m}$ is rejected and that subbasin scale influences m at the 0.1 level of significance, but the channel bed material is an insignificant variable to influence m. Adding an interactive term to the model, the R^2 improved and the role of the bed material improved to 0.2586 from 0.9924. But in general, as shown in Figure

6.40, as subbasin size increases, the m values increase as well. However, the relationship is not strong; actually the role of the bed material is weaker than f or b.

Table 6.30 m and Subbasin Log Size and Bed Material Types

Dep Var: m	N:43	R^2: 0.0858	
	df	F-ratio	P
Log Size	1	3.843	0.0570
Dep Var: m	N:43	R^2: 0.0857	
	df	t	P
Log Size	1	1.9004	0.0646
Bed Material	4	0.0096	0.9924
Dep Var: m	N:43	R^2: 0.1190	
	df	t	P
Log Size	1	1.8126	0.0776
Bed Material	4	1.1465	0.2586
Bed Material * Log Size	4	-1.2134	0.2323



	Rock	Cobble	Gravel	Sand	Silt*	Clay*	Overall
Intercept	0.2938	0.4431	0.4496	0.3891	0.7352	-0.2867	0.3842
Coefficient	0.0954	0.0145	0.0272	0.0404	-0.2260	0.3058	0.0505
R^2	0.3660	0.0079	0.0248	0.0344	1.0000	0.4359	0.0857

Figure 6.40 m and Subbasin Log Size in all Channel Bed Material Types
Note: Since silt and clay have only 2 subbasins each, they are excluded from the analyses.

6.8.3 f > m in Sand Bed with Increasing Stream Discharge

As an empirical theory, it is known that, in sand bed channels, the change rate of depth is greater than that of velocity as discharge increases. To test this, the null hypothesis is set so that the change rate of depth is not greater than that of velocity as discharge increases, such that H_0: $f - m < 0$. Sixteen study area channels are categorized as sand bed channels, and 12 of these have 50% or more sand content in the channel bed.

Difference of means analysis of f – m values between sand beds with any amount of sand and non-sand bed indicates that sand beds are statistically insignificant at the 0.1

level. However, the mean difference analysis indicates that sand beds with 50% or more sand versus non-sand beds are statistically significant at the 0.1 level (actually significant at the 0.02 level). It is concluded that the role of sand bed with 50% or more sand content is statistically significant for the values of f - m. The higher the channel bed sand content, the rates of channel depth changes are greater than that for flow velocity (Figure 6.41). The average f - m values for the total 16 sand beds is -0.1131, and -0.0507 for sand beds with 50% or more sand content.

The t-value between H_0 mean, 0.000, and that of the beds with 50% or more sand, -0.05071, is statistically insignificant (0.3727 level). Therefore, H_0 cannot be rejected for f – m < 0 when the bed is composed of 50% or more with sand (Figure 6.42). Even though the empirical theory is not applicable in this study area, the study trend shows that depth increases faster is consistent (Table 6.31).

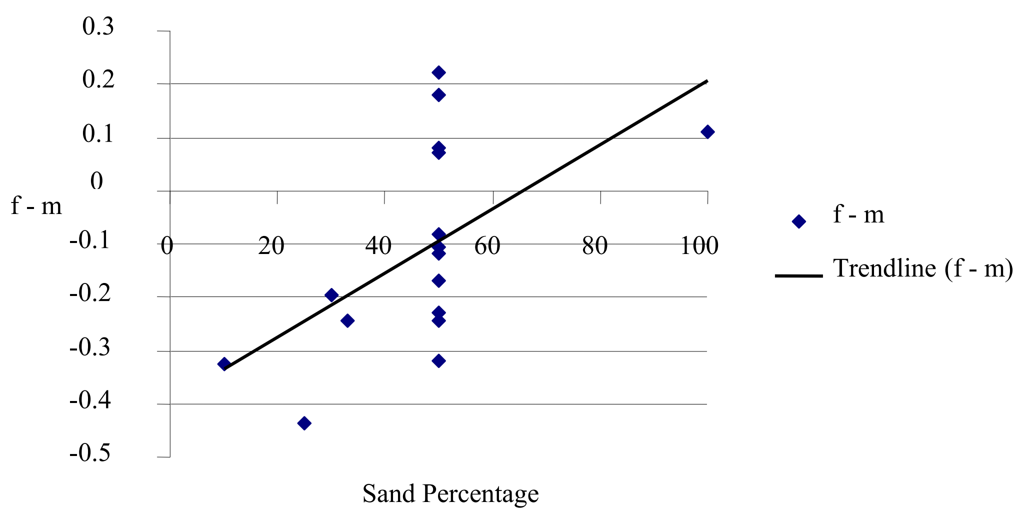


Figure 6.41 f – m Analysis in Sand Bed Channel

Table 6.31 Differences of Mean f - m Values in Sand Beds and all Study Channel Beds

	N	Mean f – m	R^2	t	Probability	Mean f - m Difference
Sand	16	-0.1131				
Non-Sand	27	-0.1991				0.0860
t-test				1.3894	0.230	
Sand > 50%	12	-0.0507				
Non-Sand > 50%	31	-0.2121			**0.030**	0.1614
t-test				2.5451		
H_0		0.0000				
Sand > 50%	12	-0.0507	0.0801	0.9332	0.3727	
Log Size			0.0251	0.5077	0.6227	
Sand > 50% & Log Size			0.2137			
Log Size				1.2368	0.2475	
Sand > 50%				1.4694	0.1758	

Adding the scale factor to the regression of sand > 50% bed channels and f – m value, the R^2 become 0.2137 from 0.0801 for just sand > 50% bed material and f – m. The R^2 for log size and f – m values in sand > 50% bed is 0.0251 (Table 6.31). This indicates that combination of scale and sand > 50% substantially contributes the R^2 value. In the scale context, the t test indicates that the statistical significance of the sand > 50% to f – m value improved to 0.1758 from 0.3727. Therefore, it can be concluded that there is no discernable differences between f and m in the study area channels and scale factor is statistically insignificant but with the combination of scale and sand > 50% influence f – m at the 0.1758 level.

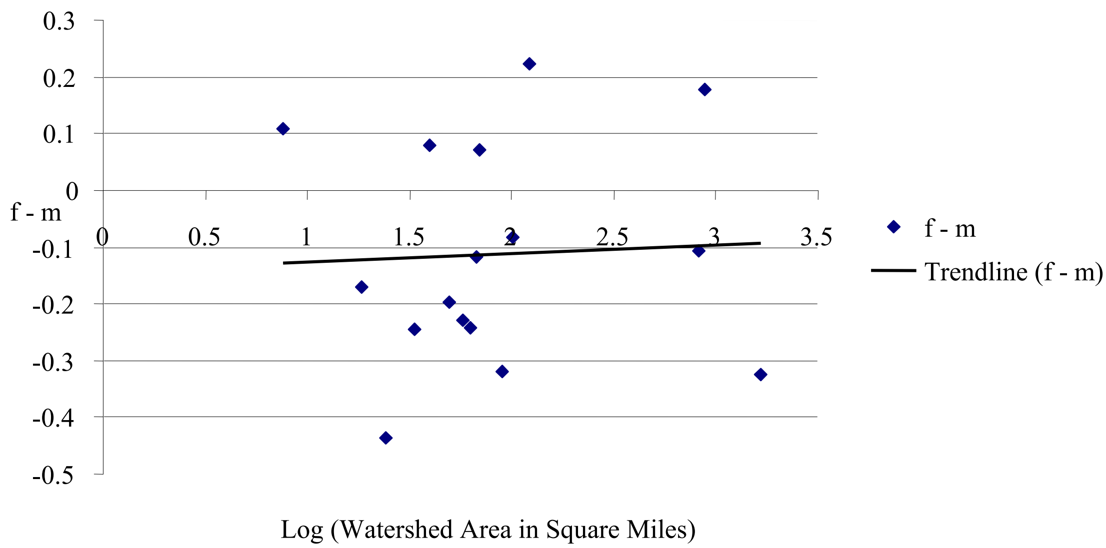


Figure 6.42 f – m and Subbasin Size in All Sand Bed Channels

6.8.4 Empirical Theory, f < m in Gravel Bed with Increasing Stream Discharge

Another empirical theory, in gravel bed channels, that the change rate of flow velocity is greater than that of channel depth as discharge increases, is examined in a scale context. Similarly to sand beds, the null hypothesis is set so that the change rate of velocity is not greater than that of depth as discharge increases, such that H_0: f – m > 0. Twenty seven study area channels are categorized as gravel bed channels, and 21 of these have 50% or more gravel content in the channel bed.

Difference of means analysis between gravel and non-gravel beds for the f – m value indicates that the difference is statistically insignificant at the 0.1 level[12]. The t-test of the difference of means between gravel >50% and non-gravel beds demonstrated that

[12] The calculated t value is -0.8060 and the critical value for t with 2 degrees of freedom at the 0.05 level is 2.021 and the 0.1 level is 1.684.

the f – m values are much less significant. Clearly, f < m can be explained by the suppressed resistance of the water flow from increased stream discharge, which makes the velocity increases greater than the channel depth change rate. However, the hypothesis that in gravel channel, the f - m > 0, is statistically non-supportive in the study area. In general, the study area channels have higher m values than f. The average f - m value for subbasins with gravel bed is -0.1830, and -0.1767 for the subbasins where 50% or more of the bed content is gravel. The higher the channel gravel content, the rates of the velocity become greater than depth changes (Figure 6.42 and Table 6.32). The slope of the linear relationship between the content of gravel in the bed and the f – m values is -0.00086 (Figure 6.43 and Table 6.32).

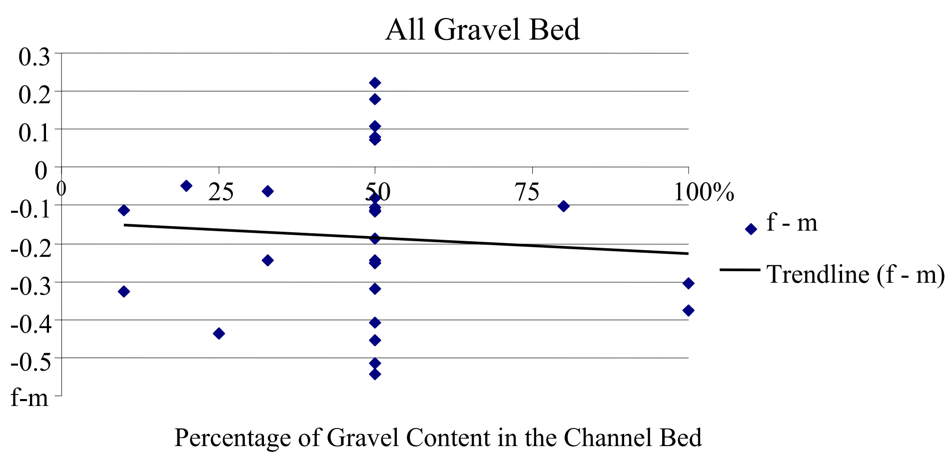


Figure 6.43 f – m Analysis in Gravel Bed Channel

Table 6.32 Differences of Mean f - m Values in Gravel and All Non-Gravel Channel Beds

	N	Mean f – m	R^2	t	Probability	Mean f - m Difference
Gravel	27	-0.1830				
Non-Gravel	16	-0.1402				0.0282
t-test				-0.6788		
Gravel>50%	21	-0.1767				
Non-Gravel>50%	22	-0.1579				0.0188
t-test				-0.3093		
H_0		0.0000				
Gravel>50%	21	-0.1767	0.0395	-0.8836	0.3879	
Log Size			0.0264	0.7183	0.4813	
Gravel & Log Size			0.0817			
Log Size				0.9097	0.3750	
Gravel>50%				-1.0407	0.3118	

Examining gravel bed channels and f – m values in a scale context, the influence of scale to the f – m in gravel bed channels is statistically insignificant (0.4813 level), and much less significant than gravel > 50% for f – m values. As expected, with both gravel 50% and scale, the R^2 improved and both gravel > 50% and scale's roles became more statistically significant, but still not significant at the 0.1 level. By visual inspection (Figure 6.44), it is easy to conclude that subbasin scale factor is insignificant, especially since there is no correlation around the subbasins of about 100 square miles. Beyond that size the trend line may well differ from those of subbasins smaller than 100 square miles.

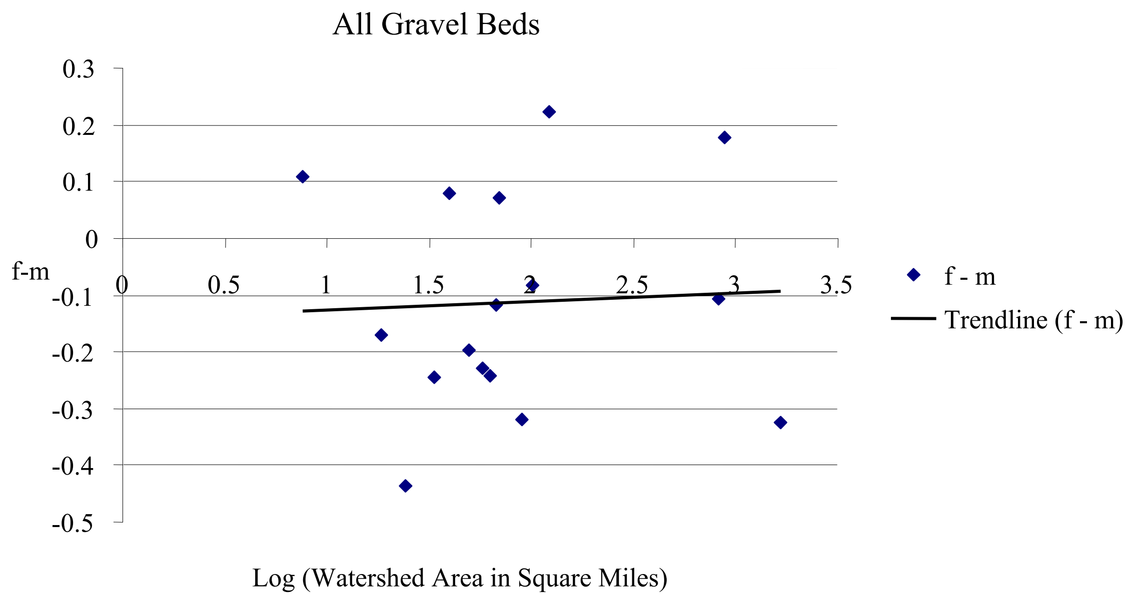


Figure 6.44 f – m Relation in All Gravel Bed Channels

6.8.5 Summary

Comparing difference of means values, it is found that f values are statistically discernible between sand and non-sand bed channels. The differences of b means between cobble and non-cobble channels as well as the difference of b and m means in gravel and non-gravel channels are also found to be sufficiently different. In the geographic scale context, even though there are statistically significant correlations between scale and b, f, and m, the overall influencing role of bed materials on b, f, and m is indiscernible.

The role of sand bed is statistically significant for f > m and, the higher the sand content in the channel bed, the rates of the depth changes are greater and the difference of f > m gets smaller. Adding the scale factor to the regression of sand bed channels and f –

m, the sand bed material is statistically insignificant at 0.1 level, and scale became further insignificant.

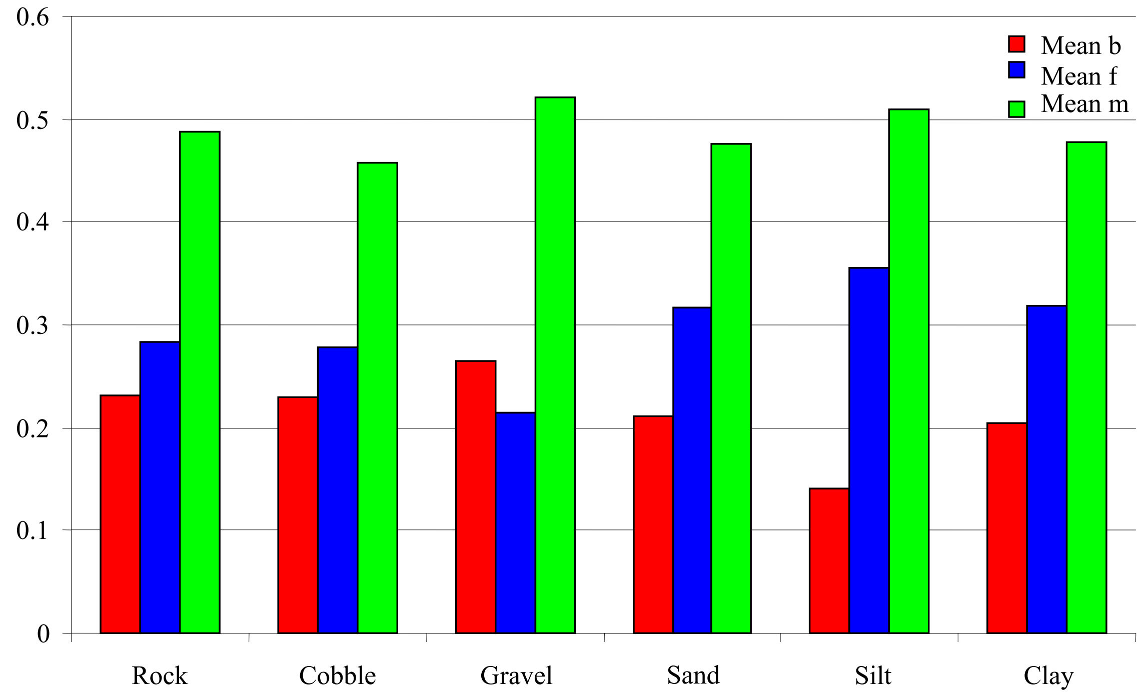
Investigating the empirical theory, that the change rate of depth gets greater than that of velocity as discharge increases in sand bed channels, it is found that the role of sand beds with 50% or more sand content is statistically significant, and that the rates of channel depth changes are greater and the difference of f – m gets smaller. However, the rates of the depth changes in these sand > 50% channels are not greater than that for flow velocity within the entire study area.

Investigation of gravel bed channels confirms the empirical theory that the change rates of flow velocity is greater than that of channel depth as discharge increases. Examining the gravel bed channels and f – m values in a scale context, it is found that the influence of scale on the f – m in gravel bed channels is statistically insignificant. The higher the channel gravel content, the differences between the rates of flow velocity and channel depth changes become greater.

6.9 The Role of Channel Bank Material

The study region encompasses six major channel bank material types; nine subbasins have rock channels; 12 cobble; 3 gravel; 30 sand; 11 silt, and 4 clay bed channels[13]. Since the gravel and the clay bank material channels are represented by only 3 and 4 subbasins, these two bank materials are excluded from the analyses. The comparative analysis of the b, f, and m average values for the various bank materials are graphed (Figure 6.45).

[13] The channel bed material of each subbasin is identified by visual inspection by the author's field trip and the USGS's field notebook. In case of multiple bed material subbasins, each bed material is counted as a separate subbasin, therefore the 43 subbasin sample size increased to 69 subbasins.



	Rock	Cobble	Gravel	Sand	Silt	Clay
N	9	12	3	30	11	4
Mean b	0.231	0.229	0.2629	0.2104	0.1403	0.2052
Mean f	0.2831	0.2775	0.2148	0.3167	0.3547	0.3178
Mean m	0.4875	0.4583	0.5212	0.4753	0.5093	0.4779

Figure 6.45 Average b, f, and m Values by Bank Material
Note: Since gravel and clay have only 3 and 4 subbasins, respectively, they are excluded from the analyses.

6.9.1 Each Bank Material Type's Influence

The influence of bank material on b, f and m values is examined using a t-test for difference of mean values. Comparing subbasins with the silt and non-silt banks, the mean differences of b are the greatest among all other bank material type channels. Using a 0.1 % test, silt for b is statistically discernable, cobble for f and silt for f (Table 6.33)[14], are insignificant at the 0.1 level.

[14] The critical value for t with sample size of 62 at the 0.01 level is 2.488; at 0.05 level, 1.99, and 0.1 level 1.665.

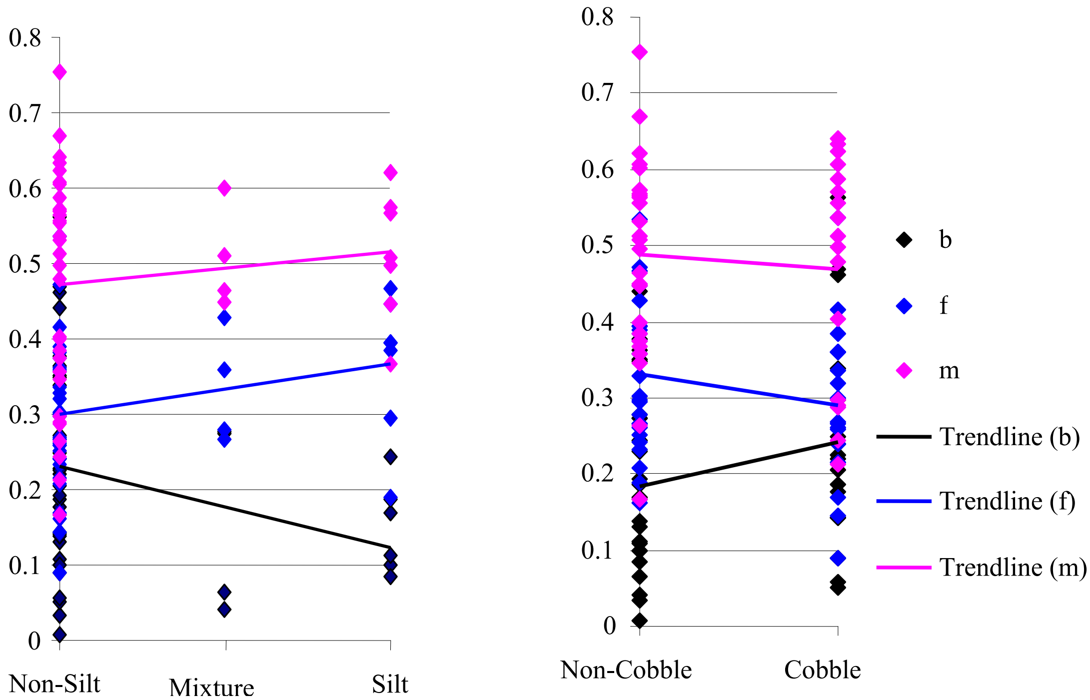


Figure 6.46 Mean Differences between Silt and Cobble vs. Other Bank Material

Table 6.33 Differences of Mean b, f, and m within Each Bank Material

	Number of Subbasins	Mean b	Mean b Difference	Mean f	Mean f Difference	Mean m	Mean m Difference
Rock	9	0.2310		0.2831		0.4875	
Non-Rock	53	0.2011	0.0299	0.3224	0.0393	0.4796	0.0079
t-test			0.5889		-1.0403		0.1518
Cobble	12	0.2290		0.2775		0.4583	
Non-Cobble	50	0.1990	0.0300	0.3284	0.0509	0.4812	0.0229
t-test			0.6511		-1.5018		-0.4800
Sand	30	0.2104		0.3167		0.4753	
Non-Sand	32	0.2004	0.0100	0.3084	0.0083	0.4951	0.0198
t-test			0.2221		0.2436		-0.4312
Silt	11	0.1403		0.3547		0.5093	
Non-Silt	51	0.2304	0.0901	0.3002	0.0545	0.4716	0.0377
t-test			**-1.986**		1.5705		0.7841

Note: The critical value for t with 2 degrees of freedom at the 0.01 level is 2.488; at 0.05 level, 1.99, and 0.1 level 1.665. The statistical significance level is 0.1 and les are in **Bold**.

Considering channel bank material only, everything else being equal, the expected order of b change is sand, gravel, cobble, and rock in the order of the easiest to erode to the most resistant (Table 6.34). In easily eroded bank material, a relatively wide shallow channel develops, while in cemented bank materials, the channel becomes deeper and narrower (Friedkin, 1945). In the case of flow velocity, as streams begin eroding their banks, their channel cross-sections become wide and shallow with consequent reduction of flow velocities (Friedkin, 1945).

Table 6.34 Bank Material Based Mean b, f, and m Values and Expected b, f, and m Changes

	N	Expected Order of b Change	b Values	Expected Order of f Change	f Values	Expected Order of m Change	m Values
Rock	9	4	0.2310	1	0.2831	4	0.4875
Cobble	12	3	0.2290	2	0.2775	3	0.4583
Sand	30	2	0.2104	3	0.3167	2	0.4753
Silt	11	1	0.1403	4	0.3547	1	0.5093

Source: Expected order of b, f, and m changes are inferred from the Friedkin (1945) and Bathurst's (1993) finding. The b, f, and m values are calculated by the author.

Contrary to the expected order of changes in b, rock banks have the highest rate of b and the 2nd lowest rate of f changes. Also, more resistant banks result in higher rates of m changes than less resistant banks. In easily erodable bank materials, a relatively wide shallow channel develops but in the study area small rates of width and bigger rates of depth changes occur. Since each bank, typically, is not of uniform material, but rather a mixture of materials, it is understandable that the observed results are different from the expected order of b, f, and m changes.

6.9.2 b, f, and m and Channel Bank Material in Scale Context

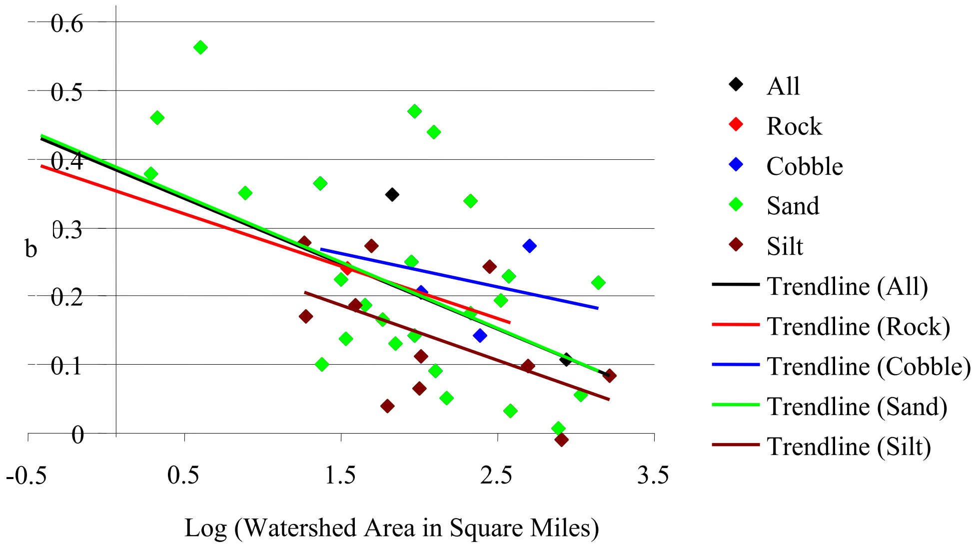
The role of the channel bank material relative to b, f, and m in a scale context is investigated by the model, b (f, m) = $a_{0.b}(a_{0.f}, a_{0.m}) + a_{1.b}(a_{1.f}, a_{1.m})$ * log10(size) + $a_{2.b}$ $(a_{2.f}, a_{2.m})$ * channel bank material variable. The null hypothesis is that the scale of subbasins and the channel bank material have no bearing on b, f, and m values.

b Exponents (Figure 6.47 and Table 6.35)

The computed t-test value of $a_{1.b}$, -3.960, exceeds the critical values for level at $\alpha = 0.0003$, but, the computed t-test value for $a_{2.b}$, -1.620, does not exceed the critical value at the 0.1 level (but exceeds it at 0.1132). Therefore, it is concluded that scale influences b, but channel bank material is not a significant predictor variable to influence b at the 0.1 level of statistical significance. Adding an interaction term to the model does increase the R^2, but the role of bank material degraded. Therefore, it is concluded that the interaction term does not explain the influence of bank material on b.

Table 6.35 b and Subbasin Log Size and Bank Material

Dep Var: b	N:69	R^2: 0.3105	
	df	t-ratio	P
Log Size	1	18.512	0.0000
Dep Var: b	N:69	R^2: 0.3529	
	df	t-value	P
Log Size	1	-3.9604	0.0003
Bank Material	5	-1.6195	0.1132
Dep Var: b	N:69	R^2: 0.3602	
	df	t-value	P
Log Size	1	-2.3322	0.2148
Bank Material	5	-1.0682	0.8859
Bank Material * Log Size	5	-0.6679	0.5081



	Rock	Cobble	Sand	Silt	Overall
N	9	12	30	11	69
Intercept	0.3577	0.3347	0.4300	0.3098	0.3889
Coefficient	-0.0758	-0.0485	-0.1151	-0.0813	-0.0944
R^2	0.4151	0.0505	0.3093	0.3014	0.3111

Figure 6.47 b and Subbasin Log Size in Channel Bank Materials

f Exponents (Figure 6.48 and Table 6.36)

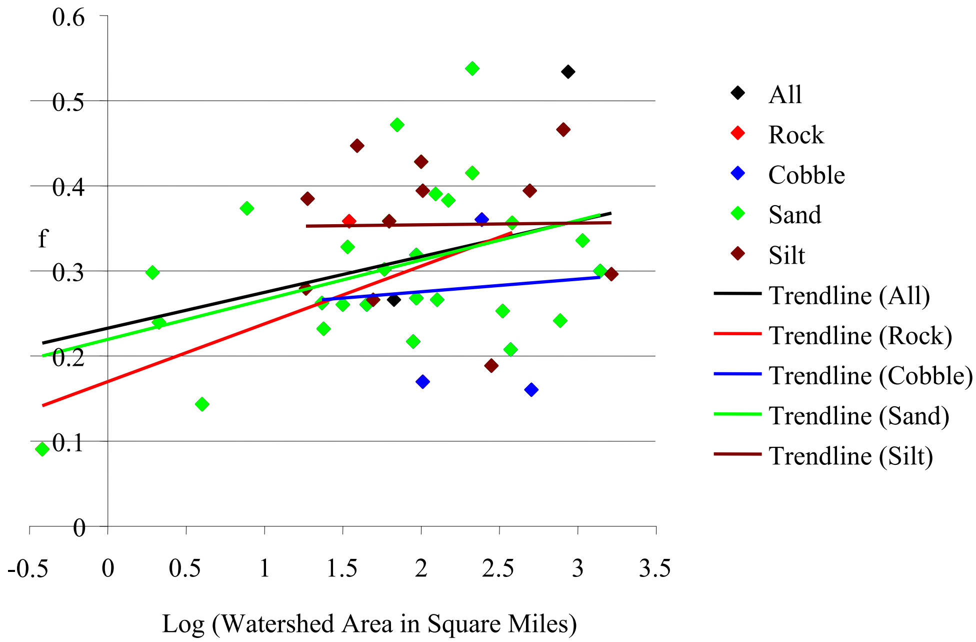
As expected, the computed t-test value of $a_{1.f}$, 2.01, exceeds the critical values for $\alpha = 0.0509$, which is not a surprise since systematic changes of f and scale exist. However, the t-test value for $a_{2.f}$, -1.235, does not exceed the critical value at the 0.1 level. Therefore, it is concluded that channel bank material is not a significant variable to influence f at the 0.1 level, which is statistically less significant compared to the relationship between b and channel bank materials. This is expected since bank material influences b more than f. There is a positive relationship between f and subbasin size, and specific bank material types and f values in a scale context are positive, but the intensity is not strong, as for overall bank material types and f values.

Since the influencing role of channel bank material on f is not significant, the interaction between scale and bank material is investigated by adding an interaction term to the model, f = $a_{0.f}$ + $a_{1.f}$ * log10(size) + $a_{2.f}$ * channel bank material + $a_{3.f}$ * log (size) * channel bank material. The statistical significance of the role of bank material type on f is significantly improved to the 0.0479 level. This indicates that variables channel bank material and scale clearly interact. Therefore, the interaction of the role of bank material to f values and geographic scale needs to be considered for the examination of the role of bank material on f.

Table 6.36 f and Subbasin Log Size and Bank Material

Dep Var: f	N:43	R^2: 0.1091	
	df	t-test	P
Log Size	1	2.241	**0.0310**
Dep Var: f	N:43	R^2: 0.1418	
	df	t-value	P
Log Size	1	2.0127	**0.0509**
Bank Material	5	-1.2351	0.2240
Dep Var: f	N:43	R^2: 0.1982	
	df	t-value	P
Log Size	1	-0.8486	0.4013
Bank Material	5	-2.0425	**0.0479**
Bank Material * Log Size	5	1.6551	0.1059

Note: The statistical significance level is 0.1 and les are in **Bold**.



	Rock	Cobble	Sand	Silt	Overall
N	9	12	30	11	69
Intercept	0.1698	0.2453	0.2451	0.3513	0.2333
Slope	0.0678	0.0148	0.0375	0.0016	0.0420
R^2	0.4607	0.0050	0.0779	0.0002	0.1091

Figure 6.48 f and Subbasin Log Size in Channel Bank Materials

m Exponents (Figure 6.49 and Table 6.37)

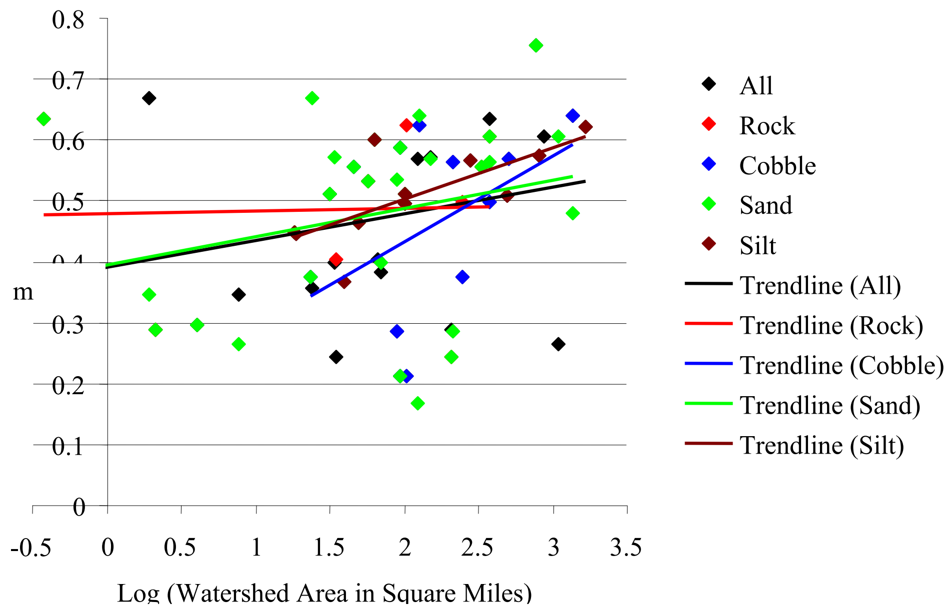
The computed t-test value of $a_{1.m}$, 1.87, exceeds the critical values for $\alpha = 0.069$, but the t-test value for the channel bank material term, $a_{2.m}$, 0.058, does not exceed the critical value at 0.1 level. Therefore, it is concluded that channel bank material alone is an insignificant variable influencing m. Overall, the relationship between m and bank material type in a scale context is positive. In particular, the relationships between silt banks and m (R^2 of 0.5227) are much stronger than the overall relationship.

Considering the interaction of geographic scale and bank material type, the role of bank material to m becomes significantly improved from the 0.954 to 0.119 level of statistical significance. At the same time, the statistical significance of scale impact on m deteriorates from a level of 0.069 to 0.413. This indicates that there is a strong interaction between subbasin scale and bank materials that influences m values, and this fact is clearly illustrated by having a 0.069 level for the interaction term, $a_{3.m}$ * log (size) * channel bank material. Therefore, when considering the role of bank material on m values, the interaction of subbasin scale and bank material needs to be taken into account.

In general, m values are high for all bank material types, especially silt channel banks where b values are low. This implies that, in addition to bank material, there are many more predictor variables such as channel pattern and shape that influence m values.

Table 6.37 m and Subbasin Log Size and Bank Material

Dep Var: m	N:43	R^2: 0.0857	
	df	t-test	P
Log Size	1	1.960	0.0570
Dep Var: m	N:43	R^2: 0.0858	
	df	t-value	P
Log Size	1	1.8689	0.0690
Bank Material	5	0.0577	0.9543
Dep Var: m	N:43	R^2: 0.1610	
	df	t-value	P
Log Size	1	-0.8281	0.4127
Bank Material	5	-1.5942	0.1190
Bank Material * Log Size	5	1.8703	0.0690



	Rock	Cobble	Sand	Silt	Overall
N	9	12	30	11	69
Intercept	0.4804	0.4212	0.3339	0.3332	0.3842
Coefficient	0.0043	0.0333	0.0742	0.0845	0.0505
R^2	0.0010	0.0140	0.1247	0.5227	0.0857

Figure 6.49 m and Bank Materials on Subbasin Log Size

6.9.3 Summary

Contrary to the expected order of changes in b, rock banks have the highest rate of b changes and the 2nd lowest rate of f changes. Since each bank, typically, is not of uniform material, but rather a mixture of materials, it is understandable that the observed results are different from the expect order of b, f, and m changes.

Scale influences b, f, and m, but channel bank material is not a significant predictor variable to influence b, f, nor m at 0.1 level of statistical significance, but adding interaction between scale and channel bank materials, the interaction term became statistically significant for m and f. Therefore, the interaction of the role of bank material to f and m values and geographic scale needs to be considered for the examination of the role of bank materials on f and m.

6.10 The Role of Channel Asymmetry (Figure 6.50 and Table 6.38)

Without consideration of the shifting direction of channels such as left or right, the relationships between b, f, and m values and channel asymmetry are examined. The relationships between the b, f, and m and channel asymmetry are not strong. The R^2 values for linear regression between b, f, and m and asymmetry are very low (under 3%). The slopes of the linear regression scatter plot between b and m and channel asymmetry are much steeper (almost 0.4) than that of f. The b values get bigger as channels become more asymmetrical and the m values get smaller. The f values do not have strong slope. The positive stronger relationship between b and asymmetry is expected because when the thalweg of channel moves from the center of the channel, the width of channel will inevitably change. Since stream power is consumed in widening the channel, the m must be reduced. It is expected that the overall depth does not have any net changes.

Even though the b and m regression slopes are steep, the b and m values are not statistically significant. However, the rate of m convergence is so small that b and m will converge and start to diverge before f completely converges into a common absolute asymmetry value. The trend is as the absolute asymmetry index gets bigger, around 0.25, the b values will be bigger than f values.

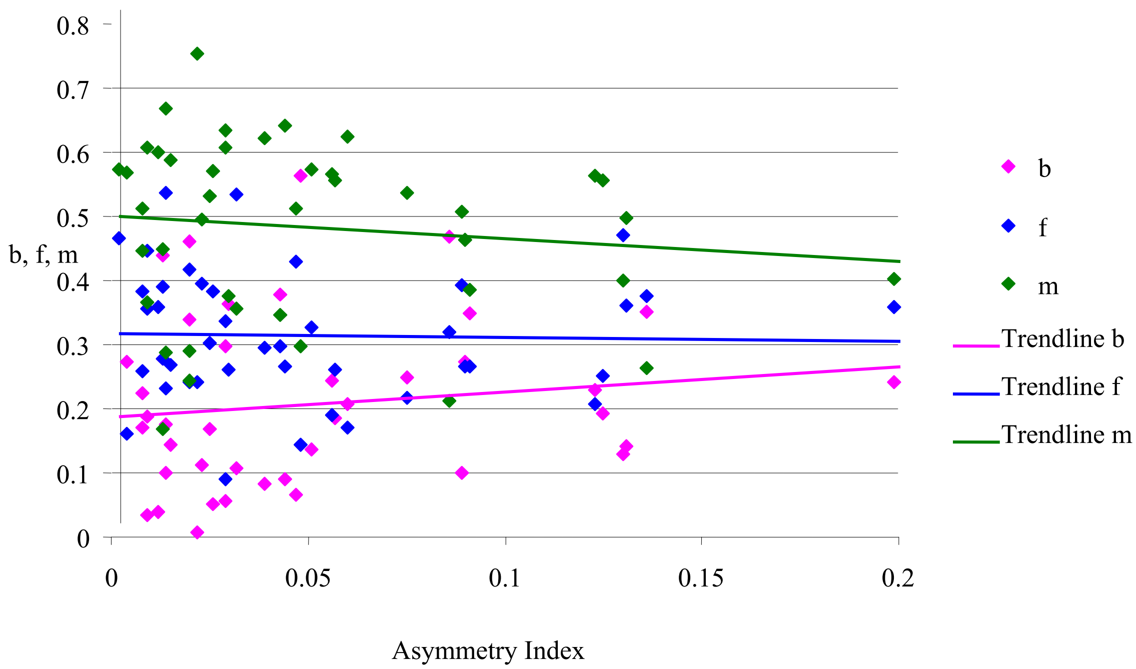


Figure 6.50 b, f, and m and Channel Asymmetry

6.10.1 b, f, and m and Channel Asymmetry in a Scale Context (Figure 6.51)

Introducing the scale of each subbasin to the relationship of b, f, and m with asymmetry, the R^2 relationships increased to over 0.354 for b and over 0.114 and 0.113 for f and m from 0.023, 0.001, and 0.018, respectively. It can be explained by observing the influence of scale on the b, f, and m. Since the R^2 between scale and b is 0.311, with a statistical significance of 0.0001level, the scale and asymmetry variables influenced b much more than asymmetry did by itself. Also, the statistical significance is improved by adding the scale variable, but the statistical significance is not at the 0.1 level in b (though the statistical significance of asymmetry's role on b is at the 0.11 level), and in the f and m cases, the role of symmetry and scale are insignificant at that level (Table 6.38).

Table 6.38 Statistical Significance of Asymmetry and b, f, and m Relationships

N = 43		Asymmetry	
	b	f	m
Log Size R^2	0.3105	0.1091	0.0857
Coefficient	-0.0940	0.0420	0.0500
Log Size: t	-4.3030	2.2410	1.9600
Log Size: p	0.0000	0.0310	0.0570
Asymmetry R^2	0.0227	0.0010	0.0177
Coefficient	0.3950	-0.0640	-0.3580
Asymmetry: t	0.9690	-0.2060	-0.8586
Asymmetry: p	0.3380	0.8378	0.3956
Log Size & Asymmetry R^2	0.3545	0.1137	0.1128
Log Size: t	-4.5360	2.2545	2.0715
Log Size: p	0.0001	0.0297	0.0448
Asymmetry: t	1.6504	-0.4531	-1.1063
Asymmetry: p	0.1067	0.6529	0.2752
Log Size - Log Size & Asym R^2	0.0440	0.0046	0.0271
Contribution*	0.0638	0.0052	0.0296

Note: Contribution is the ratio of the unexplained and the difference between R^2 of b, f, and m with log size and with log size and asymmetry combined.

The relationship between asymmetry and subbasin size is not strong; the independence of these two predictor variables are maintained for relationships of both predictor variables with b, f, and m. The contribution of scale is stronger for b than for f or m. The role of asymmetry for b, f, and m in a scale context is stronger on b than on f or on m.

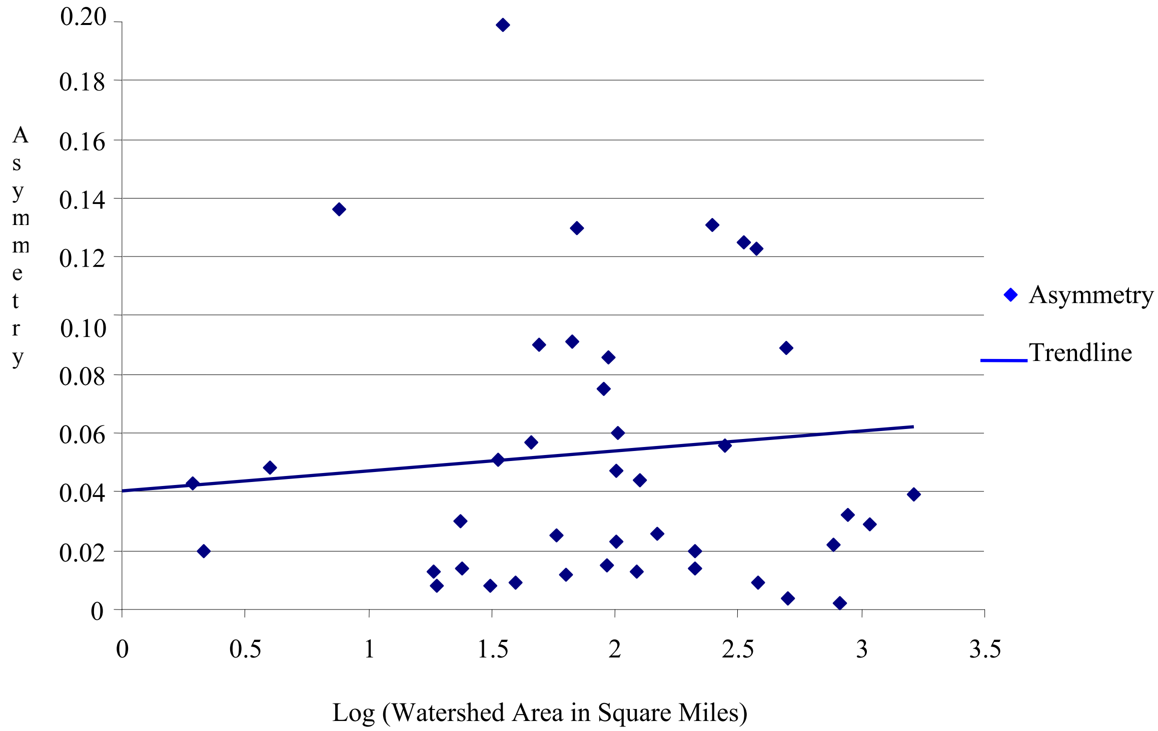


Figure 6.51 Subbasin Size versus Asymmetry

6.10.2 Summary

As expected, the relationship between b and asymmetry is the strongest among the hydraulic geometry exponents but, as a whole, the relationships between asymmetry and b, f, and m are weak, meaning that asymmetry is not a good predictor variable for b, f, and m. With the scale variable, the asymmetry variable and the b, f, and m exponents relationships become stronger than for asymmetry alone and the asymmetry's role on b becomes statistically significant at the 0.11 level, not quite at the 0.1 level. Therefore, it is concluded that the asymmetry predictor variable is still statistically insignificant at the 0.1 level.

6.11 The Role of Topographic Index

Topography is recognized as an important factor in determining the stream flow response of drainage. Topography determines the effects of gravity on the movement of water in the drainage, and therefore it influences many aspects of geomorphic and hydrologic systems. The energy of stream flow is determined by the slope of the surface. A steeper slope results in greater energy, and as the energy of a stream increases, its ability to transport more and larger particles also increases. Therefore, steeper slopes result in a greater potential for erosion. Topography has been shown to affect the flow path that precipitation follows before it becomes stream flow (Wolock, et al., 1990). And the shape of a surface determines how water will flow across it. Therefore, characterization of the topography of the subbasins should provide a significant dimension of information about the watershed setting. Four levels of topographic indices: topographic maximum, topographic minimum, topographic mean, and topographic standard deviation, are correlated with b, f, and m in a scale context.

6.11.1 Strength of the Relationship between Topographic Index and b, f, and m

As stated in Chapter 4, topographic indices characterize the ability for subbasins to contain and transport discharge and the discharge can be equated to the drainage size. The topographic index is considered as an important indicator effecting hydraulic geometry. The description of the topographic indices and the calculation of these indices have been reported in Chapter 4.

The relationships between the b, f, and m and any topographic index are not strong. The R^2 values (Table 6.39) for linear regression between b, f, and m and the topographic index are very low (under 0.1). The R^2 between b and the topographic index is stronger than that f and m (Figure 6.52), and the statistical significance of the topographic indices' role on b is much stronger than that for f and m. It is expected that because the topographic index is, in a way, a measurement of saturation capacity, and the wetness of both sides of a channel bank is gradually decreasing from the stream, but when as a flow runs over the previous bank, the side of channel banks will easily be saturated and the banks will be easily eroded and so width increases. If the channel banks are saturated then the stream power can be applied to erode the channel banks and therefore, b can be changed.

The roles of a topographic index on other exponents are weak, but the role of the topographic index on b is statistically significant at the 0.005 level for the maximum and standard deviation of the topographic indices and minimum topographic index, and the b relationship is statistically significant at 0.104 level (Table 6.39).

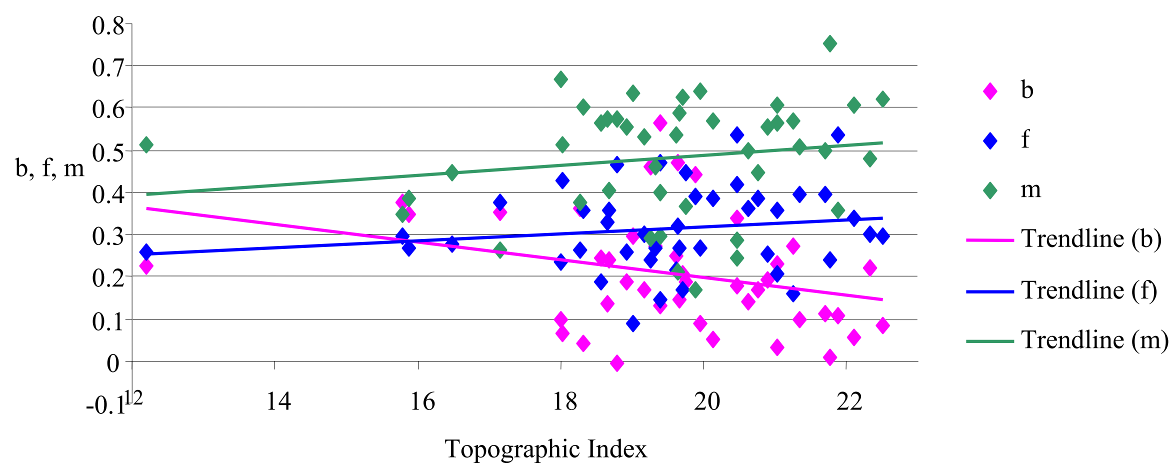


Figure 6.52 b, f, and m and Topographic Index

6.11.2 b, f, and m and Topographic Index in a Scale Context (Table 6.39)

Introducing the scale of each subbasin to the relationship of b, f, and m with the topographic index improved the R^2. It is expected that the relationship increases in multi-variable regression than that of single variable regression. However, the increased R^2 are mainly due to the scale variable; the contributions of topographic indices to the R^2 are under 2%, except the b and minimum topographic index (2.3%). The topographic variable impact is very low.

Even including the scale variable, none of the topographic indices became statistically significant, at least at the 0.1 level. The 0.05 level of statistically significant relationship between topographic index maximum and topographic index standard deviation b became insignificant with scale predictor variable included.

To determine the relative importance of topographic index variable in predicting b, f, and m, standard partial regression coefficients are calculated. The magnitudes of the coefficients (scale = 0.311 and topographic index maximum = 0.095) indicate that scale has approximately three times as much effect on predicted b as do the topographic index variables. The R^2 difference between the multi-regression of the scale and topographic index maximum and the single regression of topographic index maximum and b is 0.0003 which is very insignificant and the difference contributes 0.0004 of the variation left unexplained.

Table 6.39 Statistical Significance of Topographic Indices and b, f, and m Relationships

N = 43	Topo Index Min			N = 43	Topo Index Max		
	b	f	m		b	f	m
Log Size R^2	0.3105	0.1091	0.0857	Log Size R^2	0.3105	0.1091	0.0857
Coefficient	-0.0940	0.0420	0.0500	Coefficient	-0.0940	0.0420	0.0500
Log Size: t	-4.3030	2.2410	1.9600	Log Size: t	-4.3030	2.2410	1.9600
Log Size: p	**0.0000**	**0.0310**	**0.0570**	Log Size: p	**0.0000**	**0.0310**	**0.0570**
TopoIndexMin R^2	0.0631	0.0274	0.0175	TopoIndexMax R^2	0.0951	0.0271	0.0297
Coefficient	0.0160	-0.0080	-0.0080	Coefficient	-0.0210	0.0080	0.0120
TopoIndexMin: t	1.6600	-1.0750	-0.8540	TopoIndexMax: t	-2.0840	1.0690	1.1200
TopoIndexMin: p	0.1040	0.2890	0.3980	TopoIndexMax: p	**0.0430**	0.2910	0.2690
Log Size & TopoIndexMin R^2	0.3265	0.1176	0.0902	Log Size& TopoIndexMax R^2	0.3108	0.1102	0.0857
Log Size: t	-3.9561	2.0223	1.7875	Log Size: t	-3.5325	1.9330	1.5654
Log Size: p	0.0003	0.0499	0.0814	Log Size: p	0.0011	0.0603	0.1254
TopoIndexMin: t	0.9756	-0.6213	-0.4435	TopoIndexMax: t	0.1341	-0.2248	0.0177
TopoIndexMin: p	0.3351	0.5379	0.6598	TopoIndexMax: p	0.8940	0.8233	0.9860
R^2 Difference	0.0160	0.0085	0.0045	R^2 Difference	0.0003	0.0011	0.0000
Contribution	0.0232	0.0095	0.0049	Contribution	0.0004	0.0012	0.0000

N = 43	Topo Index Mean			N = 43	Topo Index stdev		
	b	f	m		b	f	m
Log Size R^2	0.3105	0.1091	0.0857	Log Size R^2	0.3105	0.1091	0.0857
Coefficient	-0.0940	0.0420	0.0500	Coefficient	-0.0940	0.0420	0.0500
Log Size: t	-4.3030	2.2410	1.9600	Log Size: t	-4.3030	2.2410	1.9600
Log Size: p	**0.0000**	**0.0310**	**0.0570**	Log Size: p	**0.0000**	**0.0310**	**0.0570**
TopoIndexmean R^2	0.0010	0.0000	0.0020	TopoIndexstv R^2	0.0973	0.0279	0.0329
Coefficient	-0.0090	-0.0050	0.0140	Coefficient	-0.2540	0.1030	0.1510
TopoIndexMean: t	-0.1670	-0.1170	0.2610	TopoIndexstv: t	-2.1010	1.0840	1.1810
TopoIndexMean: p	0.8680	0.9070	0.7960	TopoIndexstv: p	**0.0420**	0.2850	0.2440
Log Size& TopoIndexMean R^2	0.3196	0.1096	0.0917	Log Size& TopoIndexstv R^2	0.3215	0.1109	0.0912
Log Size: t	-4.3298	2.2157	1.9909	Log Size: t	-3.6363	1.9333	1.6016
Log Size: p	0.0001	0.0325	0.0534	Log Size: p	0.0008	0.0603	0.1171
TopoIndexMean: t	-0.7309	0.1508	0.5130	TopoIndexstv: t	-0.8052	0.2871	0.4925
TopoIndexMean: p	0.4691	0.8809	0.6108	TopoIndexstv: p	0.4255	0.7755	0.6250
R^2 Difference	0.0091	0.0005	0.0060	R^2 Difference	0.0100	0.0018	0.0055
Contribution	0.0132	0.0006	0.0066	Contribution	0.0160	0.0020	0.0060

Note: Contribution is the ratio of the unexplained and the difference between R^2 of b, f, and m with log size and with log size and asymmetry combined. Statistical Significance at the 0.1 level is in **Bold**.

6.11.3 Summary

As expected, the relationship between b and a topographic index is stronger than for the f and m exponents. Topographic index maximum and topographic index standard deviation values for b are statistically significant at the 0.05 level, but including the scale variable, none of the topographic indices and scale variable impacts the b in a statistically significant way. By including the scale variable with to the topographic index, the R^2 improved. However, the increased R^2 is due to the role of scale; the topographic index has very little impact, i.e., is less than 3 % of the variation is left unexplained.

6.12 Which Predictor Variables are most influential on b, f, and m?

In addition to investigating the roles of scale and selected predictor variables on b, f, and m, individually, the research examined which subset of predictor variables appear to be the most influential.

6.12.1 Size and which other Predictor Variables?

This is investigated by using a backward elimination stepwise regressions method. This procedure allows a single regression equation from several possible combinations of predictor variables. Even though the predictor variables are selected because they are theoretically and empirically relevant, a smaller subset of these variables may provide a satisfactory model for the hydraulic geometry exponents. In selecting the best subset of predictor variables, a trade-off between obtaining the best prediction possible using a large number of predictor variables and keeping the model as parsimonious as possible is achieved. This clearer interpretation of the interactions between the predictor(s) and the b, f, and m was made under constraints of 0.1 probability by maximizing R^2 while minimizing the number of predictor variables. The results of the backward stepwise regressions for b, f, and m are shown as Table 6.40.

6.12.2 Multivariate Linear Regression for b

Including all predictor variables, except size, the R^2 for the regression equation for b, the R^2 is 0.688. However, none of the watershed variable is statistically significant and the statistically significant variable is channel pattern (at the 0.127 level). With statistically significant predictor variables at the 0.561 level, b can be calculated with an R^2 of 0.614. Excluding channel shape and physiography, using only the 0.5 level of statistically significant variables, the b can be calculated with an R^2 of 0.504. With predictor variables which are statistically significant at the 0.1 level only, lithology, channel pattern, and slope, b can be calculated with an R^2 of 0.381.

Including all predictor variables in the regression equation for b, the R^2 becomes 0.792. However, only asymmetry and size are statistically significant (at the 0.079 and 0.024 levels). With predictor variables with statistical significance (at 0.561 level), b can be calculated with an R^2 of 0.614. Excluding lithology, landuse, and bed and bank material, using only the 0.4 level of statistically significant variables, the b can be calculated with an R^2 of 0.704. Using predictor variables which are statistically significant at the 0.1 level only, channel pattern, topographic index minimum, topographic index maximum, topographic index standard deviation, and size, b can be calculated with an R^2 of 0.541.

6.12.3 Multivariate Linear Regression for f

Including all predictor variables, except for size, the R^2 for the regression equation for f is 0.673. However, none of the predictor variables is statistically significant at the 0.1 level. Using predictor variables with statistical significance at the 0.59 level, f can be calculated with an R^2 of 0.646. But with predictor variables statistically significant at the 0.395 level, f can be calculated with an R^2 of 0.613. Excluding bank material (0.590 level of statistical significance) from the multivariate regression, the R^2 becomes 0.488. Therefore, statistically insignificant bank material must have been erroneously included in the estimation of the f values. However, the bank material variable of my study is not a clean cut variable due to the mixed nature of heterogeneous materials. Using only a 0.46 level of statistically significant variables, the f can be estimated with an R^2 of 0.484. After excluding lithology (0.46 level of statistical significance), the remaining variables, bed material and channel pattern, are statistically significant at 0.02 and 0.05 levels, respectively. Eliminating the lithology variable, with bed material and channel pattern variables which are statistically significant at the 0.002 and 0.006 levels, f can be calculated with an R^2 of 0.448. It can be concluded that bed material and channel pattern are decidedly the predictor variables for estimation of the f values.

Including all predictor variables in the regression equation for f, the R^2 is 0.765. However, only size is statistically significant (at the 0.043 level). With predictor variables with statistical significance (at 0.549), f can be calculated with an R^2 of 0.762. Excluding channel shape, asymmetry, and topographic index minimum, using only the 0.46 level of statistically significant variables, the f can be calculated with an R^2 of 0.738.

With predictor variables which are statistically significant at the 0.2 level only, physiography, lithology, bed material, channel pattern, topographic index maximum, topographic index standard deviation, and size, f can be calculated with an R^2 of 0.683. With predictor variables which are statistically significant at the 0.1 level only, that is, bed material, channel pattern, and size, f can be calculated with an R^2 of 0.512.

6.12.4 Multivariate Linear Regression for m

Including all predictor variables, except for size, the R^2 for the regression equation for m, is 0.552. However, no predictor variable is statistically significant at the 0.1 level. Using up to the 0.49 level of statistically significant variables, the m can be calculated with an R^2 of 0.510. With predictor variables which are statistically significant at the 0.1 level only, that is, lithology, m can be estimated with an R^2 of 0.152. It can be concluded that m is hard to estimate even with all predictor variables and with a constraint of 0.1 statistical significance, only lithology is a useful predictor variable to estimate the m values.

Including all predictor variables in the regression equation the R^2 for m, is 0.559, but none of the predictor variables are statistically significant at the 0.1 level. With predictor variables with statistical significance of the 0.493 level, including predictor variables such as physiography, lithology, bed material, channel shape, and asymmetry, m can be estimated with an R^2 of 0.510. Further, excluding channel shape, bed material, and asymmetry, using only the 0.22 level of statistically significant variables, the m can be calculated with an R^2 of 0.385 level. Only the size variable, is statistically significant at the 0.1 level and the m can be estimated with R^2 of 0.008.

Clearly, the estimation of m values with mostly static predictor variables, including the size variable, is statistically insignificant and it can be concluded that the rate of flow velocity change due to increasing discharge volumes is hard to estimate. However, the underlying principle of the hydraulic geometry, $b + f + m = 1$, allows m to be deduced from known b and f values.

Table 6.40 Stepwise Regression for b, f, and m with All Predictor Variables

Backward Stepwise Regression for b with All Predictor Variables

b	R^2	Eliminated	b w/size R^2	Eliminated
step 0	0.688		0.792	
step 1	0.664	bed material	0.791	landuse
step 2	0.652	landuse	0.772	bed material
step 3	0.651	topo index min		
step 4	0.614	channel shape	0.729	bank material
step 5	0.504	physiography	0.704	lithology
step 6	0.450	bank material	0.669	channel shape
step 7	0.424	asymmetry	0.562	physiography
step 8	0.390	topo index max	0.541	asymmetry
step 9	0.381	topo index stdev		
Remained lithology: 0.078 channel pattern: 0.011			Remained channel pattern: 0.006 topomin: 0.030 topomax: 0.004 topostdev: 0.007 logsize: 0.000	

Backward Stepwise Regression for f with All Predictor Variables

Backward Stepwise Regression for m with All Predictor Variables

f	R^2	Eliminated	f w/size R^2	Eliminated	m R^2	Eliminated	m w/size R^2	Eliminated
step 0	0.673		0.765		0.552		0.559	
step 1	0.673	topomin	0.765	topomin	0.543	landuse	0.555	chpatt
step 2	0.670	landuse	0.762	landuse	0.536	chpatt	0.554	landuse
step 3	0.646	chshape	0.741	chshape	0.516	bank mat	0.553	topostdev
step 4	0.646	asym	0.738	asym	0.514	topostdev	0.522	bank mat
step 5	0.613	bank mat	0.703	bank mat	0.512	topomax	0.517	topomax
step 6	0.488	phys			0.510	topomin	0.515	topomin
step 7			0.541	phys	0.459	chshape	0.510	logsize
step 8	0.487	topomax	0.525	litho	0.401	bedmat	0.459	chshape
step 9	0.484	topostdev	0.519	topostdev	0.385	asym	0.401	bedmat
step10	0.448	litho	0.512	topomax	0.194	phys	0.385	asym
step11							0.265	litho
step12							0.066	phys
Remained bed mat: 0.002 chpatt: 0.006			Remained bedmat: 0.002 chpatt: 0.007 logsize: 0.035		Remained litho: 0.089		Remained none Added logsize: 0.038 R^2 becomes 0.108	

Note: Statistical significances of the remained predictor variable are shown.

6.12.5 Conclusion

Using multivariate regression methods to estimate b, f, and m values, a balance between the statistical significance of the considered predictor variables and higher correlation needs to be maintained. Considering all predictor variables for the estimation of b, f, and m values, regardless of the statistical significance of the predictor variables, b, f, and can be estimated with an R^2 of 0.792, 0.765, and 0.552, respectively. The majority of the predictor variable values used for this study are more or less static and easily obtainable, and once the values are obtained, they can be used for various stream discharge volumes.

Based on the statistical significance of predictor variables at the 0.1 level, the predictor variables needed to estimate b are channel pattern, topographic indices, and size of the subbasin, and b can be estimated with an R^2 of 0.541. The predictor variables needed to estimate f are bed material, channel pattern, and size of the subbasin, and f can be estimated with an R^2 of 0.512. Except the size of the subbasin, no predictor variable at the 0.1 level of statistical significance can predict m. Since b and f can be estimated with 0.1 level of statistically significant predictor variables, m can be calculated with the continuity law.

6.13 Constrained b, f, and m Values

To further examine the validity of the statistical results, two additional analyses are conducted. First of all, I examined a subset of subbasins which meet a constraint criterion, and, secondly, I analyzed all the subbasins using weighted samples.

6.13.1 Constrained Hydraulic Geometry and Scale

The continuity equation implies a constraint that the hydraulic exponents should sum to one. To estimate the hydraulic geometry values, a log-linear model (LLM) is used one-at-a-time, and the constraint is not imposed on the b, f, and m. The sum of the b, f, and m are noted in Chapter 5 (Table 5.1). Rhodes (1977) recommended a screening procedure which rejects b, f, and m whose sum is outside of the range of 0.95 – 1.05. The summation of all study area b, f, and m values are within 1 ± 0.05. Out of the 43 study subbasins, two subbasins show the sum of the three exponents as 1.038 and 1.032, and two subbasins show 1.0214 and 1.0212. The rest of the subbasins are all within ± 0.01 from the unit. Therefore, all 43 subbasins are included in the analyses. Even though the summation constraints of b, f, and m values are within ± 0.05, the validity of the b, f, and m values need to be verified. This is to ensure that the study area subbasins are comprised of reasonably constrained b, f, and m values.

Using the R^2 values of the b, f, and m correlated with discharge and each channel width and depth, and flow velocity, each subbasin is categorized as well constrained (at least two out of three exponents have R^2 of 0.9), moderately constrained (at least two exponents have R^2 of 0.8), or poorly constrained subbasins (personal communication with Dr. Karen Prestegaard, Oct. 2005). Eleven subbasins are well constrained; 12, moderately; and 20 poorly constrained (Table 6.41).

Table 6.41 Distribution of Coefficient of Determination for b, f, and m

$R^2b/R^2f/R^2m$	Frequency		
	b	f	m
<0.5	6	4	1
0.5	8	3	3
0.6	4	9	4
0.7	7	4	4
0.8	12	8	8
0.9	6	15	23

With 23 well and moderately constrained subbasins, selected statistical analyses such as correlations between b, f, and m and scale and stepwise regressions are conducted. This aids in determining the roles of scale on b, f, and m and in selecting the best statistical subset of predictor variables in order to obtain reliable estimates under constraints of maximizing the R^2 with 0.1 statistically significant variables.

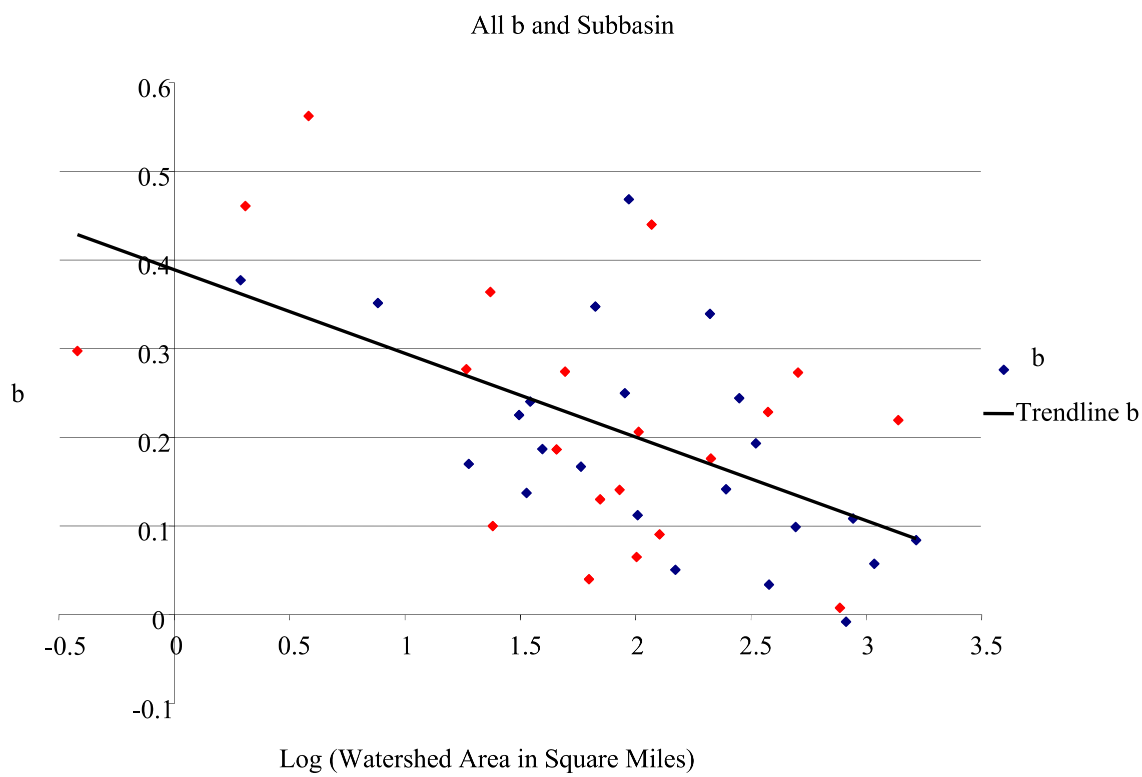
The relationships between the b and m and the subbasin size (scale) in well and moderately constrained subbasins are stronger than that of all the study subbasins by 0.055 and 0.142, respectively. However, the relationship between scale and f deteriorated by 0.076, and the scale becomes statistically not a significant predictor variable for f at the 0.1 level. Even though the R^2 improved for b, the role of scale on m became statistically less significant; however, the influence of scale is still within the 0.1 probability level.

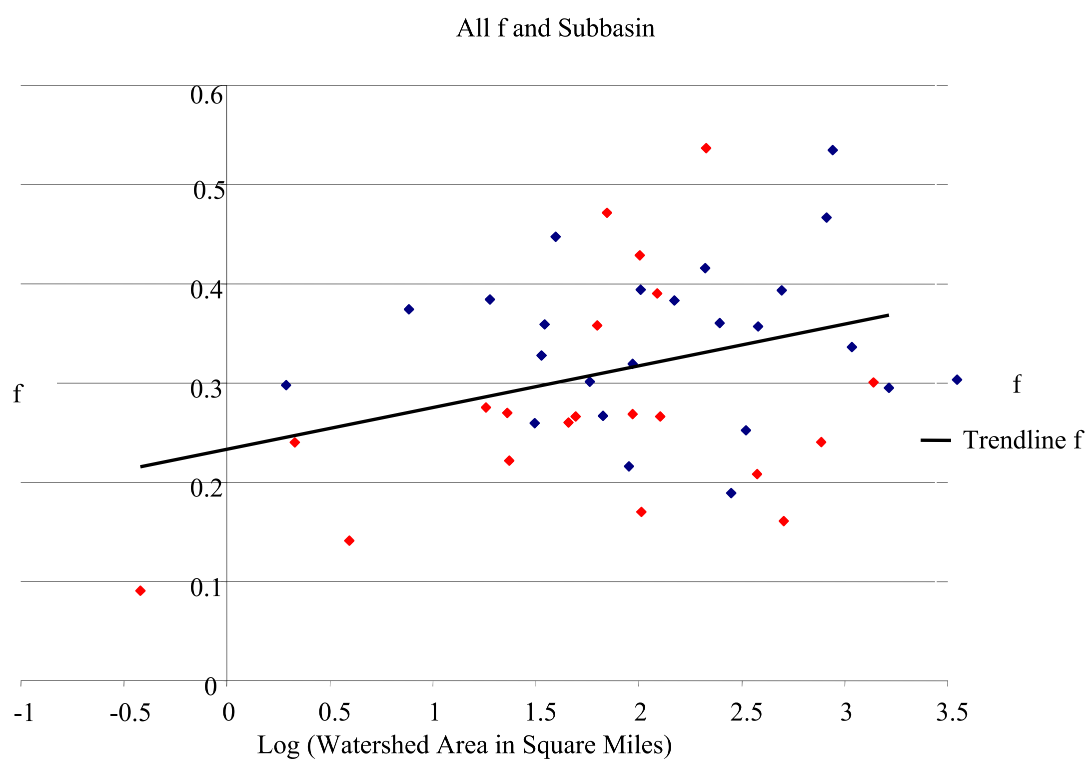
Table 6.42 Regression of the Combined Well and Moderately Constrained Subbasin b, f, and m with Subbasin Size

	b	f	m
N	23	23	23
R^2	0.366	0.033	0.228
t Value	-3.479	0.842	2.492
Significance/ Probability[1]	**0.002**	0.409	**0.021**
Constant	0.404	0.303	0.301
Coefficient	-0.104	0.020	0.081

Note: 1. With 1 degree of freedom, the critical value at the 0.01 is 2.831, 0.05 is 2.080, and at the 0.1 level is 1.721. Statistically significant values at 0.05 level are in bold.

The poorly constrained subbasins highlighted in red on Figure 6.43 which are removed from the regression analyses of b, f, and m and scale are in a random distribution pattern and are not in statistical significant correlation with subbasin size, except that the majority (15 out of 20) of the removed subbasins are less than 150 square miles in size. That means investigations of b, f, and m in smaller subbasins with scale, and predictor variables roles need to be differentiated from those of the larger subbasins.


All b and Subbasin
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
b
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
b
Trendline b
Log (Watershed Area in Square Miles)


All f and Subbasin
0.6
0.5
0.4
0.3
0.2
0.1
0
f
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
f
Trendline f
Log (Watershed Area in Square Miles)

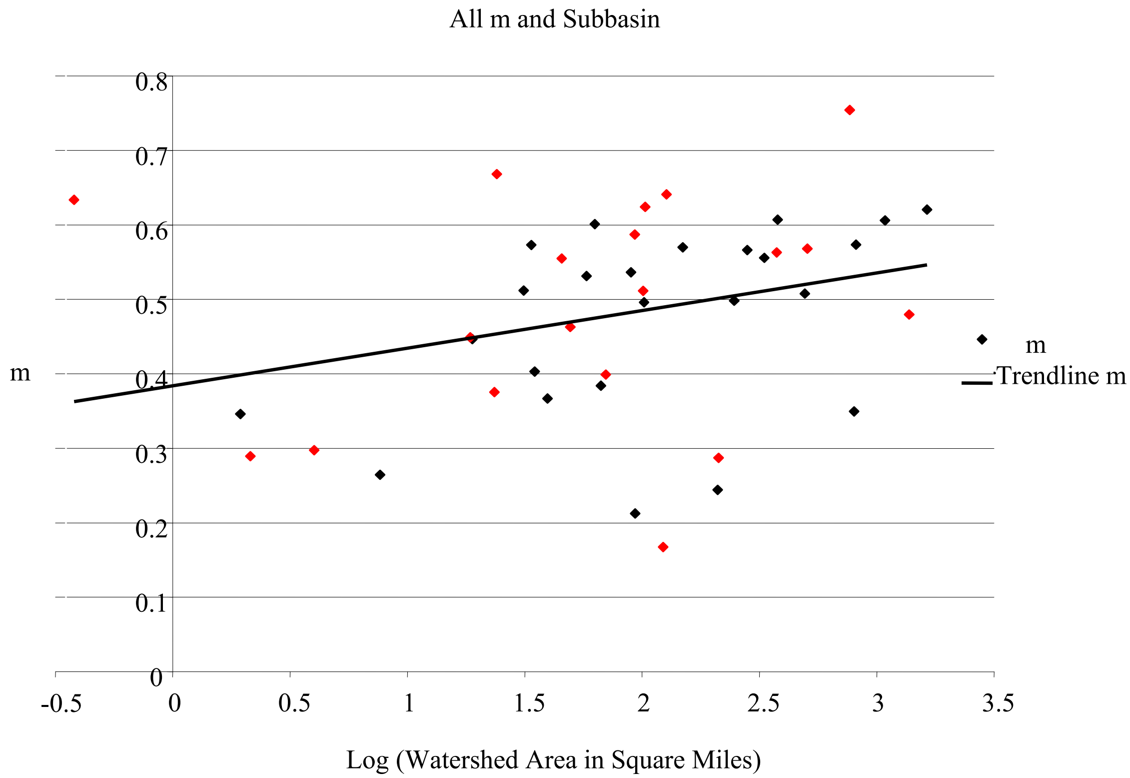


Figure 6.53 b, f, and m with Subbasin in Log (Watershed Area in Square Miles)

Even with only 23 subbasins, the role of scale is statistically significant at the 0.1 level for b and m. With the summation constraint, f can be estimated since b and m are known. It is hard to judge whether the role of the scale predictor variable is stronger in the well and moderately constrained subbasin than for the original 43 study subbasins. There are no big changes in the fundamental relationships between scale and b, f, and m such that within the study subbasin size (1,642 square miles), as scale gets bigger the b value gets smaller and f and m values get bigger.

Table 6.43 Regression b, f, and m with Subbasin Size for All and the Combined Well and Moderately Constrained Subbasins

Regression of Constrained and all Subbasins b, f, and m on Subbasin Size

	b	f	m	b	f	m
N[1]	23	23	23	43	43	43
R^2	0.366	0.033	0.228	0.311	0.109	0.086
t Value	-3.479	0.842	2.492	-4.303	2.241	1.960
Significance/ Probability[2]	0.002	0.409	0.021	0.000	0.031	0.057
Constant	0.404	0.303	0.301	0.389	0.233	0.384
Slope	-0.104	0.020	0.081	-0.094	0.042	0.050

Note: 1. N = 23 denotes total number of well and moderately constrained subbasins. N = 43 denotes total number of study subbasins.

2. With degree of freedom 41, the critical t value at 0.1 probability is 1.684.

3. With degree of freedom 21, the critical t value at 0.1 probability is 1.721.

6.13.2 Impact on the Choice of Predictor Variables for b, f, and m

I examined the subset of subbasins in stepwise regression analyses using 23 subbasins. The results of the stepwise analyses on 23 subbasins compared with all subbasin cases, that were reported in 6.2 through 6.13, are examined for the pattern of best predictor variables rather than for a comparison of the magnitudes of correlations. Also stepwise regression results for the 23 subbasins are compared with results from weighted regression based on the sample size of each observed subbasins. The expectation of these comparisons is that well and moderately constrained subbasins would have a higher R^2 than that of all study subbasins and the weighted regression analyses would also provide higher R^2 values.

Stepwise regression analyses of the well and moderately constrained subbasins are done with a forward selection method due to the lack of degrees of freedom with only 23 subbasins. The backward elimination methods are utilized for N = 43 stepwise regression. Therefore, comparing the results from forward selection and backward elimination methods might not be prudent, but examining the results of best predictor variables for either forward or backward methods provides a valuable insight of the role of scale either in N = 43 or N = 23 cases (Table 6.44).

Table 6.44 Stepwise Regressions for b, f, and m with all Predictor Variables

	N = 23 (Forward)	N = 43 (Backward)	N = 43 (Weighted[1], Backward)
	Well and Moderately Constrained Subbasins	All Study Subbasins	All Study Subbasins
b			
R^2	0.599	0.541	0.718
Significant[2] Predictor Variables	Channel Pattern	Channel Pattern	Physiography
	Size	Topo Min Index	Bank Material
	Asymmetry	Topo Max Index	Asymmetry
		Size	Topo Index Stdev
		Topo Index Stdev	Size
f			
R^2	0.571	0.512	0.640
Significant[2] Predictor Variables	Topo Min Index	Bed Material	Bed Material
	Bed Material	Channel Pattern	Channel Shape
	Size	Size	Asymmetry
			Topo Min Index
			Size
m			
R^2	0.229	0.108	0.150
Significant[2] Predictor Variables	Size	Size	

Note: 1. All study subbasins are weighted by their sample sizes.
2. Statistically significant at the 0.1 level.

In addition to the scale variable, including statistically significant predictor variables at the 0.1 level, the correlation of estimation of b, f, and m improved from 0.366 to 0.599 for b. For the estimation of b, the statistically significant predictor variables at the 0.1 level are channel pattern, size, and asymmetry and with these variables, b can be estimated with R^2 of 0.599.

Scale is one of the significant predictor variables for f, but the role of scale appears to be infinitesimally small. With the scale variable the estimation of f improved 0.08 more (0.571) in R^2 value.

The influence of scale on m is also notable. Without the scale variable, no statistically significant predictor variable is identified for the estimation of m. However, with the scale variable, m can be estimated with R^2 of 0.228. This reaffirms that poorly constrained subbasins might not have the flow resistance related factors and removing these poorly constrained subbasins, m can be estimated.

Statistically significant predictor variables for b, f, and m, identified for 43 subbasins in section, 6.12 (Table 6.40), are used for regression analyses for each b, f, and m in the well and moderately constrained subbasins. Besides the scale variable, not all the significant predictor variables for the original study subbasins become significant for the well and moderately constrained subbasins. However, bed material, channel pattern, and topographic minimum, and topographic maximum indices are common predictor variables for both situations.

The rationale for the deterioration of the scale impact on f, even though only two subbasins with R^2 f of 0.9 are removed from the analyses, might be due to the smaller sample size. Therefore, to keep the original study subbasins for the stepwise regression analyses, weighted stepwise regression analyses are employed. The weights are given to each subbasin based on the sample size of each subbasin.

Since several of the poorly constrained subbasins have the largest sample sizes among the study area subbasins, and since the summation of the b, f, and m are within ± 0.002, instead of removing these subbasins from the analyses, each subbasin is weighted based on its sample size (number of hydrographic survey and measurements) and examined by weighted stepwise regression analyses.

Comparing the backward elimination stepwise regression results with the original study subbasins, many predictor variables become statistically significant; therefore, including all significant variables in the estimation of b, f, and m models, the R^2 values for each b, f, and m become much higher. That is to say, b can be estimated with physiography, bank material, topographic standard deviation, asymmetry index, slope, and size with R^2 of 0.722 (Table 6.44). However, the weighted stepwise regression does not consider the hydraulic and channel geometry constraints, and many of the predictor variables needed for the estimation of b, f, and m . Therefore, weighted stepwise regression might not be the best method to predict hydraulic geometry. Using a high number of well and moderately constrained subbasins will aid reliable estimation of b, f, and m with statistically significant predictor variables for each b, f, and m.

6.14 Summary

The findings of the study on the roles of scale and watershed variables on the hydraulic geometry exponents are described in the next chapter. The scale and statistically significant, at least at the 0.05 level, watershed variables are discussed. In addition, the influence of scale on b, f, and m, the “Best” individual watershed predictor variable, and the most influential watershed predictor variables among the selected variables are addressed. Needed future research areas are also discussed.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary of Research Objectives and Hypotheses

The main objectives of this study have been to determine whether (a) at-a-station hydraulic geometry changes significantly with watershed scale (which is manifested by the size differences of each subbasin area); and (b) the selected watershed variables of physiography, topography, lithology, geomorphology, landuse, channel pattern, channel shape, and bed and bank materials, affect the size and shape of stream channels and, thus, the at-a-station hydraulic geometry.

The working hypothesis for the first objective of this study was that the hydraulic geometry exponents (b, f, and m values), the change rates of channel width and depth, and flow velocity with regard to discharge (not with time), are not random, but that there are systematic changes as a function of watershed scale. The expected changes in the at-a-station hydraulic geometry as a function of scale is that channel width does not change much, depth increases rapidly, and flow velocity change rates will also increase.

The working hypothesis of the second objective is that watershed variables influence channel morphology by affecting stream discharge and sediment characteristics such as the size and the amount of sediments delivered to the channels. The expected correlations between particular watershed variables and b, f, and m were stated in Chapter 1.

As a practical matter, the research analysis has been undertaken via empirical statistical correlations and analysis of variances, in order to:

(1) discern relationships between a geographical scale factor (subbasin size) and b, f, and m;

(2) account for the roles of the selected individual watershed predictor variables for b, f, and m, including the empirical findings of f > m in sand beds and f < m in gravel beds;

(3) account for the roles of the selected individual watershed predictor variables for b, f, and m including the empirical findings of f > m in sand beds and f < m in gravel beds within the scale context;

(4) ascertain the significant watershed variables, without the scale variable, for b, f, and m via stepwise multi-variable regression; and

(5) ascertain the significant watershed variables jointly with the scale variable, for b, f, and m via stepwise multi-variable regression .

In addition to investigating the influence of scale and selected watershed variables on b, f, and m, individually, the study also investigated which subsets of watershed variables might be the best predictors. The use of a single stepwise regression equation helps to ascertain several possible combinations of predictor variables for the estimation of the b, f, and m values. The watershed variables used in this study were: physiography, lithology, landuse, channel pattern, channel shape, channel bed material, channel bank material, all of which are categorical variables, and quantitative measures of channel asymmetry and topography.

To test the hypotheses that b, f, and m values are functions of subbasin size and selected predictor variables, the following models were used:

b (f, m) = $a_{0.b}$ ($a_{0.f}$, $a_{0.m}$) + $a_{1.b}$ ($a_{1.f}$, $a_{1.m}$) * scale + $a_{2.b}$ ($a_{2.f}$, $a_{2.m}$) * predictor variable + $a_{3.b}$ ($a_{3.f}$, $a_{3.m}$) * predictor variable * scale;

where, $a_{0.b}$ ($a_{0.f}$, $a_{0.m}$) are constants, $a_{1.b}$ ($a_{1.f}$, $a_{1.m}$) are coefficients of the scale factor, $a_{2.b}$ ($a_{2.f}$, $a_{2.m}$) coefficients of a predictor variable, and $a_{3.b}$ ($a_{3.f}$, $a_{3.m}$) are coefficients of interaction between the scale factor and a watershed variable. Theoretically, as stream discharge increases, channel width and depth and flow velocity would increase as well, but the focus of the study is the coefficients of these models. The null hypotheses are $H_{0.b}$ ($H_{0.f}$, $H_{0.m}$): $a_{1.b}$ ($a_{1.f}$, $a_{1.m}$) = 0, $H_{0.b}$ ($H_{0.f}$, $H_{0.m}$): $a_{2.b}$ ($a_{2.f}$, $a_{2.m}$) = 0, and $H_{0.b}$ ($H_{0.f}$, $H_{0.m}$): $a_{3.b}$ ($a_{3.f}$, $a_{3.m}$) = 0. And the alternative hypotheses are $H_{1.b}$ ($H_{1.f}$, $H_{1.m}$): $a_{1.b}$ ($a_{1.f}$, $a_{1.m}$) ≠ 0, $H_{1.b}$ ($H_{0.f}$, $H_{0.m}$): $a_{2.b}$ ($a_{2.f}$, $a_{2.m}$) ≠ 0, and $H_{1.b}$: $a_{3.b}$ ($a_{3.f}$, $a_{3.m}$) ≠ 0.

Determination of the significant roles of scale and selected watershed predictor variables for b, f, m, f > m, and f < m is guided by the statistical significance level of 0.05. However, readers can also interpret the documented statistical significance of the predictor variables for b, f, m, f > m, and f < m based on their specific interests by using the probability values tabulated in Chapter 6.

7.2 Findings and Discussion: Scale Influence on b, f, and m

Scale issues in hydrology arise because different hydrological processes are dominant at different scales. As Leopold and others have mentioned there is a relationship between at-a-station and downstream hydraulic geometry, implying a scale relationship, but the scale implications are not quantified by researchers except for Leopold's demonstration of systematic differences of b, f, and m in different sizes of subbasins. Notable examples are the relationships among the average b, f, and m values with discharge in the hydraulic geometry of three rivers of different size: Watts Branch drainage area in Potomac River, 3.7 square miles; Seneca Creek in Potomac River, 100 square miles; and the Amazon River at Obiodos drainage area of 1.9 million square miles (Leopold, 1994).

Despite Ridenour's (1999) finding that there is no significant functional relationship between drainage area and hydraulic geometry, the findings in this study of the relationships between the subbasin size in $\log_{10}$ and b, f, and m, indicate that, even though the R^2s are not high, there are statistical relationships between scale and b and for f. Both these relationships are statistically significant at the 0.05 level, thus supporting the hypothesis that there are systematic changes in hydraulic geometry exponents as a function of subbasin size. Unlike the relationships between b and scale ($R^2 = 0.311$) and f and scale ($R^2 = 0.109$), the relationship between scale and m ($R^2 = 0.086$) is not statistically discernable at the 0.05 test level.

For purposes of estimation, the hydraulic geometry in the study area can be determined by the empirical models (Table 7.1):

b = 0.389 - 0.094 * scale (log (subbasin area (mi^2)) with R-squared of 0.311;

f = 0.233 + 0.042 * scale (log (subbasin area (mi^2)) with R-squared of 0.109; and

m = 0.384 + 0.050 * scale (log (subbasin area (mi^2)) with R-squared of 0.086, provided caution is exercised in the case of m.

Unexpectedly, the b value changes negatively, and b's increase is high which is expected as b is higher in downstream hydraulic geometry. f increases not as much as expected, but m changes very much as expected. As Leopold (1953) suggested, the m value increases in downstream hydraulic geometry which is usually in large drainage basins.

Table 7.1 Regressions of All and the Well and Moderately Constrained Subbasin b, f, and m with Subbasin Size (in Logarithms)

Regression of b, f, m on Scale for All and Well/Moderately Constrained Subbasins	b		f		m	
N[1]	23	43	23	43	23	43
R^2	0.366	0.311	0.033	0.109	0.228	0.086
t Value	-3.479	-4.303	0.842	2.241	2.492	1.960
Significance/Probability[2]	**0.002**	**0.000**	0.409	**0.031**	**0.021**	0.057
Regression Constant	0.404	0.389	0.303	0.233	0.301	0.384
Regression Coefficient	-0.104	-0.094	0.020	0.042	0.081	0.050

Note: 1. N = 23 denotes the total number of well and moderately constrained subbasins. N = 43 denotes the total number of study subbasins.

2. With 41 degrees of freedom, the critical t value at the 0.05 probability is 2.021. With 21 degrees of freedom, the critical t value at the 0.05 level is 2.080. Statistical significance at the 0.05 level is in **Bold**.

A more robust analysis based on the removal of twenty subbasins led to some change in the statistical results (Table 7.1). Even though the summation of the b, f, and m values for the original 43 subbasins is within ± 0.02 from unity and the sample sizes of some of the subbasins are high, only 23 well and moderately constrained (at least two out of three exponents have R^2 of 0.8 or higher) subbasins are kept. The sizes of 15 of the eliminated 20 poorly constrained subbasins are under 150 square miles.

As the R^2 improved for b and m, based on use of the constrained subbasins, the influence of scale on m also became statistically significant at the level of 0.05, a small but important improvement over the 0.057 probability value using all 43 subbasins. The relationships (R^2) between the b and m and the subbasin size in well and moderately constrained subbasins are stronger than that of all the study subbasins by 0.055 and 0.142, respectively. The relationship (R^2) between scale and f deteriorated by 0.076, and the scale becomes, statistically, not a significant predictor variable for f at the 0.05 level.

The improvement in the R^2 and statistical significance may be due simply to the elimination of the poorly constrained subbasins. However, it is hard to judge whether the role of the scale predictor variable is stronger in the well and moderately constrained subbasins than for the original 43 study subbasins. As the coefficients of b, f, and m in both cases show (Table 7.1), there are no significant changes in the fundamental relationships between scale and b, f, and m such that, within the study subbasin size (1, 642 square miles), as scale increases the b value gets smaller and f and m values increase, with the m values changing more than those of f.

Yet, in general, it needs to be recognized that the relationship between scale and b, f, and m is weak and that the relationship is limited to the watershed sizes of 0.38 to 1, 642 square miles in the Potomac River Basin. With these caveats, b, f, and m can be extrapolated with these estimating equations up to watershed sizes of a little over 10,000 square miles (log of 4.138 watershed size). Over 10,000 square miles of watershed size, the underlying model implies that the width of the channels will actually decrease as discharge increases, which is physically and geomorphologically impossible.

Because of the paucity of research on the influence of geographic scale on at-a-station hydraulic geometry relationships, it is hard to judge the universal goodness of the particular R^2 values as produced by this research. Nonetheless, recognizing the high probability of the relationship being as stated, and considering the heterogeneous nature of the study subbasins in terms of physiography, lithology, channel pattern and shape, bed and bank material, and topography, the statistically discernible relationships between scale and b and f are notable.

7.3 Findings and Discussion: What Are the "Best" Predictor Watershed Variables for b, f, and m?

The results of the statistical analysis for the relationships of b, f, and m, with each watershed variable, scale, and with interaction relationships, are shown in Table 7.2. Watershed predictor variables statistically significant at the 0.05 level are highlighted in red and the scale variable is highlighted in blue.

An examination of the relationships of the seven categorical and two quantitative watershed variables and b, f, and m, individually both with and without consideration of scale, has led to four principal conclusions:

(1) There is a more reliable prediction of the rate of width changes (based on statistical significance) using a single watershed variable, than for depth and flow velocity. This

Table 7.2 Summary of b, f, and m, Scale, and Selected Predictor Variable Relations

Note: Statistically significant watershed predictor (except for scale) variables are highlighted in red an scale variable highlighted in blue when it meets the 0.05 level of statistical significance.

b vs Scale R^2	**0.3110**		**f vs Scale**	**0.1090**		**m vs Scal**	**0.0860**	
Probability	**0.0000**		**Probabili**	**0.0310**		**Probabili**	**0.0570**	
Coefficient	**-0.0940**		**Coefficie**ı	**0.0420**		**Coefficie**ı	**0.0500**	

	Physio	Litho	Landuse	Ch. Patt	Ch. Shape	Bed Mat	Bank Mat	Asym
b vsPred/scale R	0.3877	0.3589	0.3129	0.3883	0.3454	0.3309	0.3529	0.0227
Scale Prob.	0.0000	0.0016	0.0020	0.0004	0.0002	0.0001	0.0003	
Pred. Prob.	0.4867	0.5979	0.9344	0.0977	0.5719	0.2763	0.1132	0.3380
b vs pred/Inter R	0.4190	0.4370	0.3157	0.4927	0.3755	0.3399	0.3602	0.3545
Scale Prob.	0.8357	0.6133	0.3799	0.0068	0.0102	0.0249	0.2148	0.0001
Pred. Prob.	0.7615	0.2165	0.9032	0.0648	0.8409	0.2920	0.8859	0.1067
Interaction. Prob.	0.8890	0.3532	0.9264	0.0311	0.6444	0.4691	0.5081	
f vs Pred/scale R	0.2504	0.1788	0.1306	0.2587	0.2504	0.1407	0.1418	0.0010
Scale Prob.	0.0167	0.0259	0.0264	0.0523	0.0170	0.0204	0.0509	
Pred. Prob.	0.2634	0.5425	0.6210	0.0278	0.2630	0.2327	0.2240	0.8378
f vs pred/Inter R^2	0.3843	0.3121	0.1640	0.2789	0.3843	0.0960	0.1982	0.1137
Scale Prob.	0.0174	0.1061	0.8855	0.3237	0.0170	0.1661	0.4013	0.0297
Pred. Prob.	0.3934	0.1977	0.6804	0.4416	0.3930	0.5917	0.0479	0.6529
Interaction. Prob.	0.2707	0.1977	0.4843	0.5990	0.2710	0.3221	0.1059	
m vs Pred/scale I	0.2203	0.1884	0.0910	0.0994	0.1196	0.0857	0.0858	0.0177
Scale Prob.	0.0908	0.2252	0.0821	0.0945	0.0651	0.0646	0.0690	
Pred. Prob.	0.3098	0.3395	0.8936	0.7455	0.6925	0.9924	0.9543	0.3956
m vs pred/Inter R	0.3939	0.3159	0.1277	0.1636	0.1276	0.1190	0.1610	0.1128
Scale Prob.	0.0477	0.4563	0.4999	0.1472	0.2466	0.0776	0.4127	0.0448
Pred. Prob.	0.1224	0.0857	0.5731	0.1975	0.9177	0.2586	0.1190	0.2752
Interaction. Prob.	0.1469	0.2142	0.4664	0.2542	0.9558	0.2323	0.0690	

b,f,m & Predictor	Topomin	Topomean	Topomax	Topostdev	f-m in Sand	R^2	p
b vs Pred R^2	0.0631	0.0010	0.0951	0.0973	sand>50% vs non-sand		0.0310
Pred. Prob.	0.1040	0.8680	0.0430	0.0420	Sand>50% & Size	0.0251	
b, Scale, vs Pred R^2	0.3265	0.3196	0.3108	0.3215	Size		0.6227
Scale Prob.	0.0003	0.0001	0.0011	0.0008			
Pred. Prob.	0.3351	0.4691	0.8940	0.4255	f-m & Sand>50%	0.0801	
					Sand >50%		0.3727
					f-m, Size, Sand>50%	0.2137	
f vs Pred R^2	0.0274	0.0000	0.0271	0.0279	Size		0.2475
Pred. Prob.	0.2890	0.9070	0.2910	0.2850	Sand> 50%		0.1758
f, Scale, vs Pred R^2	0.1176	0.1096	0.1102	0.1109	f-m in Gravel	R^2	p
Scale Prob.	0.0499	0.0325	0.0603	0.0603	Gravel > 50% vs Non-Gravel		-0.3093
Pred. Prob.	0.5379	0.8809	0.8233	0.7755	f-m & Size	0.0264	
					Size		0.4813
m vs Pred R^2	0.0175	0.0020	0.0297	0.0329	f-m & Gravel>50%	0.0395	
Pred. Prob.	0.3980	0.7960	0.2690	0.2440	Gravel> 50%		0.3879
m, Scale, vs Pred R^2	0.0902	0.0917	0.0857	0.0912	f-m & Gravel>50%	0.0817	
Scale Prob.	0.0814	0.0534	0.1254	0.1171	Size		0.3750
Pred. Prob.	0.6598	0.6108	0.9860	0.6250	Gravel>50%		0.3118

Note: Each b, f, and m is individually correlated with individual watershed predictor variable by itself, with scale, and with scale and a predictor variable interaction. Statistically significant watershed predictor (except for scale) variables are highlighted in red and scale variable highlighted in blue when it meets the 0.05 level of statistical significance.

finding is expected, in a hydrogeomorphological sense, for more watershed variables influence directly the width and depth of the channel. That is, width changes are directly influenced by erodability of the bank and channel pattern. Depth is determined by the watershed variables and the stream power, more so than it would be for width. However, flow velocity is influenced by a combination of bed material and friction of the flow from bank and bed. The friction at the bed comes from the combination of bed material and level of flow (depth). The rate of changes in flow velocity is inherently complex, and the role of individual watershed variables for m is not obvious. Even if m can be determined from the continuity of b + f + m = 1, there is a weakness because the less reliable f has to be included in the equation. Therefore, m also is not so reliably predicted. f is less reliable because depth is inherently unstable, based on the bank and bed materials. For an easily erodable bank and bed channel, based on the stream power, sediments from the eroded bank and bed materials can be deposited on the bed, which, in turn, alters the depth of the channel.

(2) There are more individually influential watershed variables for b than for f, and more than for m, based on the R-squared values for single-variable regressions (Table 7.2). The most important variables, statistically speaking, are channel pattern, two measures of topography, and possibly also bed material. Considered individually, channel pattern, topographic maximum index, and topographic index standard deviation are significant predictor variables for b, but only channel pattern is for f, and there are none for m. This finding reflects the role of several geomorphic agents. However, for f, the role of an individual watershed variable is quite obscured by interactions among the process agents. Worse yet, m is a reflection of b and f which comprise channel geometry and flow dynamics within that channel geometry.

(3) Prediction is improved by concentrating on subbasins with a particular group characteristic within a selected watershed variable, for example, just straight channels within the channel pattern variables. This finding clearly indicates that reducing the

heterogeneity of the subbasins by grouping them into a homogeneous unit will improve the predictability of b, f, and m.

Generally speaking, this implies that different models should be developed for subbasins classified into different composite characteristics.

To cite just one example, in the case of straight channel subbasins b values are more similar (low standard deviations) compared with the b values of the rest of the subbasins which are mixture of meandering and braided channel patterns. The difference of means test indicates that the b values for straight channel are at the 0.025 level of statistical significance. This finding confirms that fluvial characteristics of straight channels have almost vertical channel banks, seen in A low variability in b; therefore, channel flow could not erode the banks easily, which results in a small b value.

(4) The results of this study suggest that the particular watershed characteristics of greater importance are the impact of sand versus non-sand bed material on f, and silt versus non-silt bank material on b. Also, the distinction between Great Valley versus non-Great Valley provinces in physiography, and crystalline versus non-crystalline lithology regions is important for the estimation of m, although neither of these watershed variables generally is influential for m. These findings need further investigation regarding geomorphic process content. Does this mean the flow resistance will be distinctly different in the Great Valley physiographic region, and the crystalline or siliciclastic lithology region compared other regions?

These findings match with the fact that cohesive bank material channels have smaller b values and smaller variability among cohesive bank material channels, therefore cohesive bank material is a good indicator for b value estimation. Also, this study demonstrated that channels of non-cohesive bed material (sand) versus other types of bed material channel would have distinctly different responses for f. These findings confirm Knighton's (1998) conclusion that b is largely a function of channel geometry and, therefore, boundary composition, while the rates of change of depth (f) and velocity (m) are dependent partly on cross-sectional form and partly on transport- and resistance-related factors which tend to be more variable.

In what follows only the statistically significant predictor variables by itself and with a scale context with the specific watershed predictor variables: channel pattern, bed material, bank material, and topographic indices, are examined in detail. The findings that all other watershed predictor variables (physiography, lithology, landuse, channel shape, bank material, and channel asymmetry), individually, by itself and with the scale context, were statistically insignificant, were discussed in detail in Chapter 6. The failure to detect significant statistical impacts for more variables is understandable given that the b, f, and m are responses to the interaction of various watershed influences on b, f, and m, and it might simply be that there are no relationships between the selected watershed predictor variables and b, f, and m. Hence, we need to recognize that a seemingly influential watershed variable by itself could turn out to be an insignificant predictor for b, f, and m by itself with and without consideration of scale.

7.3.1 Channel Pattern

As expected, comparing the average values of b, f, and m for each channel pattern shows that there are significant differences among the three channel pattern types.

Discernable differences are in the b values in straight versus non-straight channels. It is expected that in straight channels width and depth do not change much, but that flow velocity would change more with increasing discharge.

The found correlations between channel pattern and b, f, and m are that, in straight channels, b values are lower than those of depth; in meandering channels, relatively higher rates of changes in width than those of depth. Meandering channels seem to be associated with relatively low b values, although not as low as those for straight channels. The mean m value appears to be the smallest among the three channel pattern types. These findings make sense in that straight channels are typically symmetrical and meandering channels are normally asymmetric in cross-section at the bends; asymmetry provides for a relatively greater rate of increase in width, but f will probably still be greater than b. Braided channels are typically broad and shallow because of the unstable nature of their banks and the width-depth ratio commonly increases with increasing discharge. Braided channels are often, but not always, associated with sandy or unstable friable bank materials and steep slopes with variations in flow. As expected, higher m values are observed than for those of meander channels and they have the widest range of maximum and minimum values of b, f, and m.

Channel pattern by itself is not a statistically significant predictor variable for b. However, the relationship between b and the interaction of scale and channel pattern is strong and the statistical significance is at the 0.05 level. Channel pattern is a statistically significant variable for f by itself as well as in a scale context. Specifically, the influence of channel patterns on the f value, with a statistical significance level of 0.0278, is notable. However, the channel pattern's influence on m is indiscernible. It is expected that channel pattern would influence, primarily, width and depth change rates rather than that of flow velocity. The statistical results supported the expectations.

The straight channels have the highest m value (0.517) and the smallest mean b value (0.092) which is not as dramatically low as Knighton's (1975) finding, 0.03, while the b values for the meander and braided channels' are 0.215 and 0.239, respectively.

Comparing straight, meander, and braided channels, the straight channels have the smallest range of maximum and minimum values for all b, f, and m, which indicate that straight channels have very similar b, f, and m values among themselves. And, the mean f value for braided channels also has a very small standard deviation meaning that the rates of depth changes with discharge are similar within braided channels.

The influence of channel patterns, on f values as a whole, has been clearly demonstrated. Specifically, the meander channels show that channel pattern does explain b value in a scale context, as revealed by an R^2 of 0.758. By adding an interaction term to the model for b, R^2 increased from 0.388 to 0.493, and the statistical significance of channel pattern for b improved to the level of 0.05.

Even though the stepwise regression chose channel pattern as an influential predictor variable for b and f for the original 43 subbasins as well as for b values for the 23 well and moderately constrained subbasins, channel pattern is not an influential variable for f. This can be explained by the fact that other watershed variables, such as bed material and topographic minimum index, play a greater role for f. Therefore, channel pattern does not become an influential variable for f in well and moderately constrained subbasins. The R^2 for each channel pattern and f value in a scale context is lower compared to the mean differences of straight vs. non-straight and braided vs. non-braided channels. This can be explained by the fact that the regression slope lines between channel pattern types and f values are in opposite directions among the three channel pattern types, and the f values are scattered in the scale domain of braided and straight channels.

7.3.2 Bed Material

In general, an increase in stream discharge or channel depth results in a decrease in the relative roughness of the bed materials, and, thus, in flow resistance, resulting in higher m values. For sand-bed channels, however, the accompanying increase in stream power with increased water discharge can also produce a change in bed form, from plane bed to ripples to dunes. The effect of decreasing channel bed relative roughness is, therefore, partly offset by the effect of increasing bedform drag, producing a relatively restrained rate of increase of flow velocity with higher discharge (Richards, 1982). The channel profile of basin m48 shows that the bedform is not smooth, however, the high flows submerged these riffles or sand dune bedforms with resultant m values as high as 0.668. The other example is the v38 channel profile case. Here, the flow is low and the uneven bedform must have caused high bedform drag which caused the mean m value to be as low as 0.168. The mean m value of the 16 sand bed channel profiles illustrates this point by having low m values compared to the other channel bed types.

Based on Bathurst's research (1993), as discharge increases, the expected correlations between bed material and b, f, and m are that the flow velocity increases as the bed material size increases such that, for sand-bed channels, $m < 0.40$; for gravel-bed channels, $m = 0.35$ to 0.45; and for boulder-bed channels, $m = 0.45$ to 0.55.

In gravel-bed (containing both gravel and cobble and gravel and rock) channels, drops in flow resistance are achieved by the drowning of roughness elements as discharge rises, therefore causing high m values in all gravel channels. Subbasins v52 and v19 both had low flows during the study period, and exhibit low m values, 0.212 and 0.346, respectively. On the other hand, in gravel-bed channels not much bedform development is expected; therefore, the f values are low and the flow velocity increases at a higher rate as the discharge increases.

In the rock-bed channels, at low flows, the rock-bed channels are expected to have low m values, and as discharge increases, the rock bed channels are expected to have the highest m values among the different bed material types because of drowning of the rough bed material and, hence, smoothing of the roughness of the rocks protruded through the flow. As expected, the exponent m values increased, moving up the network from sand-bed channels (m = 0.467), via gravel, cobble (m = 0.503) and boulder-bed channels (m = 0.487), excepting gravel beds. Gravel-beds have the highest m value (0.503), higher than for cobble and rock bed channels. Since gravel-beds are defined as containing both gravel and cobble and gravel and rock, it is understandable for gravel-bed channels in the study area to have higher m values than would be expected for just those containing gravel. Excluding the two lowest m value subbasins, m31 and m311, the rock channel beds would have the highest mean m value and follow the expectation of being high m value channels. Subbasin m311 has the highest b value (0.562) in the study area followed by subbasin m31 (0.461). Having the higher b values, either f and m values would be lower to meet the continuum theory.

A total of 16 sand-bed channels, of which 12 contained 50% or more sand content, were investigated for the applicability of an empirical theory, **f > m in sand bed with increasing stream discharge**. A difference of means analysis of (f – m) values between sand beds with any amount of sand and non-sand bed indicates that sand beds are statistically insignificant at the 0.05 level. However, the mean difference analysis indicates that the role of sand beds with 50% or more sand content is statistically significant at the 0.05 level for the values of (f – m). The higher the channel bed sand content, the higher the rates of channel depth changes become. Even though f is smaller than m in the study area, the trend shows that depth increases more in 50% or more of sand-bed channels. This trend indicates that, as discharge increases, the sand-bed channels will have more eroded bed materials in the flow which would hamper the flow velocity; therefore, eventually f becomes higher than the m value.

Adding the scale factor to the regression of bed channels, for sand > 50% and (f – m) value, the R^2 as well as the statistical significance, improved. However, the statistical significance is not at the 0.05 level. Therefore, it can be concluded that there is no discernable differences between f and m in the study area.

Comparing difference of means values, it is found that f values are statistically discernible between sand and non-sand bed channels. The differences for b means between cobble and non-cobble channels as well as the difference of b and m means in gravel and non-gravel channels are also found to be sufficiently different. In the geographic scale context, even though there are statistically significant correlations between scale and b, f, and m, the overall influencing role of bed material on b, f, and m is indiscernible. Even though there is a correlation between f and sand bed channels at the 0.05 level, the overall influence of bed material on f is statistically indiscernible.

7.3.3 Bank Material

The expected correlations for channel bank material and b, f, and m are such that the value of the change in b will become larger in sequence from the least to the most resistant bank material: sand, gravel, cobble, and rock. In easily eroded channel banks, with the eroded bank material in the discharge, the rate of depth and flow velocity changes would be much less than the b values. So that in easily eroded banks, such as sand banks, a relatively wide, shallow channel develops, while in cemented bank materials (silt), the channel becomes deeper and narrower. As streams begin eroding their banks, their channel cross-sections become wide and shallow with consequent reductions of flow velocities.

Without the scale context, the influence of bank material on b, f and m values is examined using a t-test for difference of mean values. Comparing subbasins with the silt and non-silt banks, the mean differences of b are the greatest among all the other bank material type channels. However, the difference between silt versus non-silt bank materials for b is statistically indiscernible at the 0.05 level.

Contrary to the expected order of changes in b, rock banks have the highest b values and the 2nd lowest rate of f changes. The more resistant banks should result in higher rates of m changes than the less resistant banks. In easily erodable bank materials, a relatively wide shallow channel develops but, in the study area, small rates of width and bigger rates of depth changes occur. Since each bank, typically, is not of uniform material, but rather a mixture of materials, it is understandable that the observed results differ from the expected order of b, f, and m changes.

Without the scale context, the relationships (R^2) between b and f with rock, m with silt bank material are 0.4151, 0.4607, and 0.5227, respectively. These are among the highest correlations of determination of all the other watershed variables with b, f, and m. These findings are not expected. There must have another watershed variables in rock bank channel which strongly influencing b values.

With the scale context, the computed t-test value scale exceeds the critical values for b at the level of 0.0003, but, not the t-test value for the bank material variable for b. Therefore, it is concluded that channel bank material is not a significant predictor variable to influence b in the scale context.

With the scale context, channel bank material is not a significant variable to influence f at the 0.05 level. Including the interaction term between scale and bank material in the model, the statistical significance of the role of bank material type on f is significantly improved and became statistically significant at the 0.05 level. This indicates that the channel bank material variable and scale interact. Therefore, the interaction of the role of bank material on f values and geographic scale should be considered in any examination of the role of bank material on f.

Even though, the relationships between silt banks and m (R^2 of 0.5227) are much stronger than the role of any other bank material on b, f, and m, in the scale context, channel bank material alone is an insignificant variable influencing m.

In general, m values are high for all bank material types, especially silt channel banks where the b values are low which is geomorphologically expected in the silt bank subbasins.

Scale influences b and f, but channel bank material is not a significant predictor variable to influence b, f, nor m at 0.05 level of statistical significance, but adding an interaction term between scale and channel bank materials resulted in statistically significant for m and f. Therefore, interactions between the role of bank material on f and m values and geographic scale need to be considered when examining the role of bank materials on f and m.

7.3.4 Topographic Index

Statistical results support somewhat the expected outcomes and the statistical significance of the relationships between topographic maximum and topographic index standard deviation by themselves (without the scale context) with b only at the level of 0.05.

Topographic indices characterize the ability for subbasins to contain and transport discharge and, hence are considered as an important variable effecting hydraulic geometry. The expected correlations between topographic index and b, f, and m are that higher values of ln (area/tanβ) indices are reflective of a wide floodplain or area having a greater potential for increased runoff due to easily saturated areas which implies that areas with a higher topographic index will have high b, and the areas where the small differences between maximum and minimum topographic indices also influence b. Since maximum topographic indices are influencing variable for b, it is understandable that areas with highly different maximum and minimum ln (area/tanβ) values might negate the maximum topographic index's role on b which would results in not close relationship between b and topographic maximum index. The R^2 and the statistical significance between b and topographic index**,** specifically in indices of topographic minimum, topographic maximum, and topographic standard deviation, are stronger than those of f and m. However, any of the topographic indices are not influencing variables for f and m. It is understandable that topographic indices are more for width changes rather than depth of channel nor for flow velocity measure.

The relationships between the b, f, and m and topographic index in the scale context are not strong and the statistical insignificant at the 0.05 level. A little better relationship between b and topographic index is expected because it is, in a way, a measurement of saturation capacity. That is, the wetness of both sides of a channel bank gradually diminishes away from the stream. But, when a flow runs over the previous bank, the channel banks will be easily saturated and the banks will be easily eroded and so width increases. If the channel banks are saturated then the stream power can be applied to erode the channel banks and, therefore, b can be changed.

It is interesting that the strong, statistically significant relationship between topographic indices and b became highly insignificant when correlated with the scale variable. The subbasin size and topographic maximum correlate well ($R^2 = 0.58$) positively, but the b value and subbasin size correlate negatively. Could this be due to the interaction among topographic index, b, and scale? It needs further investigation, but it might be that high topographic index area (high area/tanβ), might not necessarily mean only wide, flat floodplain area, but also areas of increased runoff due to saturation.

Out of the 54 combinations of relationships between watershed predictor variables and b, f, and m, individually, five relationships (Great Valley vs. Non-Great Valley physiography for m; Crystalline vs. Non-Crystalline lithology for b and m; straight vs. non-straight channel pattern for b; sand vs. non-sand bed material for f), and, with the scale context including interaction term, five relationships (channel pattern for b and f; bank material for f; topographic maximum index for b; and topographic standard deviation index for b) are shown as statistically significant. These statistically significant watershed variables, specifically, channel pattern, bed and bank materials are also geomorphologically significant variables for b, f, and m. We have to recognize that some of the geomorphologically significant watershed variable such as channel shape is not indicated as influential variable for b, f, and m, which indicates that some of the watershed predictor variables are simply not scale related. Also, watershed predictor variables interact with other watershed predictor variables so the true nature of the influencing factor is not easily identifiable. This implies that, in addition to a single watershed variable, researchers need to investigate the roles of subset of most influential variables for b, f, and m to understand the resultants of their individual roles to b, f, and m.

7.4 Findings and Discussion: Which Subset of Watershed Predictor Variables Are Most Influential on b, f, and m?

Stepwise regressions were conducted for the original 43 subbasins and for the 23 well and moderately constrained subbasins (Table 7.3) as an aid to assess the most influential and statistically significant predictors for the estimation of b, f, and m values.

Since two different techniques of stepwise regressions were used, the comparisons of the regression results (Table 7.3) are presented for this purpose, rather than for comparing the magnitude of R^2.

Table 7.3 Most Significant Predictor Variables from Stepwise Regressions for b, f, and m

	N = 23 (Forward)	N = 43 (Backward)	N = 43 (Weighted[1], Backward)
	Well and Moderately Constrained Subbasins	All Study Subbasins	All Study Subbasins
b			
R^2	0.599	0.541	0.718
Significant[2] Predictor Variables	Channel Pattern	Channel Pattern	Physiography
	Size	Topo Min Index	Bank Material
	Asymmetry	Topo Max Index	Asymmetry
		Size	Topo Index Stdev
		Topo Index Stdev	Size
f			
R^2	0.571	0.512	0.640
Significant[2] Predictor Variables	Topo Min Index	Bed Material	Bed Material
	Bed Material	Channel Pattern	Channel Shape
	Size	Size	Asymmetry
			Topo Min Index
			Size
m			
R^2	0.2288	0.108	0.150
Significant[2] Predictor Variables	Size	Size	

Note: 1. All study subbasins are weighted by their sample sizes.
2. Statistically significant at the 0.05 level.

The rate of changes in width, b, can be estimated with all the predictor variables with an R^2 of 0.792. However, only asymmetry and size are statistically significant at the

0.05 levels in this model. Using predictor variables which are statistically significant at the 0.05 level only, channel pattern, topographic index minimum, topographic index maximum, topographic index standard deviation, and size, b can be estimated with an R^2 of 0.541.

In the 23 well and moderately constrained subbasins, using variables significant at the 0.05 level, b can be estimated via channel asymmetry and size, with an R^2 of 0.599. A difference with that for the 43 subbasins indicates that, for the well and moderately constrained subbasins, more easily changeable dynamic predictors such as channel asymmetry are required. However, for all subbasins, without any consideration of the constraints, the more or less static predictors, such as physiography or lithology which changes little over long time, can be used to estimate b. That is, general trends of b can be estimated with static variables, but a refined estimate of b needs to be made with dynamic variables.

The rate of change in depth, f, can be estimated with all predictor variables in the regression equation with the R^2 of 0.765; however, only size is statistically significant at the 0.05 level for the 43 original subbasins. Progressively eliminating insignificant variables in each stepwise regression, only bed material, channel pattern, and size remained, and f can be calculated with these statistically significant variables with an R^2 of 0.512. For 23 subbasins, with the 0.05 level of statistically significant variables, bed material, topographic minimum index, and size, f can be estimated with R^2 of 0.571, which indicates that well and moderately constrained subbasins have higher correlation with influential predictor variables than that of all the subbasins. As expected, bed material is an influential predictor variable for f for both the 43 and the subset of well and moderately constrained subbasins.

The similarity of the selected watershed predictor variables for b, f, and m for the 43 and the 23 subbasins indicates that in addition to the more or less static predictor variables (size and channel pattern or topographic minimum index), a dynamic predictor variable (a channel sediment related predictor variable such as bed material), is needed.

The rate of change in flow velocity, m, can be estimated with **all predictor variables** in the regression equation with an R^2 of 0.559, and with the sole statistically significant predictor variable, size, m can be estimated with an R^2 of only 0.108 in the 43 subbasin case. In the 23 subbasin case, m, can be estimated with **all predictor variables** in the regression equation with an R^2 of 0.240, and with the sole statistically significant predictor variable, size, m can be estimated with an R^2 of 0.229. Just as in the 43 subbasin case, only scale is identified as the statistically significant predictor variable in the 23 subbasins. As expected, in well and moderately constrained subbasins, the relationship between scale and m are higher than the case of 43 subbasins. Also m is harder exponents to be estimated compared to b and f. And, the scale variable is not statistically significant for m as it is for b and f. . Since estimating m is problematic, it is expected that, having a high confidence of b and f estimates, m can be derived.

Comparing the pattern of variables for the estimation of b, f, and m between the cases of 43 and 23 subbasins b can be estimated with higher R^2 values compared to those for m, and m is the hardest hydraulic geometry exponent to estimate. Clearly, any success in the estimation of m values is difficult with either only the significant predictor variable, scale, or even with all predictor variables and with a constraint of the 0.05 or better statistical significance.

7.5 Conclusions in a Broader Context for Future Research

In conclusion, this study has shown that the behavior of b, f, and m under higher discharges mainly results in higher m and f, with slight increases in cross-sectional area (f with negative b) in a scale context. With static predictor variables, the foundation of the b, f, and m can be estimated with the model. However, for a refined estimation of b, f, and m values, a more controlled selection of well constrained subbasins and flow resistance data should be used. More robust results are likely to be obtained by generating estimation equations recognizing composites of subbasin characteristics. Also, even though this study did not include flow frequency of the discharge data into the model, it is clear that including the flow frequency of the discharge data into the model for at-a-station hydraulic geometry, will provide more confident estimation of b, f, and m. Broeren and Singh's (1990) work demonstrated flow frequency of the discharge data into the model which improved downstream hydraulic geometry estimation in Illinois.

Since scale is proved to be an influential predictor variable for the estimation of b and f values, further investigation of the scale's role across various sizes such as under 150 square miles, over 150 square miles to 1,000 square miles , and larger than 1,000 square miles streams needs to be considered. That is, usually smaller streams are unstable and out of phase with the steady state condition in the main stream. McConkey and Singh (1992) found and declared that the power function relations are reasonable for watersheds greater than 100 square miles but may not be reliable for smaller drainage area streams. As their finding is evidenced in this study, by the fact that more than 2/3 of the poorly constrained subbasins are under 150 square miles in size, the power function relationship performed poorly for low flows. That is, because of the existence of riffle and pools in natural streams, the hydraulic geometry relations are rendered less reliable, especially at low stream flows.

However, it needs to be recognized that the statistical relationship between scale and b, f, and m is weak and that the relationship is limited to the watershed sizes of 0.38 to 1, 642 square miles in the Potomac River Basin. The findings are reasonably useful up to watershed sizes of a little over 10,000 square mile[s] (log of 4.138 watershed size). However, extrapolation is not warranted over 10,000 square miles of watershed size because, as the chosen mathematical model implies, the width of the channels will actually decrease as discharge increases. Clearly, this is physically and geomorphologically impossible.

It has increasingly been realized that to achieve a proper understanding of fluvial processes via hydraulic geometry, a function of the interactions of many hydraulic and physical drainage system characteristics and fluvial process-response relationships with watershed variables, including the sizes of channels and subbasins, we need to assess geographic scale as a variable influencing drainage basin response. Furthermore, this study's establishment of the differences of the influential predictor variables at various scales should help focus data collection efforts for the prediction of b, f, and m.

This study demonstrated that the change rates of channel width, depth, and flow velocity at at-a-station hydraulic geometry are systematic changes and a function of watershed scale. When considering the heterogeneous nature of subbasins in terms of their physiography, lithology, landuse, channel pattern and shape, bed and bank materials, and topographic index, the statistically significant relationships between geographic scale and b and f (but not m), are notable. In every selected predictor variable case, investigation of the correlations between b, f, and m with a single selected predictor variable in a scale context resulted in a noticeable improvement over the correlations between b, f, and m with a single selected predictor variable without the scale factor.

Even though it may be useful to strive for further demonstrating general trends of the scale impacts on b, f, and m prediction in complex interactions in a channel, there are needs to generate comprehensive datasets which will help formulate and test physical-statistical theories of spatial and scale variability of subbasins for the calculation and analyses of hydraulic geometry. More controlled measurements of various predictor variable values would yield much more consistent general trend information of the role of scale on b, f, and m. Such could be the consideration of stream flow reference levels, the understanding of recovery and response rates, and the cycles of the flood/draught extremes during the hydrographic survey measurements periods of channel width, depth and flow velocity, and discharge volume.

At best, the field hydrographic survey data used for this study are rated by the surveyors as 90% accurate and the locations of the survey points are sometimes roughly estimated from a reference point. Utilizing the advanced Light Detection and Range (LIDAR) technology, more accurate and precise measurements of channel width, depth, and flow velocity can be obtained. Also, the locations of the gage positions and hydraulic survey points can be obtained with much higher accuracy such that we can avoid the locations of stream gages being outside of their subbasins. The reason that some of the current stream gages are located outside of their basins is the result of a combination of inaccuracies in the stream locations as determined from digital elevation data, and inaccuracies in the location of the stream gage as defined by coordinates of latitude and longitude. Future models and empirical analyses should be based more accurate DEM representations of the terrain. Since the summation of b, f, and m values is unity and their individual values are decimal points, a minute difference can make a big impact on the analyses of scale impacts on the channel width and depth and stream flow velocity. Therefore, more accurate width, depth, and flow velocity measurements as well as more suitable locations of the hydrographic observation points and channel gage stations will improve measurement of the general trends of scale impacts on b, f, and m values.

In addition, accurate and higher spatial resolution of digital elevation data can eliminate many encountered problems such as spikes, depressions, and merging of cells for the delineation of subbasin boundaries and flow path determination using the digital elevation model. Despite the global availability of satellite-derived digital elevation data, a critical assessment of how their vertical and horizontal accuracies affect landforms is lacking and once the effect of satellite-derived digital elevation data errors on hydrogeographic analyses is better understood, delineation of drainage area boundaries and the sizes of drainage basins can better incorporate uncertainty analysis into catchment management decisions. Also, using Global Positioning System (GPS) could improve the positioning of the discharge, width, depth, and velocity survey points. In shallow channels, usage of LIDAR can eliminate manual hydrographic survey.

This research has demonstrated through inductive reasoning that there is evidence of geographic scale's role on at-a-station hydraulic geometry. Now, the future scientific endeavor is to formulate the findings into a theory. However, more rigorous hydrological principles and a mathematics-based theory of the scale impacts on b, f, and m is needed for the current empirical equations of at-a-station hydraulic geometry; written as scaling relations, using the equations for momentum, flow resistance, and continuity of open channel flow. Since there is a relationship between at-a-station hydraulic geometry and downstream hydraulic geometry and there is a limited and localized hydrological principle-based downstream hydraulic geometry model, theory-based at-a-station hydraulic geometry models are feasible.

The main limitation of the hydraulic geometry analysis is its neglect of the feedback from flow to form when discharge is competent to erode channel banks or bed. Hydraulic adjustments within a fixed channel are reversible, but there is plenty of evidence that hydraulic geometry relationships evolve over time. Models of channel response to changing flow must be based on the knowledge of the relative response time of hydraulic values under a range of flow conditions as well as the recovery time of subbasin into quasi-equillibrium.

Even though the representative elementary area (REA) in the literature has been historically much smaller (1 - 5 km^2) than 100 square miles in size, there are numerous cases of implied evidence of the similar concept of the REA in many hydraulic geometry variables in the study area. The REA is defined as a critical area at which implicit continuum assumptions may be used without knowledge of patterns of variable values although some knowledge of the underlying distributions may still be necessary. At scales smaller than the REA, the actual patterns of variability are important in determining the hydrological response. At larger scales a statistical description of spatial variability should suffice. In accord with the suggestion of Bloschl et al. (1995) and Beven (1995) that the size of the rea might vary between watershed environments and processes, it could be that the rea would be at 100 square miles for the at-a-station hydraulic geometry in the study area?

Another example is that Hogan and Church (1989) found that the relationships of at-a-station hydraulic geometry for Hangover Creek were well described by power functions, but that the plots displayed a discontinuity in the relationship at a certain discharge ($1m^3/s$,) which can be equated to drainage area size. They found that below this threshold, increases in discharge are attributable primarily to increases in mean velocity and channel width, with little change in mean depth. They noted that above this threshold, increases in discharge are attributable primarily to increases in mean depth and velocity, with little change in channel width.

The major predictor variables which can adjust to accommodate flows at a site are locally unstable in the sense that a change or perturbation to any system component will result in a new set of relationships among the components rather than a restoration of the previously existing quasi-equilibrium. This suggests that there may be no single, universally applicable method of predicting hydraulic geometry relationships and that stable configurations in natural alluvial channels cannot be expected to persist over time. However, this research indicates that subbasin size clearly influences hydraulic geometry and that some of the subbasin characteristics such as physiography, lithology, and scale are more or less static variables (static in longer temporal scale) that can be used for prediction of hydraulic geometry of un-surveyed channels. In addition, the temporal scale, such as recovery time, needs to be considered in the development of hydraulic geometry models.

Natural channels undergo continuous change, and the hydraulic geometry exponents describing a cross-section vary annually or during bankfull floods if bed and banks are modified. The flow variables are mutually interdependent, meaning that a change in any single parameter requires a response in one or more of the others. The difficulty in understanding rivers is when you consider that discharge and load are in continuous flux, and so all the hydraulic variables must always be adjusting.

In situations where all hydraulic parameters can vary and where they do not respond to changing conditions at equal rates and intensities, multiple modes of adjustments are likely. Even though there is a notion of inherent instability of hydraulic geometry, with it's implication that hydraulic geometry is not particularly precise and cannot be site independent, hydraulic geometry processes are determinate based on laws of hydraulics and relations of flow resistance. The wide range of frictional characteristic and channel shapes would not allow a universally-applicable set of at-a-station hydraulic geometry. However, including temporal information on the flow reference level (bankfull or low flow) into a model, the flow resistance and frictional characteristics can be better understood and, therefore the hydraulic geometry of channels can be better estimated.

APPENDICES

USGS Hydrographic survey data over the study area such as stream discharge (volume per second), channel width, depth, and flow velocity, as well as information on cross section are included in Appendix A.

Algorithms for subbasin boundary delineation and Topographic Index calculation algorithms are in Appendix B.

Data which characterize each subbasin, which are collected from the hydrographic surveys, calculated and or derived are in Appendix C.

APPENDIX A

USGS HYDROGRAPHIC FIELD NOTE/DATA FOR THE POTOMAC RIVER BASIN AREA (STREAM DISCHARGE, CHANNEL WIDTH, MEAN VELOCITY ON STREAM CROSS-SECTIONS

bfile1a	obs. #		width	area	mean vel.	gageht.	Discharge	depth	w/d	cum_width	Asym
[1,]	538	6/18/85	79	76	1.27	2.27	96.4	0.96	82.12	38.25	-0.287
[2,]	540	9/12/85	61	41.2	0.69	1.68	28.5	0.68	90.32	28.00	-0.284
[3,]	542	1/17/86	73	81	1.09	2.23	87.9	1.11	65.79	35.00	-0.188
[4,]	544	4/8/86	90	145	1.74	2.86	253	1.61	55.86	43.50	0.000
[5,]	545	6/30/86	64	62.3	0.85	1.98	52.7	0.97	65.75	31.25	-0.115
[6,]	546	8/15/86	67	44.7	0.64	1.69	28.5	0.67	100.43	32.00	-0.076
[7,]	547	10/3/86	68	64.9	0.88	2.02	57.1	0.95	71.25	32.50	0.129
[8,]	549	3/19/87	86	131	1.88	2.84	246	1.52	56.46	41.50	-0.080
[9,]	550	6/10/87	78	87.4	1.19	2.3	104	1.12	69.61	38.50	-0.290
[10,]	551	7/16/87	69	63.6	0.73	1.94	46.4	0.92	74.86	33.50	-0.159
[11,]	552	8/31/87	68	47.7	0.61	1.72	29	0.70	96.94	32.75	-0.217
[12,]	553	10/14/87	65	49.7	0.68	1.79	33.8	0.76	85.01	31.75	-0.166
[13,]	554	2/19/88	84	131	1.46	2.65	191	1.56	53.86	40.50	0.042
[14,]	555	3/30/88	90	181	1.68	2.97	304	2.01	44.75	43.25	-0.153
[15,]	557	6/28/88	70	61.9	0.85	1.99	52.6	0.88	79.16	34.00	-0.195
[16,]	558	8/10/88	68	63.7	0.46	1.72	29.5	0.94	72.59	32.50	0.000
[17,]	559	9/15/88	66	52.7	0.73	1.85	38.5	0.80	82.66	32.00	-0.227
[18,]	560	10/27/88	67	63.5	0.66	1.89	41.9	0.95	70.69	32.25	-0.097
[19,]	561	12/6/88	78	80.4	1.04	2.21	83.3	1.03	75.67	37.75	0.194
[20,]	563	7/19/89	90	178	1.92	3.05	342	1.98	45.51	43.50	-0.120
[21,]	564	8/17/89	78	94.2	1.2	2.34	113	1.21	64.59	38.00	-0.059
[22,]	565	10/3/89	87	129	1.83	2.83	236	1.48	58.67	42.00	-0.208
[23,]	566	11/7/89	77	100	1.58	2.55	158	1.30	59.29	36.50	-0.195
[24,]	568	3/13/90	84	119	1.35	2.56	161	1.42	59.29	42.00	0.244
[25,]	570	10/5/90	76	93.6	1.38	2.44	129	1.23	61.71	36.50	-0.232
[26,]	574	7/9/91	67	69.1	0.76	1.99	52.6	1.03	64.96	32.50	-0.253
[27,]	575	7/16/91	66	58.3	0.68	1.86	39.9	0.88	74.72	32.25	-0.143
[28,]	582	6/11/92	87	131	1.65	2.75	216	1.51	57.78	41.25	-0.266
[29,]	583	9/4/92	73	79.8	0.82	2.09	65.2	1.09	66.78	35.00	-0.387
	Ave		75	88.99	1.11	2.24	114.37	1.15	68.09	36.22	-0.131
bfile2a											
[1,]	608	2/13/85	240	951	4.02	5.51	3820	3.96	60.57	117.50	-0.104
[2,]	609	4/1/85	249	1660	4.53	8.5	7520	6.67	37.35	123.50	0.048
[3,]	610	10/25/85	213	511	2.56	3.67	1310	2.40	88.78	104.50	0.029
[4,]	611	12/4/85	248	1350	4.58	7.2	6180	5.44	45.56	121.50	0.033
[5,]	615	2/3/87	228	654	2.74	3.99	1790	2.87	79.49	112.00	0.139
[6,]	620	5/10/88	235	742	3.27	4.51	2430	3.16	74.43	111.25	-0.040
[7,]	623	1/19/89	240	839	2.81	4.44	2360	3.50	68.65	117.25	0.029
[8,]	628	5/30/90	251	1700	4.64	8.49	7880	6.77	37.06	124.00	0.029
[9,]	632	10/24/90	250	1610	4.35	8.04	7010	6.44	38.82	125.00	0.061
[10,]	633	10/25/90	235	913	4.15	5.64	3790	3.89	60.49	117.50	0.142
[11,]	634	10/30/90	200	460	2.5	3.54	1150	2.30	86.96	100.00	0.086

[12,]	635	11/9/90	197	431	2.32	3.34	1000	2.19	90.04	96.75	0.087
[13,]	641	2/19/92	184	405	2.4	2.96	971	2.20	83.60	92.00	0.010
[14,]	642	2/26/92	223	1410	3.84	7.21	5420	6.32	35.27	111.90	0.066
[15,]	643	3/2/92	207	647	3.71	4.25	2400	3.13	66.23	103.50	0.082
[16,]	644	5/1/92	204	622	1.95	3.2	1210	3.05	66.91	96.75	0.017
[17,]	648	1/8/93	211	585	2.95	4.13	1730	2.77	76.10	98.50	0.037
[18,]	649	3/24/93	243	1880	4.54	9.95	8540	7.74	31.41	111.25	-0.010
[19,]	650	4/6/93	221	893	4.2	5.46	3750	4.04	54.69	107.50	-0.046
[20,]	651	5/6/93	212	524	2.98	3.76	1560	2.47	85.77	99.00	-0.040
[21,]	652	6/16/93	186	329	1.72	2.86	567	1.77	105.16	89.50	0.017
	Ave		223	910.3	3.37	5.27	3447.05	2.19	65.40	108.60	0.032
bfile3a								pg3			
[1,]	524	1/3/85	121	228	1.66	2.29	378	1.88	64.21	58.00	0.107
[2,]	526	6/17/85	120	177	1.21	1.82	214	1.48	81.36	58.25	0.091
[3,]	527	7/29/85	118	185	1.24	1.92	230	1.57	75.26	56.75	0.118
[4,]	528	9/12/85	110	134	0.93	1.48	124	1.22	90.30	53.00	0.101
[5,]	529	10/22/85	116	150	1.02	1.62	153	1.29	89.71	55.75	0.098
[6,]	532	4/7/86	128	279	1.91	2.69	533	2.18	58.72	61.00	-0.183
[7,]	533	7/1/86	110	137	0.96	1.51	132	1.25	88.32	52.25	0.091
[8,]	534	7/30/86	110	132	0.86	1.43	114	1.20	91.67	53.50	0.157
[9,]	535	10/1/86	107	109	0.74	1.27	80.4	1.02	105.04	51.50	0.165
[10,]	536	11/18/86	110	127	0.84	1.43	107	1.15	95.28	53.00	0.000
[11,]	537	12/22/86	122	243	1.7	2.41	414	1.99	61.25	59.00	0.218
[12,]	538	3/16/87	123	248	1.86	2.49	461	2.02	61.00	59.50	0.191
[13,]	539	6/8/87	123	203	1.4	2.06	285	1.65	74.53	58.50	0.094
[14,]	540	9/1/87	108	114	0.74	1.29	84.6	1.06	102.32	52.50	0.140
[15,]	541	10/13/87	113	138	0.94	1.5	130	1.22	92.53	55.00	0.138
[16,]	542	11/23/87	120	194	1.32	1.97	257	1.62	74.23	57.00	0.113
[17,]	543	2/17/88	123	242	1.93	2.54	467	1.97	62.52	59.50	0.132
[18,]	545	6/27/88	117	164	1.16	1.74	191	1.40	83.47	56.00	0.110
[19,]	546	8/9/88	114	135	0.9	1.47	122	1.18	96.27	55.00	0.000
[20,]	547	9/14/88	115	142	0.97	1.54	138	1.23	93.13	56.00	0.117
[21,]	548	10/24/88	119	136	0.99	1.5	134	1.14	104.13	59.50	0.072
[22,]	549	12/5/88	121	176	0.9	1.61	158	1.45	83.19	58.50	0.144
[23,]	551	4/10/89	130	307	2.12	2.88	650	2.36	55.05	63.00	0.090
[24,]	553	8/16/89	126	220	1.42	2.13	312	1.75	72.16	63.00	-0.118
[25,]	554	10/3/89	125	215	1.38	2.12	296	1.72	72.67	62.50	0.135
[26,]	555	11/6/89	114	160	1.06	1.66	169	1.40	81.23	55.00	0.079
[27,]	557	3/12/90	122	210	1.39	2.07	292	1.72	70.88	61.00	0.000
[28,]	558	10/3/90	105	118	0.85	1.35	100	1.12	93.43	50.50	0.104
[29,]	559	11/8/90	127	247	1.67	2.39	413	1.94	65.30	61.50	0.126
[30,]	561	6/4/91	119	173	1.18	1.79	204	1.45	81.86	57.00	0.129
[31,]	562	7/15/91	114	134	0.9	1.44	121	1.18	96.99	55.50	0.147
[32,]	563	10/2/91	102	117	0.8	1.81	93.5	1.15	88.92	49.50	0.124
[33,]	564	2/4/92	117	147	1.05	1.58	154	1.26	93.12	58.50	0.145
[34,]	565	5/7/92	133	267	1.74	2.47	464	2.01	66.25	64.50	-0.110
[35,]	566	6/4/92	124	217	1.52	2.18	330	1.75	70.86	60.50	0.135
[36,]	567	6/10/92	136	307	1.86	2.77	570	2.26	60.25	66.50	-0.093
[37,]	568	9/2/92	121	150	1.03	1.59	155	1.24	97.61	58.50	0.125
[38,]	569	10/5/92	120	145	0.97	1.53	141	1.21	99.31	57.50	0.126
[39,]	571	2/17/93	130	247	1.62	2.37	400	1.90	68.42	63.00	0.126
[40,]	573	6/18/93	127	194	1.22	1.9	236	1.53	83.14	62.50	0.134

[41,]	574	8/2/93	122	150	0.95	1.56	142	1.23	99.23	59.50	0.130
[42,]	575	9/7/93	125	179	1.09	1.8	196	1.43	87.29	59.50	0.112
[43,]	576	10/5/93	126	186	1.15	1.87	214	1.48	85.35	60.00	-0.146
[44,]	577	10/27/93	127	168	1.01	1.72	170	1.32	96.01	121.00	0.056
[45,]	579	8/1/94	136	244	1.69	2.41	413	1.79	75.80	65.00	0.217
		Ave	120	184.3	1.24	1.89	247.61	1.52	81.99	59.42	0.089
bfie4a											
[1,]	202	2/14/85	16	13.3	1.34	1.34	17.8	0.83	19.25	6.25	0.072
[2,]	204	6/17/85	15	8.66	0.49	0.95	4.23	0.58	25.98	6.75	-0.060
[3,]	205	7/29/85	13	7.6	0.43	0.89	3.25	0.58	22.24	5.75	0.047
[4,]	209	4/7/86	15.5	13.1	1.38	1.35	18.1	0.85	18.34	7.25	0.099
[5,]	210	7/1/86	13.1	7.64	0.6	0.96	4.62	0.58	22.46	6.15	0.001
[6,]	213	10/1/86	6.5	1.43	0.57	0.74	0.82	0.22	29.55	2.85	0.203
[7,]	214	11/18/86	11.8	4.34	0.27	0.81	1.16	0.37	32.08	5.30	0.177
[8,]	215	12/19/86	13	7.6	0.72	1.02	5.48	0.58	22.24	6.13	0.198
[9,]	216	3/16/87	14	8.95	1.09	1.15	9.74	0.64	21.90	6.63	0.194
[10,]	217	6/8/87	14	7.66	0.92	1.07	7.05	0.55	25.59	6.50	-0.029
[11,]	218	9/1/87	11.5	3.47	0.33	0.8	1.16	0.30	38.11	5.30	0.014
[12,]	220	11/23/87	9.5	2.72	0.65	0.85	1.77	0.29	33.18	4.38	-0.222
[13,]	221	2/17/88	14	7.39	0.81	1.04	5.99	0.53	26.52	6.38	-0.027
[14,]	222	3/29/88	12.5	7.35	0.6	0.98	4.44	0.59	21.26	5.63	0.078
[15,]	223	8/9/88	13	4.49	0.46	0.87	2.05	0.35	37.64	6.00	-0.078
[16,]	224	9/14/88	9.3	3.23	0.49	0.84	1.59	0.35	26.78	4.43	-0.186
[17,]	225	10/24/88	10	3.08	0.46	0.83	1.43	0.31	32.47	4.65	-0.127
[18,]	226	12/5/88	8.7	3.24	0.5	0.84	1.62	0.37	23.36	4.20	0.099
[19,]	227	1/18/89	13	6.08	0.81	1	4.93	0.47	27.80	6.03	-0.006
[20,]	228	4/10/89	14	7.96	1.1	1.12	8.74	0.57	24.62	6.63	0.044
[21,]	230	8/16/89	13.7	6.82	0.59	0.97	4.04	0.50	27.52	6.60	-0.043
[22,]	231	10/2/89	14.5	7.76	0.79	1.05	6.14	0.54	27.09	7.25	0.074
[23,]	232	11/6/89	9.9	3.74	0.59	0.88	2.22	0.38	26.21	4.60	-0.051
[24,]	234	1/31/90	15	10.1	1.03	1.16	10.4	0.67	22.28	7.50	0.014
[25,]	235	4/23/90	13	6.72	0.73	1	4.93	0.52	25.15	6.00	0.028
[26,]	236	8/28/90	8.7	4.02	0.68	0.91	2.72	0.46	18.83	4.30	-0.020
[27,]	237	10/2/90	10	3.98	0.48	0.87	1.92	0.40	25.13	4.95	-0.099
[28,]	238	11/8/90	15	10.4	0.82	1.12	8.5	0.69	21.63	7.00	0.028
[29,]	239	4/22/91	15	12.8	1.11	1.29	14.2	0.85	17.58	7.50	0.012
[30,]	240	6/4/91	14	8	0.59	0.99	4.74	0.57	24.50	6.50	0.090
[31,]	241	7/15/91	12.5	5.12	0.45	0.88	2.29	0.41	30.52	5.75	0.029
[32,]	242	10/2/91	13	6.44	0.38	0.89	2.45	0.50	26.24	6.50	0.022
[33,]	243	2/3/92	14	8.33	0.54	0.98	4.5	0.60	23.53	7.00	0.044
[34,]	244	4/30/92	14.8	15.9	1.41	1.39	22.4	1.07	13.78	6.70	0.035
[35,]	245	6/4/92	15	12.7	1.31	1.3	16.7	0.85	17.72	7.00	0.071
[36,]	246	9/1/92	14	9.72	1.19	1.2	11.6	0.69	20.16	6.50	0.134
[37,]	247	10/5/92	15	9.87	0.99	1.15	9.76	0.66	22.80	6.88	-0.081
[38,]	248	11/18/92	13	9.57	0.55	1.03	5.28	0.74	17.66	6.50	-0.134
[39,]	249	1/6/93	15.3	15.3	1.31	1.39	20.1	1.00	15.30	7.03	-0.070
[40,]	250	2/17/93	16.5	12.1	1.34	1.3	16.2	0.73	22.50	7.50	0.075
[41,]	252	5/12/93	16	17.6	1.68	1.8	29.6	1.10	14.55	8.00	0.082
[42,]	253	6/23/93	15	13	1.14	1.27	14.8	0.87	17.31	7.00	0.042
[43,]	254	8/2/93	14.5	9.97	0.82	1.11	8.21	0.69	21.09	6.63	0.018
[44,]	255	9/7/93	13	7.17	0.47	0.94	3.39	0.55	23.57	6.00	0.107
[45,]	256	10/27/93	13	8.55	0.34	0.92	2.94	0.66	19.77	6.50	0.113

[46,]	257	12/7/93	15	17.5	1.34	1.47	23.5	1.17	12.86	7.00	-0.085
[47,]	258	2/1/94	15	14.2	1.09	1.31	15.5	0.95	15.85	7.50	0.064
	Ave		13.2	8.44	0.80	1.06	7.98	0.61	23.46	6.20	0.008
bfile6a											
[1,]	469	1/3/85	69	150	1.51	2.83	227	2.17	31.74	33.00	-0.148
[2,]	471	6/17/83	67	131	1.54	2.75	202	1.96	34.27	31.75	-0.222
[3,]	472	7/29/85	63	116	1.34	2.59	156	1.84	34.22	30.25	-0.162
[4,]	473	9/12/85	60	104	1.25	2.47	130	1.73	34.62	29.50	-0.181
[5,]	474	10/22/85	67	128	1.72	2.81	220	1.91	35.07	32.25	-0.203
[6,]	476	4/7/86	75	156	2.37	3.18	370	2.08	36.06	36.00	-0.026
[7,]	477	7/1/86	58	106	1.49	2.6	158	1.83	31.74	27.75	-0.082
[8,]	478	7/30/86	56	99.2	1.22	2.44	121	1.77	31.61	26.75	-0.008
[9,]	479	10/1/86	56	91.4	1	2.32	91.7	1.63	34.31	26.50	0.027
[10,]	480	12/19/86	69	168	1.7	2.97	286	2.43	28.34	33.00	-0.003
[11,]	482	6/8/87	64	129	1.53	2.73	198	2.02	31.75	30.75	-0.071
[12,]	483	9/1/87	58	104	1.14	2.44	119	1.79	32.35	27.00	-0.074
[13,]	484	10/13/87	58	101	1.03	2.36	104	1.74	33.31	27.75	0.253
[14,]	485	2/17/88	64	145	1.61	2.83	234	2.27	28.25	30.25	-0.007
[15,]	486	3/29/88	65	129	1.43	2.67	184	1.98	32.75	31.00	-0.106
[16,]	487	5/9/88	78	190	1.91	3.15	362	2.44	32.02	37.50	-0.036
[17,l	488	8/9/88	59	109	1.09	2.42	119	1.85	31.94	27.75	0.004
[18,]	489	10/26/88	56	104	0.93	2.32	96.4	1.86	30.15	26.50	-0.090
[19,]	490	12/5/88	56	103	0.93	2.32	95.5	1.84	30.45	26.50	-0.090
[20,]	491	1/18/89	60	133	1.41	2.7	188	2.22	27.07	28.75	-0.084
[21,]	492	4/10/89	69	153	1.76	2.93	270	2.22	31.12	33.00	0.086
[22,]	493	8/16/89	59	120	1.31	2.57	157	2.03	29.01	27.75	-0.173
[23,]	494	10/2/89	69	127	1.59	2.73	202	1.84	37.49	33.50	0.274
[24,]	495	11/6/89	49	96.5	1.13	2.4	109	1.97	24.88	23.50	-0.100
[25,]	497	3/12/90	62	119	1.65	2.74	196	1.92	32.30	54.50	-0.087
[26,]	498	8/28/90	58	106	1.5	2.61	159	1.83	31.74	29.00	-0.056
[27,]	499	10/2/90	50	96	1.14	2.37	109	1.92	26.04	23.50	-0.091
[28,]	500	11/8/90	69	136	1.93	2.9	262	1.97	35.01	32.75	-0.261
[29,]	502	6/3/91	64	119	1.72	2.73	205	1.86	34.42	32.00	-0.302
[30,]	503	7/15/91	60	102	1.2	2.43	122	1.70	35.29	28.75	0.161
[31,]	504	10/1/91	54	107	1.26	2.48	135	1.98	27.25	25.50	0.102
[32,]	505	2/3/92	59	109	1.36	2.53	148	1.85	31.94	28.25	-0.144
[33,]	507	6/4/92	68	141	1.99	2.98	281	2.07	32.79	32.75	-0.293
[34,]	508	9/2/92	58	106	1.47	2.58	156	1.83	31.74	60.25	-0.183
[35,]	509	10/5/92	55	106	1.42	2.56	151	1.93	28.54	26.00	0.086
[36,]	511	2/17/93	70	154	2.12	3.09	326	2.20	31.82	33.25	0.107
[37,]	514	8/2/93	58	104	1.49	2.57	155	1.79	32.35	28.00	0.097
	Ave		61.9	121.6	1.46	2.65	183.91	1.95	31.78	31.16	-0.056
bfile7a											
[1,]	382	8/18/88	16	5.09	0.42	1.43	2.12	0.32	50.29	8.00	-0.124
[2,]	383	10/11/88	16.3	6.56	0.54	1.48	3.51	0.40	40.50	8.15	0.113
[3,]	384	11/15/88	30	18.3	0.7	1.65	12.9	0.61	49.18	15.00	0.334
[4,]	385	1/3/89	32	21.4	1	1.75	21.3	0.67	47.85	16.00	0.265
[5,]	388	5/1/89	32.5	26.5	1.4	1.87	37	0.82	39.86	16.25	0.248
[6,]	389	6/13/89	43	34.4	1.46	1.94	50.2	0.80	53.75	21.50	0.304
[7,]	390	7/25/89	42.5	33.4	1.35	1.92	45	0.79	54.08	21.25	0.236
[8,]	391	10/4/89	36	19.6	0.68	1.65	13.3	0.54	66.12	18.00	0.211
[9,]	392	11/16/89	41.5	31.7	1.71	1.98	54.2	0.76	54.33	20.75	0.351

[10,]	393	1/22/90	41.5	28.9	1.5	1.91	43.4	0.70	59.59	20.70	0.380
[11,]	394	2/12/90	66	60.6	1.85	2.22	112	0.92	71.88	33.00	0.032
[12,]	395	3/27/90	63.5	46.6	1.53	2.07	71.5	0.73	86.53	31.75	0.057
[13,]	396	5/17/90	65.5	73.1	2.19	2.39	160	1.12	58.69	32.75	0.024
[14,]	397	6/21/90	63.5	28.9	1.05	1.82	30.3	0.46	139.52	31.75	0.112
[15,]	398	8/14/90	28	13.2	0.7	1.59	9.28	0.47	59.39	14.00	0.274
[16,]	400	11/14/90	62.5	34.1	1.21	1.9	41.3	0.55	114.55	31.25	0.078
[17,]	401	1/10/91	65	70	2	2.34	140	1.08	60.36	63.63	-0.997
[18,]	402	3/6/91	64.5	64.3	2.17	2.33	139	1.00	64.70	32.25	0.033
[19,]	403	4/18/91	65	52.3	1.72	2.14	89.8	0.80	80.78	32.50	0.028
[20,]	409	1/6/92	45	39.8	1.56	2.02	61.9	0.88	50.88	22.50	0.214
[21,]	410	2/20/92	47	46.3	1.87	2.13	86.7	0.99	47.71	23.50	-0.227
[22,]	411	4/1/92	66.3	65.1	2	2.29	130	0.98	67.52	33.15	-0.065
[23,]	412	5/20/92	59.1	46.2	1.15	1.97	53.1	0.78	75.60	29.55	0.233
[24,]	413	7/9/92	33.8	19.1	1.11	1.73	21.1	0.57	59.81	16.53	0.315
[25,]	415	10/7/92	24.6	13.1	1.17	1.67	15.3	0.53	46.20	12.30	-0.156
	Ave		46	35.94	1.36	1.93	57.77	0.73	63.99	24.24	0.091
bfile8a											
[1,]	12	1/8/91	43	50.8	1.08	1.79	55	1.18	36.40	21.50	-0.017
[2,]	13	3/11/91	32.2	24.1	0.7	1.5	16.8	0.75	43.02	16.10	-0.017
[3,]	14	4/15/91	42	38.6	1.1	1.7	42.8	0.92	45.70	21.00	0.085
[4,]	23	1/3/92	33.6	28.6	0.86	1.56	24.7	0.85	39.47	16.80	-0.009
[5,]	24	2/18/92	43	46.3	1.51	1.86	69.8	1.08	39.94	21.50	0.089
[6,]	25	3/31/92	42	46.6	1.28	1.8	59.8	1.11	37.85	17.00	-0.053
[7,]	26	5/18/92	34	21.9	0.5	1.39	10.9	0.64	52.79	21.00	0.025
[8,]	27	5/21/92	29.9	17.3	0.37	1.31	6.4	0.58	51.68	14.95	0.025
[9,]	28	6/1/92	39.5	30.6	0.88	1.57	27	0.77	50.99	19.75	-0.042
[10,]	29	7/13/92	17.6	9.2	0.38	1.23	3.45	0.52	33.67	8.80	-0.149
[11,]	30	8/17/92	28.5	17.7	0.41	1.34	7.22	0.62	45.89	14.25	-0.069
[12,]	31	10/2/92	28.4	17	0.32	1.3	5.45	0.60	47.44	14.20	-0.018
[13,]	32	11/17/92	30.6	21.2	0.53	1.41	11.2	0.69	44.17	15.30	0.048
	Ave		34.2	28.45	0.76	1.52	26.19	0.79	43.77	17.09	-0.008
bfile9a											
[1,]	354	11/17/88	67	56	0.63	1.03	35	0.84	80.16	33.50	-0.042
[2,]	355	2/16/89	70	117	1.44	1.78	168	1.67	41.88	35.00	0.030
[3,]	356	3/23/89	70	92.6	1.09	1.46	101	1.32	52.92	35.00	0.006
[4,]	357	5/3/89	70	111	1.38	1.74	153	1.59	44.14	35.00	-0.005
[5,]	358	7/27/89	72	67.7	0.84	1.21	56.8	0.94	76.57	36.00	-0.122
[6,]	359	10/3/89	70	74.1	0.99	1.3	73.1	1.06	66.13	35.00	-0.114
[7,]	360	11/20/89	70	74.6	1.02	1.32	75.9	1.07	65.68	35.00	-0.075
[8,]	362	1/31/90	70.5	144	1.92	2.25	276	2.04	34.52	35.25	-0.055
[9,]	363	2/14/90	70	88.3	1.3	1.55	115	1.26	55.49	35.00	-0.062
[10,]	364	3/26/90	62	69.8	1.4	1.44	97.4	1.13	55.07	31.00	-0.054
[11,]	365	5/15/90	73	117	1.46	1.84	171	1.60	45.55	36.50	-0.063
[12,]	367	6/29/90	61.5	53.9	0.98	1.16	52.9	0.88	70.17	30.75	-0.031
[13,]	368	8/8/90	60	51.4	1.01	1.15	52	0.86	70.04	30.00	-0.039
[14,]	369	10/4/90	60	43.2	0.75	0.98	32.4	0.72	83.33	30.00	-0.066
[15,]	372	11/9/90	62	57.5	0.97	1.18	56	0.93	66.85	31.00	-0.071
[16,]	373	1/8/91	62	92.7	1.78	1.77	165	1.50	41.47	31.00	-0.029
[17,]	374	3/11/91	63	77.1	1.03	1.52	79.3	1.22	51.48	31.50	-0.045
[18,]	375	4/15/91	63	86.7	1.55	1.63	134	1.38	45.78	31.75	-0.049
[19,]	376	6/4/91	61	51.6	0.77	1.07	39.6	0.85	72.11	30.50	-0.049

[20,]	377	7/9/91	54	37.4	0.63	0.9	23.5	0.69	77.97	27.00	-0.009
[21,]	378	7/25/91	42.5	28.3	0.41	0.78	11.7	0.67	63.83	21.25	-0.084
[22,]	379	8/19/91	44	29	0.36	0.76	10.4	0.66	66.76	22.00	-0.048
[23,]	380	10/1/91	59	41.2	0.68	0.96	27.9	0.70	84.49	29.50	-0.055
[24,]	381	11/12/91	59	43.5	0.77	1.01	33.6	0.74	80.02	29.50	-0.084
[25,]	382	1/3/92	62	64.7	1.23	1.32	79.6	1.04	59.41	31.00	-0.032
[26,]	383	2/18/92	72.5	98.4	1.23	1.59	121	1.36	53.42	36.25	-0.101
[27,]	384	3/31/92	62.5	98.5	1.84	1.86	181	1.58	39.66	31.25	-0.014
[28,]	385	5/18/92	60.5	55.8	1.06	1.21	59.1	0.92	65.60	30.25	-0.028
[29,]	386	7/13/92	57	38.5	0.69	0.95	26.6	0.68	84.39	28.50	-0.091
[30,]	388	9/2/92	58	33.22	0.49	0.83	16.2	0.58	100.00	29.00	-0.092
[31,]	391	1/7/93	70	90.5	1.46	1.6	132	1.29	54.14	35.00	0.020
[32,]	395	8/19/93	66	53.8	0.85	1.13	45.6	0.82	80.97	33.00	-0.067
[33,]	396	7/8/93	68	56.2	0.78	1.12	44	0.83	82.28	32.50	0.059
[34,]	398	4/25/94	73	93.3	1.53	1.65	143	1.28	57.12	36.50	0.073
[35,]	399	6/14/94	69	54.3	0.72	1.16	47.4	0.79	87.68	34.50	-0.111
[36,]	400	7/7/94	68	55.9	1.01	1.19	56.6	0.82	82.72	34.00	0.107
[37,]	401	8/16/94	66	44.2	0.76	1.02	33.6	0.67	98.55	33.00	0.163
[38,]	402	10/3/94	68	49.7	0.84	1.09	41.6	0.73	93.04	34.00	0.137
[39,]	403	12/2/94	69	66.4	1.18	1.36	78.7	0.96	71.70	34.25	0.085
[40,]	404	3/17/95	64.5	71	1.6	1.5	114	1.10	58.60	32.25	-0.033
[41,]	405	5/12/95	61	53	1.16	1.23	61.5	0.87	70.21	30.50	-0.044
[42,]	406	7/6/95	60	44.5	0.95	1.09	42.3	0.74	80.90	30.00	0.087
[43,]	407	8/28/95	53.6	28.5	0.5	0.82	14.4	0.53	100.81	26.80	0.123
		Ave	63.8	66.42	1.05	1.29	78.57	1.02	67.76	31.87	-0.023
bfile10a											
[1,]	48	1/30/85	4.5	3.51	0.3	2.39	1.05	0.78	5.77	2.25	-0.176
[2,]	49	3/5/85	6.7	5.81	0.55	2.59	3.17	0.87	7.73	3.35	0.101
[3,]	50	4/18/85	6.5	5.16	0.34	2.46	1.75	0.79	8.19	3.25	0.041
[4,]	51	6/4/85	4	2.28	0.44	2.36	1	0.57	7.02	2.00	0.086
[5,]	54	7/16/85	4	2.23	0.28	2.19	0.62	0.56	7.17	2.00	0.121
[6,]	55	7/30/85	2.4	0.51	0.86	2.2	0.44	0.21	11.29	1.20	-0.043
[7,]	56	7/30/85	2.4	0.51	0.86	2.2	0.46	0.21	11.29	1.20	-0.104
[8,]	58	8/20/85	1.4	0.34	0.47	2.11	0.16	0.24	5.76	0.70	-0.176
[9,]	59	9/26/85	2	0.59	0.24	2.06	0.14	0.30	6.78	1.00	0.119
[10,]	60	10/8/85	1.3	0.45	0.24	2.13	0.11	0.35	3.76	0.65	0.078
[11,]	61	10/8/85	0.8	0.3	0.29	2.11	0.09	0.38	2.13	0.40	-0.033
[12,]	62	11/13/85	6.2	5.08	0.61	2.54	3.1	0.82	7.57	3.10	0.069
[13,]	63	11/26/85	6.6	5.33	1.07	2.67	5.7	0.81	8.17	3.33	0.156
[14,]	64	12/17/85	7.1	5.73	0.75	2.62	4.31	0.81	8.80	3.55	0.235
[15,]	65	1/8/86	3.5	2.04	0.69	2.41	1.4	0.58	6.00	1.75	-0.059
[16,]	68	4/2/86	6.4	4.43	0.55	2.49	2.44	0.69	9.25	3.20	0.135
[17,]	71	8/5/86	1.6	0.28	0.34	1.98	0.09	0.18	9.14	0.80	0.000
[18,]	72	10/7/86	0.9	0.18	0.28	1.95	0.05	0.20	4.50	0.45	0.000
[19,]	73	12/8/86	6.3	3.68	0.29	2.39	1.06	0.58	10.79	3.15	0.183
[20,]	74	12/31/86	6.5	4.81	0.53	2.54	2.56	0.74	8.78	6.40	-1.043
[21,]	75	1/13/87	6.2	4.49	0.32	2.43	1.45	0.72	8.56	3.10	0.047
[22,]	78	4/15/87	11.4	4.84	0.6	2.66	4.84	0.42	26.85	5.70	0.053
[23,]	79	6/4/87	4.5	2.25	0.64	2.4	1.45	0.50	9.00	2.25	0.111
[24,]	80	6/17/87	3.3	1.33	0.37	2.22	0.5	0.40	8.19	1.65	-0.019
[25,]	81	7/8/87	4	1.81	0.71	2.35	1.28	0.45	8.84	2.00	0.122
[26,]	82	8/20/87	0.7	0.2	0.2	1.94	0.04	0.29	2.45	0.35	-0.200

[27,]	83	10/7/87	2.2	0.76	0.28	2.16	0.21	0.35	6.37	1.10	0.105
[28,]	84	11/18/87	4.1	2.12	0.92	2.45	1.94	0.52	7.93	2.05	0.167
[29,]	85	1/13/88	3.5	1.56	0.69	2.46	1.08	0.45	7.85	1.75	0.095
[30,]	87	4/6/88	3.4	1.59	1.03	2.44	1.63	0.47	7.27	1.70	0.168
[31,]	134	8/26/92	4.1	1.43	0.45	1.66	0.64	0.35	11.76	2.05	0.147
[32,]	135	9/22/92	4.2	1.48	0.47	1.68	0.72	0.35	11.92	2.10	0.122
[33,]	136	10/6/92	4.1	1.32	0.33	1.62	0.44	0.32	12.73	2.05	0.159
[34,]	137	10/7/92	4.1	1.35	0.33	1.62	0.45	0.33	12.45	2.05	0.126
[35,]	142	3/24/93	18.6	20.6	2.59	2.54	53.4	1.11	16.79	9.30	0.071
[36,]	143	4/1/93	17.5	14.8	1.78	2.48	26.4	0.85	20.69	8.75	0.020
[37,]	144	4/14/93	15.5	8.14	1.02	2.16	8.35	0.53	29.51	7.48	-0.139
[38,]	149	10/15/93	4.5	1.51	0.36	1.73	0.53	0.34	13.41	2.53	-0.068
		Ave	5.18	3.285	0.61	2.25	3.55	0.51	9.80	2.68	0.020
bfile11a											
[1,]	42	3/5/85	18	11.3	0.59	0.8	6.67	0.63	28.67	9.00	-0.190
[2,]	43	4/18/85	17.5	9.68	0.46	0.68	4.5	0.55	31.64	8.75	-0.122
[3,]	44	5/14/85	17.5	11.1	0.3	0.59	3.34	0.63	27.59	8.75	-0.147
[4,]	45	6/11/85	17.2	9.67	0.24	0.5	2.36	0.56	30.59	8.60	-0.183
[5,]	53	11/13/85	18.5	15.3	0.43	0.82	6.57	0.83	22.37	9.25	-0.201
[6,]	56	4/24/86	15	9.91	0.84	0.86	8.34	0.66	22.70	7.50	-0.150
[7,]	63	3/3/87	32	25.3	0.7	1.21	17.8	0.79	40.47	16.00	0.098
[8,]	69	11/18/87	16.5	12.9	0.34	0.7	4.42	0.78	21.10	8.25	-0.080
[9,]	70	2/24/88	16	11.5	0.5	0.72	5.75	0.72	22.26	8.00	-0.068
[10,]	71	4/6/88	15.5	9.49	0.34	0.53	3.22	0.61	25.32	7.75	-0.090
[11,]	75	7/19/88	8.4	4.35	0.41	0.33	1.77	0.52	16.22	4.45	0.067
[12,]	76	8/17/88	1.5	0.55	0.32	-0.01	0.18	0.37	4.09	0.50	0.000
[13,]	79	2/15/89	16	13.1	0.67	0.76	8.78	0.82	19.54	8.00	-0.105
[14,]	80	3/22/89	16.3	12.3	0.72	0.78	8.88	0.75	21.60	8.18	-0.084
[15,]	81	5/2/89	31.5	23.2	1.06	1.29	24.5	0.74	42.77	15.75	-0.066
[16,]	82	5/12/89	31.5	24	1.07	1.32	25.7	0.76	41.34	15.63	0.065
[17,]	91	5/16/90	29.3	16	0.56	0.8	8.9	0.55	53.66	14.65	0.224
[18,]	98	3/5/91	28.8	19	0.76	1.03	14.4	0.66	43.65	14.40	0.175
		Ave	19.3	13.26	0.57	0.76	8.67	0.66	28.64	9.63	-0.048
bfile12a											
[1,]	2	6/20/90	2.6	0.63	0.56	3.72	0.35	0.24	10.73	1.27	0.012
[2,]	3	8/13/90	1.8	0.48	0.26	3.62	0.13	0.27	6.75	0.90	0.000
[3,]	4	9/13/90	1.85	0.52	0.43	3.67	0.22	0.28	6.58	0.93	-0.048
[4,]	5	10/9/90	1.8	0.49	0.23	3.6	0.11	0.27	6.61	0.90	0.000
[5,]	6	10/13/90	1.8	0.73	0.96	3.77	0.69	0.41	4.44	0.90	-0.014
[6,]	9	11/15/90	2.7	1.25	0.39	3.74	0.49	0.46	5.83	1.35	-0.060
[7,]	10	11/27/90	2.1	0.8	0.53	3.71	0.42	0.38	5.51	1.05	-0.142
[8,]	11	1/14/91	2.45	0.9	1.29	3.83	1.16	0.37	6.67	1.23	-0.011
[9,]	12	2/21/91	2.45	0.89	0.67	3.75	0.6	0.36	6.74	1.23	0.020
[10,]	13	3/5/91	3.25	1.37	1.13	3.85	1.55	0.42	7.71	1.63	-0.062
[11,]	14	4/17/91	3.3	1.12	0.76	3.75	0.85	0.34	9.72	1.65	-0.443
[12,]	15	5/29/91	2.6	0.77	0.33	3.65	0.26	0.30	8.78	1.30	0.000
[13,]	16	7/10/91	1.8	0.55	0.15	3.58	0.09	0.31	5.89	0.90	-0.107
[14,]	17	7/25/91	1.2	0.38	0.17	3.54	0.06	0.32	3.79	0.60	-0.103
[15,]	18	8/21/91	1	0.34	0.14	3.52	0.05	0.34	2.94	0.50	0.000
[16,]	19	10/2/92	0.9	0.25	0.14	3.49	0.04	0.28	3.24	0.48	0.018
[17,]	20	11/13/91	1.05	0.3	0.12	3.5	0.04	0.29	3.68	0.53	-0.017
		Ave	2.04	0.692	0.49	3.66	0.42	0.33	6.21	1.02	0.029

bfile13a

[1,]	563	5/6/87	164	507	2.11	3.41	1070	3.09	53.05	84.00	0.059
[2,]	564	5/6/87	183	537	2.05	3.41	1100	2.93	62.36	91.50	-0.048
[3,]	565	5/13/87	159	362	1.51	2.52	548	2.28	69.84	79.75	0.030
[4,]	566	6/3/87	157	305	1.28	2.14	389	1.94	80.82	78.50	0.040
[5,]	567	6/25/87	156	260	1	1.83	261	1.67	93.60	78.00	0.024
[6,]	569	10/9/87	157	266	0.98	1.81	261	1.69	92.67	78.50	0.031
[7,]	570	11/23/87	158	314	1.24	2.23	388	1.99	79.50	79.00	-0.004
[8,]	572	2/26/88	163	440	1.92	3.09	844	2.70	60.38	81.50	0.023
[9,]	573	4/6/88	156	387	1.44	2.25	442	2.48	62.88	78.00	0.010
[10,]	574	7/12/88	155	249	0.65	1.52	162	1.61	96.49	77.50	0.015
[11,]	577	11/15/88	152	274	0.82	1.77	224	1.80	84.32	76.00	0.003
[12,]	578	1/3/89	154	288	0.94	1.87	271	1.87	82.35	77.00	-0.016
[13,]	579	2/14/89	156	329	1.2	2.22	395	2.11	73.97	78.00	-0.006
[14,]	580	5/1/89	157	341	1.14	2.22	389	2.17	72.28	89.75	-0.148
[15,]	581	6/13/89	161	397	1.46	2.65	579	2.47	65.29	80.50	0.020
[16,]	582	7/25/89	158	360	1.24	2.37	447	2.28	69.34	79.00	0.003
[17,]	583	9/8/89	155	239	0.64	1.44	154	1.54	100.52	77.50	0.011
[18,]	584	10/5/89	156	287	0.91	1.82	261	1.84	84.79	78.00	0.000
[19,]	587	2/21/90	165	362	1.67	2.68	604	2.19	75.21	82.50	0.014
[20,]	588	5/23/90	162	420	1.69	2.92	708	2.59	62.49	81.00	-0.011
[21,]	589	7/5/90	159	254	0.85	1.67	216	1.60	99.53	79.50	-0.017
[22,]	592	11/16/90	165	376	1.76	2.79	661	2.28	72.41	82.50	0.010
[23,]	593	2/5/91	163	416	1.86	3.07	772	2.55	63.87	81.50	0.019
[24,]	594	3/12/91	187	444	1.76	3.02	782	2.37	78.76	92.75	0.109
[25,]	595	4/12/91	164	368	1.6	2.71	590	2.24	73.09	82.00	0.005
[26,]	596	5/31/91	160	268	0.95	1.86	254	1.68	95.52	80.00	0.060
[27,]	597	7/11/91	196	180	0.72	1.36	129	0.92	213.42	98.00	0.011
[28,]	598	8/16/91	184	137	0.52	1.16	71.7	0.74	247.12	92.00	-0.037
[29,]	599	10/2/91	196	173	0.7	1.33	121	0.88	222.06	98.00	0.000
[30,]	600	11/15/91	196	197	0.73	1.46	144	1.01	195.01	98.00	-0.006
[31,]	601	1/8/92	197	390	1.4	2.59	545	1.98	99.51	98.50	-0.022
[32,]	602	3/5/92	200	376	1.37	2.5	516	1.88	106.38	100.00	-0.004
[33,]	603	4/7/92	199	431	1.6	2.86	688	2.17	91.88	99.50	0.018
[34,]	604	5/20/92	199	376	1.27	2.4	479	1.89	105.32	99.50	-0.003
[35,]	605	7/8/92	199	294	0.99	1.9	291	1.48	134.70	97.50	0.043
[36,]	606	8/18/92	199	280	1.07	1.91	297	1.41	141.43	100.00	0.008
[37,]	607	10/6/92	199	227	0.89	1.62	201	1.14	174.45	99.50	0.001
[38,]	608	11/19/92	199	365	1.37	2.47	501	1.83	108.50	99.50	0.002
[39,]	612	7/13/93	199	254	0.9	1.7	228	1.28	155.91	99.50	-0.009
[40,]	613	8/17/93	202	254	0.76	1.56	192	1.26	160.65	100.50	-0.102
[41,]	614	10/14/93	200	445	3.31	2.6	582	2.23	89.89	100.00	-0.060
[42,]	616	5/17/94	201	444	1.6	2.82	709	2.21	90.99	97.50	-0.086
[43,]	617	8/31/94	198	302	1.16	1.95	350	1.53	129.81	99.00	0.121
	Ave		175	329.7	1.28	2.22	437.60	1.90	104.01	87.91	0.003

bfile14
a

[1,]	272	6/12/85	64	61.3	0.48	1.83	29.3	0.96	66.82	31.00	-0.189
[2,]	273	7/23/85	63.5	75.5	0.74	2.01	55.9	1.19	53.41	31.75	-0.096
[3,]	274	8/21/85	60	49.8	0.27	1.66	13.5	0.83	72.29	30.00	-0.150
[4,]	276	11/14/85	62	56.2	0.4	1.76	22.2	0.91	68.40	31.00	-0.143
[5,]	277	2/20/86	67	134	1.93	2.67	258	2.00	33.50	33.50	-0.063

[6,]	278	3/25/86	64	65.1	0.91	1.99	59.5	1.02	62.92	32.00	0.085
[7,]	283	1/21/87	65	103	1.28	2.29	132	1.58	41.02	32.50	-0.086
[8,]	284	2/26/87	63	74.8	0.75	1.91	56.2	1.19	53.06	31.50	-0.120
[9,]	285	4/13/87	65	80.5	1.11	2.08	89.6	1.24	52.48	33.00	-0.118
[10,]	291	2/26/88	66	92.3	0.73	2	67.4	1.40	47.19	42.68	0.115
[11,]	292	4/6/88	64	87.8	0.66	1.96	58.2	1.37	46.65	32.00	-0.018
[12,]	293	4/14/88	63	91.6	0.68	2.04	67.7	1.45	43.33	31.50	-0.030
[13,]	299	3/21/89	67	119	1.28	2.32	152	1.78	37.72	33.50	-0.167
[14,]	300	5/12/89	66	135	1.33	2.45	180	2.05	32.27	33.00	-0.134
[15,]	312	11/14/90	64	62.5	0.95	1.88	59.1	0.98	65.54	32.00	0.139
[16,]	313	1/10/91	66.5	77.1	1.23	2.04	94.8	1.16	57.36	33.25	0.071
[17,]	314	3/6/91	63.5	59.9	0.89	1.86	53.5	0.94	67.32	31.50	0.173
[18,]	315	4/18/91	65	66	1.2	1.96	78.3	1.02	64.02	32.75	-0.087
[19,]	322	1/7/92	59	44.7	0.8	1.72	36	0.76	77.87	29.50	0.137
[20,]	323	2/20/92	62	52.2	0.98	1.81	51	0.84	73.64	31.00	0.114
[21,]	324	4/1/92	64	65.9	1.2	1.96	78.9	1.03	62.15	32.00	0.101
[22,]	325	5/20/92	60	47.8	0.82	1.74	39	0.80	75.31	30.00	0.090
[23,]	329	11/18/92	61	51.8	0.74	1.74	38.6	0.85	71.83	30.50	0.056
[24,]	330	1/6/93	65	84.2	1.27	2.05	107	1.30	50.18	32.50	-0.032
[25,]	332	5/25/93	66	75.3	0.85	1.89	63.8	1.14	57.85	33.00	0.041
[26,]	333	7/15/93	66	67.1	0.58	1.76	38.9	1.02	64.92	33.00	-0.002
	Ave		63.9	76.17	0.93	1.98	76.17	1.18	57.66	32.31	-0.012
bfile15a											
[1,]	527	6/29/88	47.5	49.8	1.09	2.04	54.5	1.05	45.31	23.75	-0.075
[2,]	529	8/9/88	47	43	0.98	2	44	0.91	51.37	22.50	-0.056
[3,]	532	10/28/88	47	48.2	0.87	1.97	41.9	1.03	45.83	23.50	-0.040
[4,l	534	12/27/88	48	65.4	1.07	2.12	70.2	1.36	35.23	24.00	-0.088
[5,]	535	1/30/89	51	65	1.11	2.13	72	1.27	40.02	25.50	-0.104
[6,]	536	2/27/89	52.5	85.6	1.27	2.29	109	1.63	32.20	26.50	-0.126
[7,]	537	3/29/89	51	104	1.46	2.46	152	2.04	25.01	25.52	-0.123
[8,]	538	4/27/89	48.5	65	1.27	2.19	82.6	1.34	36.19	24.25	-0.046
[9,]	539	5/30/89	50	86.4	1.56	2.4	135	1.73	28.94	25.00	-0.056
[10,]	540	6/26/89	51	86.6	1.39	2.34	120	1.70	30.03	25.50	-0.023
[11,]	541	7/26/89	53	73.5	0.84	2.09	61.9	1.39	38.22	26.50	-0.037
[12,]	543	9/26/89	51	135	1.84	2.74	248	2.65	19.27	25.50	-0.046
[13,]	550	10/29/90	49	79.6	1.24	2.26	99	1.62	30.16	24.50	-0.129
[14,]	551	11/26/90	50	60.4	1	2.09	60.3	1.21	41.39	25.00	-0.139
[15,]	552	1/28/91	50.5	81.5	1.67	2.38	136	1.61	31.29	25.25	-0.104
[16,]	553	2/26/91	50	66.2	1.3	2.21	86.4	1.32	37.76	25.00	-0.154
[17,]	554	3/26/91	51	116	1.67	2.6	194	2.27	22.42	25.50	-0.071
[18,]	555	5/28/91	51	84.1	0.59	2.02	49.4	1.65	30.93	25.50	-0.042
[19,]	561	1/29/92	48.5	54.1	0.96	2.03	52.1	1.12	43.48	24.25	-0.187
[20,]	562	2/24/92	49.5	61.1	1.17	2.12	71.3	1.23	40.10	24.75	-0.130
[21,]	566	9/28/92	51.5	55	1.51	2.2	83.2	1.07	48.22	25.75	-0.039
[22,]	567	11/30/92	55	54	1.45	2.18	81.5	0.98	56.02	27.50	-0.059
[23,]	568	1/28/93	53	62.8	1.54	2.23	96.9	1.18	44.73	26.50	-0.092
[24,]	569	4/28/93	59	102	2.01	2.63	205	1.73	34.13	29.50	-0.056
[25,]	570	6/28/93	47.5	63.5	0.78	2.07	49.7	1.34	35.53	23.75	0.200
[26,]	576	5/31/94	45.6	60.2	1.17	2.13	70.4	1.32	34.54	22.80	0.188
[27,]	577	8/30/94	45	64.2	1.02	2.11	65.2	1.43	31.54	22.50	0.088
[28,]	581	3/29/95	53	65	1.24	2.17	80.9	1.23	43.22	25.63	0.236
	Ave		50.2	72.76	1.25	1.74	95.44	1.44	36.90	25.06	-0.047

bfile16a

[1,]	809	2/6/85	48	30	1.67	1.85	50	0.63	76.80	24.00	0.162
[2,]	812	4/23/85	39	18.4	0.9	1.63	16.5	0.47	82.66	19.50	0.158
[3,]	813	6/17/85	39	16.7	0.91	1.61	15.2	0.43	91.08	19.50	0.133
[4,]	814	7/31/85	35	13.9	0.68	1.54	9.52	0.40	88.13	17.50	0.154
[5,]	816	10/1/85	38.5	14.4	0.48	1.51	6.96	0.37	102.93	56.38	-1.933
[6,]	833	6/30/88	19	10.2	1	1.53	10.2	0.54	35.39	12.20	0.005
[7,]	834	8/19/88	28	10.3	0.79	1.5	8.16	0.37	76.12	14.05	0.155
[8,]	835	10/14/88	8.1	4.33	1.48	1.48	6.43	0.53	15.15	4.05	0.110
[9,]	836	11/15/88	18.3	9	1.48	1.56	13.3	0.49	37.21	9.15	0.172
[10,]	842	7/27/89	40	39.3	0.84	1.67	31.6	0.98	40.71	20.00	0.413
[11,]	843	9/7/89	30	14	0.66	1.48	9.21	0.47	64.29	14.79	-0.020
[12,]	846	11/2/89	36	20.4	1.07	1.58	21.9	0.57	63.53	18.00	-0.364
[13,]	847	1/2/90	49.5	43.6	1.51	1.85	65.8	0.88	56.20	24.75	0.342
[14,]	848	2/12/90	45	38.6	1.11	1.71	42.7	0.86	52.46	22.50	0.411
[15,]	849	3/26/90	47	33.3	1.39	1.74	46.4	0.71	66.34	23.50	0.221
[16,]	850	5/14/90	48	31.7	1.39	1.71	44	0.66	72.68	24.00	0.258
[17,]	851	6/18/90	42	22.5	1.01	1.41	22.7	0.54	78.40	21.00	0.198
[18,]	853	8/6/90	58	62.1	1.84	1.94	114	1.07	54.17	29.00	0.490
[19,]	854	10/1/90	34	26.9	0.42	1.34	11.3	0.79	42.97	17.00	0.226
[20,]	855	11/15/90	38.5	32.5	0.71	1.47	23.2	0.84	45.61	19.25	0.292
[21,]	856	1/10/91	48	44.2	1.36	1.69	60.2	0.92	52.13	24.00	0.369
[22,]	857	3/7/91	44.5	40.4	1.26	1.63	51	0.91	49.02	22.25	0.327
[23,]	858	4/3/91	42	35.7	1.16	1.57	41.5	0.85	49.41	21.00	0.327
[24,]	859	4/18/91	40.5	34.4	1.08	1.54	37.3	0.85	47.68	20.25	0.303
[25,]	860	6/3/91	36.5	25.1	0.68	1.03	17.2	0.69	53.08	18.25	-0.224
[26,]	861	6/28/91	33	22.3	0.49	1.11	10.9	0.68	48.83	16.50	0.150
[27,]	862	7/8/91	50	48.5	1.57	1.73	76	0.97	51.55	25.00	0.357
[28,]	863	8/19/91	33	19.1	0.24	0.99	4.58	0.58	57.02	16.50	0.028
[29,]	864	10/8/91	32	20.8	0.34	1.19	7.1	0.65	49.23	16.00	-0.040
[30,]	865	11/15/91	32	23.6	0.44	1.26	10.3	0.74	43.39	16.00	0.003
[31,]	866	1/8/92	41	41.2	0.66	1.43	27.3	1.00	40.80	20.50	0.236
[32,]	867	2/20/92	42	35.3	1.02	1.49	36.1	0.84	49.97	21.00	0.243
[33,]	868	3/27/92	53.5	79.6	2.68	2.13	213	1.49	35.96	26.75	0.305
[34,]	869	4/2/92	42	34.3	0.89	1.45	30.6	0.82	51.43	21.00	0.183
[35,]	870	5/21/92	39.5	30.5	0.83	1.39	25.2	0.77	51.16	19.75	0.205
[36,]	871	7/6/92	41.5	31.1	1.04	1.43	32.2	0.75	55.38	20.75	0.255
[37,]	872	8/17/92	38	23.6	0.92	1.35	21.8	0.62	61.19	19.00	0.178
[38,]	873	10/7/92	31.5	16.2	0.64	1.23	10.4	0.51	61.25	15.75	0.140
[39,]	874	11/25/92	43	30.8	1.53	1.52	47.2	0.72	60.03	21.50	-0.115
[40,]	875	1/4/93	50.5	29.2	0.92	1.4	27.6	0.58	87.34	25.25	0.302
[41,]	876	2/23/93	51.7	47	1.53	1.64	71.9	0.91	56.87	26.20	-0.136
[42,]	877	4/9/93	53.8	42.6	1.29	0.56	54.9	0.79	67.94	25.95	-0.129
[43,]	878	5/15/93	55.9	49.7	1.6	0.61	79.6	0.89	62.87	27.95	0.059
[44,]	879	6/10/93	37.5	22.9	1.22	0.77	29.2	0.61	61.41	18.75	-0.116
[45,]	880	6/29/93	32.5	16.8	0.94	0.99	15.8	0.52	62.87	14.35	0.177
[46,]	881	8/11/93	32	16.2	0.76	0.97	12.3	0.51	63.21	16.00	-0.025
[47,]	882	10/4/93	27	16.7	0.58	0.96	9.61	0.62	43.65	13.50	0.212
[48,]	883	10/18/93	26.8	16.9	0.56	0.96	9.44	0.63	42.50	13.40	0.216
[49,]	884	11/29/93	51	39.2	2.14	1.29	75	0.77	66.35	25.50	-0.072
[50,]	885	12/3/93	36	25.7	1.1	1.07	28.2	0.71	50.43	18.00	-0.221
[51,]	886	1/13/94	50.3	40.5	1.77	1.27	71.7	0.81	62.47	25.15	-0.100

[52,]	887	3/7/94	44.5	42	1.94	1.31	81.3	0.94	47.15	19.88	-0.034
[53,]	889	4/14/94	58	69.7	1.38	1.37	96.3	1.20	48.26	28.00	0.022
[54,]	890	5/3/94	35	27.2	1.34	1.1	36.4	0.78	45.04	17.50	-0.006
[55,]	891	6/14/94	33.5	19.8	0.99	1	19.6	0.59	56.68	15.88	0.020
[56,]	892	8/1/94	36.4	29.8	1.59	1.16	47.3	0.82	44.46	18.20	0.030
	Ave		39.6	30.01	1.10	1.39	37.41	0.73	56.80	20.38	0.090
bfile17a											
[1,]	213	10/20/87	15.8	5.2	0.7	2.35	3.66	0.33	48.01	7.90	-0.195
[2,]	224	5/3/89	44	88.3	2.3	4.17	203	2.01	21.93	22.00	0.218
[3,]	226	6/14/89	38.5	45.9	1.65	3.14	75.9	1.19	32.29	19.25	-0.259
[4,]	227	7/27/89	36.5	32.6	1.52	2.98	49.4	0.89	40.87	18.25	-0.272
[5,]	228	10/3/89	38	58.7	2.01	3.44	118	1.54	24.60	19.00	-0.162
[6,]	229	11/15/89	28	31.9	0.9	2.79	28.7	1.14	24.58	14.00	0.055
[7,]	230	1/5/90	29	39.9	1.51	3.04	60.1	1.38	21.08	14.25	-0.014
[8,]	231	2/14/90	29	32.7	1.5	2.96	49.2	1.13	25.72	14.50	-0.102
[9,]	232	3/29/90	29	27.4	1.18	2.83	32.3	0.94	30.69	14.50	0.087
[10,]	233	5/16/90	29	32.1	1.21	2.88	39	1.11	26.20	14.50	0.126
[11,]	234	6/20/90	29	31.9	0.99	2.83	31.7	1.10	26.36	14.50	0.165
[12,]	239	3/12/91	29	27.8	0.77	2.7	21.3	0.96	30.25	14.50	-0.069
[13,]	240	4/17/91	28	33.2	1.34	2.97	44.5	1.19	23.61	14.00	-0.226
[14,]	246	1/7/92	29	28.5	1.11	2.83	31.7	0.98	29.51	14.50	0.210
[15,]	247	2/19/92	29.5	27.1	1.19	2.84	32.2	0.92	32.11	14.75	0.220
[16,]	248	4/1/92	29	32.4	1.44	2.96	47	1.12	25.96	14.50	0.192
[17,]	249	5/20/92	28	13.6	0.77	2.54	10.5	0.49	57.65	14.00	0.126
[18,]	251	8/20/92	29	18.5	1	2.66	18.5	0.64	45.46	14.50	0.250
[19,]	252	10/6/92	28	22.6	0.78	2.65	17.7	0.81	34.69	14.00	-0.060
[20,]	253	11/18/92	28.5	23	0.93	2.72	21.6	0.81	35.32	14.25	-0.034
[21,]	254	1/7/93	29.5	37.4	1.34	3.01	50.4	1.27	23.27	14.75	-0.021
[22,]	255	3/1/93	29.2	30.2	1.29	2.91	39	1.03	28.23	14.60	-0.053
[23,]	256	4/13/93	29.6	51.7	1.95	3.41	101	1.75	16.95	14.80	0.026
	Ave		30.1	33.59	1.28	2.94	48.97	1.07	30.67	15.03	0.009
bfile18a											
[1,]	133	6/13/85	9	1.81	1.22	0.97	2.2	0.20	44.75	4.50	-0.171
[2,]	136	10/9/85	12	4.87	1.55	1.16	7.56	0.41	29.57	6.00	-0.158
[3,]	140	4/1/86	18.9	8.8	1.84	1.32	16.2	0.47	40.59	11.70	0.018
[4,]	141	5/13/86	10.5	2.95	1.49	1.06	4.41	0.28	37.37	5.25	0.100
[5,]	142	6/23/86	7.3	1.83	0.28	0.81	0.51	0.25	29.12	3.65	-0.069
[6,]	143	6/24/86	7.2	1.97	0.23	0.8	0.45	0.27	26.31	3.60	-0.040
[7,]	144	8/12/86	7	1.99	0.29	0.82	0.57	0.28	24.62	3.50	0.149
[8,]	145	10/7/86	3.1	0.8	0.31	0.77	0.25	0.26	12.01	1.55	0.044
[9,]	146	12/9/86	15.7	7.87	1.82	1.3	14.3	0.50	31.32	7.85	-0.161
[10,]	150	6/8/87	15.5	5.98	1.13	1.15	6.78	0.39	40.18	7.75	0.059
[11,]	151	7/13/87	13	4.06	0.6	0.99	2.44	0.31	41.63	6.50	0.099
[12,]	152	8/24/87	4.2	1.28	0.22	0.76	0.28	0.30	13.78	2.10	0.031
[13,]	153	10/19/87	10	3.27	0.5	0.92	1.65	0.33	30.58	5.00	-0.162
[14,]	154	11/30/87	25.5	17.1	1.53	1.47	26.2	0.67	38.03	12.75	-0.145
[15,]	155	1/27/88	25.5	12.8	1.47	1.39	18.8	0.50	50.80	12.75	-0.395
[16,]	156	2/29/88	18	9.53	1.42	1.3	13.5	0.53	34.00	9.00	-0.013
[17,]	157	4/11/88	22.7	11.8	1.64	1.38	19.4	0.52	43.67	11.35	0.222
[18,]	158	6/1/88	12	3.71	0.59	0.96	2.19	0.31	38.81	6.00	0.024
[19,]	159	11/15/88	9.2	4.5	0.44	0.94	1.99	0.49	18.81	4.60	-0.252

[20,]	160	1/4/89	15	7.2	0.83	1.11	5.94	0.48	31.25	7.50	0.219
[21,]	161	2/14/89	17	9.24	1.03	1.2	9.52	0.54	31.28	8.25	0.224
[22,]	165	5/3/89	16	7.98	0.78	1.14	6.25	0.50	32.08	8.00	0.323
[23,]	166	7/26/89	15	6.96	0.67	1.06	4.68	0.46	32.33	7.50	0.241
[24,]	168	11/15/89	20.3	12.9	1.09	1.29	14	0.64	31.94	10.15	0.019
[25,]	169	1/4/90	21.5	18.9	1.16	1.44	21.9	0.88	24.46	10.75	0.042
[26,]	170	2/14/90	22	17.3	1.25	1.43	21.7	0.79	27.98	11.00	0.010
[27,]	171	3/28/90	21	12.5	1.08	1.29	13.5	0.60	35.28	10.50	0.019
[28,]	172	5/15/90	21.5	22	1.31	1.52	28.9	1.02	21.01	10.75	0.142
[29,]	173	8/7/90	18.2	9.04	0.49	1.06	4.46	0.50	36.64	9.10	-0.146
[30,]	175	11/13/90	20.5	11.8	0.59	1.16	6.95	0.58	35.61	10.25	0.169
[31,]	176	1/8/91	22	19.4	0.97	1.41	18.9	0.88	24.95	10.55	0.183
[32,]	177	3/11/91	19	13.5	0.66	1.21	8.98	0.71	26.74	9.50	0.122
[33,]	178	4/16/91	22.5	20.8	1.01	1.43	21.1	0.92	24.34	11.25	0.145
[34,]	179	7/9/91	20.5	13.3	0.77	1.22	10.3	0.65	31.60	10.25	0.215
[35,]	180	8/20/91	15.5	5.4	0.2	0.87	1.1	0.35	44.49	7.75	-0.219
[36,]	182	11/12/91	14.2	9.19	0.41	1.04	3.78	0.65	21.94	7.10	-0.183
[37,]	183	1/6/92	21.5	20.8	1.15	1.48	23.9	0.97	22.22	10.75	0.139
[38,]	184	2/18/92	21.3	16.5	0.81	1.31	13.3	0.77	27.50	10.90	0.234
[39,]	185	3/31/92	22.5	18.7	1.08	1.42	20.2	0.83	27.07	11.25	0.165
[40,]	186	5/19/92	19	11.3	0.62	1.16	7.03	0.59	31.95	9.50	-0.159
[41,]	187	8/19/92	22	19.5	1.32	1.32	13.9	0.89	24.82	11.00	0.188
[42,]	190	1/8/93	20.5	40.4	1.78	1.93	72.1	1.97	10.40	10.25	0.304
[43,]	191	3/1/93	17.7	18.7	1.24	1.45	23.1	1.06	16.75	8.85	-0.249
[44,]	192	4/13/93	18.5	21	1.44	1.54	30.2	1.14	16.30	9.25	0.204
[45,]	193	3/17/93	18.5	22.6	1.52	1.6	34.4	1.22	15.14	9.25	-0.234
[46,]	194	7/8/93	12	10.1	0.22	0.97	2.23	0.84	14.26	6.00	0.002
[47,]	195	8/16/93	14.8	8.24	0.15	0.89	1.21	0.56	26.58	7.40	-0.146
[48,]	196	10/5/93	11.1	10	0.1	0.87	1	0.90	12.32	5.59	-0.018
[49,]	197	12/2/93	17	12	0.72	1.2	8.71	0.71	24.08	8.25	-0.268
[50,]	198	1/25/94	16.9	19	1.23	1.45	23.4	1.12	15.03	8.45	-0.240
[51,]	199	3/9/94	20.7	25	1.5	1.61	37.6	1.21	17.14	10.35	-0.197
[52,]	200	4/25/94	18	16.3	1.32	1.41	21.3	0.91	19.88	9.00	0.218
[53,]	201	5/17/94	13.5	13.5	0.8	1.24	10.8	1.00	13.50	6.75	0.154
[54,]	202	6/20/94	14.7	7.97	0.35	1	2.76	0.54	27.11	7.35	-0.082
	Ave		16.4	11.78	0.93	1.20	12.76	0.66	27.81	8.25	0.013
bfile19a											
[1,]	321	11/15/84	20.5	16.4	0.33	1.43	5.42	0.80	25.63	10.25	0.350
[2,]	322	12/17/84	23	19.3	0.52	1.53	10.1	0.84	27.41	11.50	-0.451
[3,]	323	2/7/85	26	25.3	1.23	1.79	31.1	0.97	26.72	14.00	-0.127
[4,]	325	4/23/85	21	17	0.31	1.41	5.31	0.81	25.94	10.50	0.372
[5,]	326	6/13/85	19	15.4	0.2	1.34	3.03	0.81	23.44	9.50	0.141
[6,]	328	8/26/85	23.5	20.9	0.56	1.54	11.8	0.89	26.42	11.75	-0.079
[7,]	329	10/9/85	23	18.3	0.5	1.49	9.09	0.80	28.91	11.50	-0.156
[8,]	330	12/2/85	24	48.7	2.44	2.46	119	2.03	11.83	12.00	0.021
[9,]	331	1/14/86	21	14.6	0.45	1.46	6.64	0.70	30.21	10.50	-0.304
[10,]	333	4/1/86	23	21	0.56	1.54	11.8	0.91	25.19	11.50	-0.118
[11,]	338	12/9/86	27	33.9	1.74	2.03	58.9	1.26	21.50	13.50	-0.188
[12,]	339	1/20/87	28	37.9	1.98	2.18	74.9	1.35	20.69	14.00	-0.285
[13,]	340	3/9/87	28	26.1	1.11	1.78	29.1	0.93	30.04	14.00	-0.384
[14,]	341	4/13/87	27	22	0.84	1.66	18.4	0.81	33.14	13.50	-0.364
[15,]	342	6/8/87	22	21.5	0.6	1.58	13	0.98	22.51	11.00	-0.151

[16,]	343	7/13/87	17.5	8.52	0.58	1.41	5.21	0.49	35.94	8.75	0.059
[17,]	344	8/24/87	17.6	10.7	0.18	1.27	1.88	0.61	28.95	8.80	0.035
[18,]	345	10/19/87	16	9	0.31	1.32	2.81	0.56	28.44	8.00	0.110
[19,]	346	11/30/87	28	31.1	1.33	1.9	41.3	1.11	25.21	14.00	-0.311
[20,]	347	1/27/88	27	21	0.98	1.7	20.6	0.78	34.71	13.50	0.060
[21,]	348	2/29/88	27	21.8	0.8	1.65	17.5	0.81	33.44	13.50	-0.311
[22,]	349	4/11/88	24.5	33.2	1.24	1.91	41.3	1.36	18.08	12.25	-0.055
[23,]	350	6/1/88	20.2	17.4	0.28	1.39	4.92	0.86	23.45	9.20	-0.098
[24,]	351	7/11/88	21	12.1	0.13	1.26	1.62	0.58	36.45	10.50	-0.186
[25,]	352	8/23/88	20	16.5	0.17	1.32	2.82	0.83	24.24	10.00	-0.163
[26,]	353	11/15/88	23	15.7	0.25	1.36	3.97	0.68	33.69	11.50	-0.170
[27,]	354	1/4/89	22	19.6	0.45	1.49	8.8	0.89	24.69	14.60	-0.105
[28,]	355	2/14/89	21.5	19.6	0.42	1.48	8.28	0.91	23.58	10.75	-0.108
[29,]	356	3/21/89	25	48.7	2.42	2.44	118	1.95	12.83	12.50	0.002
[30,]	358	5/2/89	23	15.6	0.44	1.46	6.94	0.68	33.91	11.50	-0.365
[31,]	359	7/26/89	19.5	11.3	0.44	1.4	4.99	0.58	33.65	9.75	-0.100
[32,]	360	10/2/89	27	31.3	1.66	1.98	52	1.16	23.29	13.50	-0.225
[33,]	361	11/14/89	20	14	0.81	1.55	11.4	0.70	28.57	10.00	0.115
[34,]	362	1/3/90	25.5	21.9	1.25	1.75	27.4	0.86	29.69	12.75	0.186
[35,]	363	2/13/90	22.5	17.7	0.94	1.64	16.7	0.79	28.60	11.25	0.025
[36,]	364	3/27/90	22.8	19	0.88	1.65	16.7	0.83	27.36	11.40	-0.126
[37,]	365	5/15/90	27	25.3	1.17	1.78	29.7	0.94	28.81	13.50	0.312
[38,]	366	8/7/90	20	13.4	0.34	1.38	4.51	0.67	29.85	10.00	-0.218
[39,]	371	4/16/91	25.2	20	1.28	1.75	25.5	0.79	31.75	12.60	0.114
[40,]	372	7/9/91	18	9.91	0.45	1.38	4.47	0.55	32.69	9.00	0.042
[41,]	373	10/1/91	24.5	12.8	0.38	1.39	4.82	0.52	46.89	12.25	-0.079
[42,]	374	11/12/91	22	19.7	0.24	1.39	4.72	0.90	24.57	11.00	-0.327
[43,]	375	1/6/92	26.5	23.1	1.42	1.82	32.8	0.87	30.40	13.25	0.130
[44,]	376	2/18/92	24.5	17	0.9	1.61	15.3	0.69	35.31	11.88	0.166
[45,]	377	3/31/92	25.5	23.2	1.32	1.82	30.7	0.91	28.03	12.75	0.126
[46,]	379	8/19/92	28.5	40.3	1.95	2.18	78.5	1.41	20.16	14.25	0.249
[47,]	380	10/5/92	23.5	19.1	0.84	1.62	16.1	0.81	28.91	12.00	0.396
[48,]	383	3/2/93	26.2	18.2	0.88	1.62	16.1	0.69	37.72	13.10	-0.251
[49,]	384	4/14/93	26	21.6	1.32	1.76	28.6	0.83	31.30	13.00	0.122
[50,]	385	5/17/93	23.5	21.2	0.73	1.61	15.4	0.90	26.05	11.75	0.095
[51,]	386	7/9/93	20.1	13.1	0.37	1.39	4.84	0.65	30.84	10.05	0.386
[52,]	387	8/16/93	22.5	10.7	0.33	1.35	3.59	0.48	47.31	11.25	0.342
[53,]	388	10/5/93	20.4	10.1	0.24	1.31	2.38	0.50	41.20	9.95	0.264
[54,]	389	12/2/93	22.5	17.7	0.36	1.43	6.39	0.79	28.60	11.25	0.092
[55,]	390	1/25/94	23	21.8	0.78	1.63	17.1	0.95	24.27	11.55	0.052
[56,]	391	3/9/94	24.7	29.2	1.73	1.98	50.6	1.18	20.89	12.35	0.119
[57,]	392	4/25/94	27.3	17.5	0.97	1.64	16.9	0.64	42.59	13.65	0.322
[58,]	393	8/3/94	27	17	1	1.63	17	0.63	42.88	13.50	0.256
[59,]	394	10/3/94	20.9	13.3	0.33	1.38	4.44	0.64	32.84	10.45	0.442
[60,]	395	11/22/94	24	27.7	1.32	1.85	36.5	1.15	20.79	12.00	0.034
[61,]	396	1/18/95	23.6	14.7	0.54	1.48	7.92	0.62	37.89	11.80	0.461
[62,]	397	3/15/95	28.7	21	0.96	1.68	20.2	0.73	39.22	12.73	0.281
[63,]	398	5/9/95	23.6	16.5	0.53	1.49	8.7	0.70	33.76	12.20	0.249
[64,]	399	7/10/95	23	15.4	0.41	1.43	6.28	0.67	34.35	11.53	0.188
	Ave		23.4	20.38	0.82	1.61	20.82	0.85	29.35	11.74	0.014
bfile20a											
[1,]	504	8/7/89	94	155	1.36	2.43	211	1.65	57.01	47.00	0.029

[2,]	507	1/17/90	97	182	1.66	2.72	302	1.88	51.70	48.50	-0.003
[3,]	508	3/22/90	95	170	1.57	2.6	267	1.79	53.09	47.50	-0.021
[4,]	509	5/9/90	94	154	1.28	2.35	197	1.64	57.38	47.00	0.007
[5,]	510	6/19/90	95	135	1.09	2.22	147	1.42	66.85	47.50	0.031
[6,]	511	8/13/90	94	104	0.66	1.9	68.1	1.11	84.96	47.00	-0.005
[7,]	512	10/1/90	93	109	0.74	1.97	80.7	1.17	79.35	46.50	-0.037
[8,]	513	11/29/90	95	145	1.14	2.29	166	1.53	62.24	47.50	0.021
[9,]	514	1/31/91	97	195	1.99	2.88	388	2.01	48.25	48.50	0.003
[10,]	516	5/16/91	98	168	1.56	2.55	261	1.71	57.17	49.00	0.004
[11,]	517	7/9/91	95	143	1.32	2.35	188	1.51	63.11	47.50	-0.015
[12,]	518	9/3/91	91	110	0.86	2	94.7	1.21	75.28	45.50	-0.006
[13,]	519	9/18/91	91	95.6	0.78	1.91	74.1	1.05	86.62	45.50	0.035
[14,]	520	10/25/91	91	101	0.66	1.91	66.9	1.11	81.99	45.50	0.050
[15,]	521	12/10/91	98	146	1.29	2.35	189	1.49	65.78	49.00	-0.017
[16,]	522	2/3/92	94	136	1.08	2.21	147	1.45	64.97	47.00	-0.046
[17,]	523	4/14/92	98	148	1.3	2.38	194	1.51	64.89	49.00	-0.002
[18,]	524	6/3/92	98	168	1.54	2.61	259	1.71	57.17	49.00	0.011
[19,]	525	7/29/92	97	135	1.05	2.19	142	1.39	69.70	48.50	0.004
[20,]	526	10/14/92	94	104	0.71	1.92	73.5	1.11	84.96	47.00	-0.085
[21,]	527	12/8/92	96	148	1.34	2.4	198	1.54	62.27	48.00	-0.076
[22,]	528	2/8/93	96	163	1.49	2.53	242	1.70	56.54	48.00	0.023
[23,]	530	6/2/93	97	148	1.33	2.37	196	1.53	63.57	48.50	-0.013
[24,]	531	7/12/93	96	122	0.83	2.04	102	1.27	75.54	48.00	-0.031
[25,]	533	10/14/93	94	111	0.76	2.02	84	1.18	79.60	47.00	-0.074
[26,]	534	12/2/93	99	213	1.98	3.03	423	2.15	46.01	49.50	-0.002
[27,]	535	2/7/94	99	213	2.06	3.01	438	2.15	46.01	49.50	-0.012
[28,]	536	4/12/94	100	245	2.53	3.39	620	2.45	40.82	50.00	-0.010
[29,]	537	6/7/94	97	132	1.16	2.23	153	1.36	71.28	48.50	-0.050
[30,]	538	7/8/94	93	115	0.87	2.04	100	1.24	75.21	47.00	-0.038
[31,]	540	8/8/94	97	154	1.32	2.44	204	1.59	61.10	48.50	0.002
[32,]	541	10/11/94	94	115	0.75	1.99	85.6	1.22	76.83	47.00	0.035
[33,]	542	11/30/94	93	112	0.73	2.03	81.2	1.20	77.22	46.50	-0.024
	Ave		95.5	145.3	1.24	2.34	195.24	1.52	65.59	47.74	-0.009
bfile21a											
[1,]	228	8/7/89	25	25.4	2.03	1.54	51.5	1.02	24.61	12.50	-0.299
[2,]	229	10/3/89	41	100	2.33	2.54	233	2.44	16.81	20.50	-0.071
[3,]	231	1/17/90	39	58.2	1.41	1.66	82	1.49	26.13	19.50	-0.154
[4,]	232	3/19/90	28	37.2	2.29	1.68	85.2	1.33	21.08	13.00	-0.139
[5,]	233	5/8/90	27	27.8	1.79	1.45	49.8	1.03	26.22	13.98	-0.300
[6,]	234	6/19/90	34	38.6	1.27	1.46	48.9	1.14	29.95	17.00	-0.333
[7,]	235	7/18/90	24	23.4	1.55	1.36	36.2	0.98	24.62	12.00	-0.210
[8,]	236	8/7/90	22	19.1	1.39	1.28	26.5	0.87	25.34	11.00	-0.199
[9,]	237	10/2/90	21	15	1.24	1.22	18.8	0.71	29.40	10.50	-0.240
[10,]	239	11/29/90	25	25	1.27	1.34	31.7	1.00	25.00	12.50	-0.263
[11,]	240	1/29/91	28	39	1.96	1.65	76.4	1.39	20.10	14.00	-0.222
[12,]	241	3/19/91	36	71.2	2.02	2	144	1.98	18.20	18.00	-0.239
[13,]	242	5/16/91	26	27.2	1.55	1.39	42.4	1.05	24.85	12.75	-0.162
[14,]	243	6/20/91	26	24.2	1.24	1.29	30	0.93	27.93	13.00	-0.223
[15,]	245	9/3/91	39	33.7	0.92	1.31	30.8	0.86	45.13	19.50	-0.047
[16,]	246	10/10/91	39	29.6	0.78	1.27	23.2	0.76	51.39	19.50	-0.083
[17,]	247	12/10/91	34	41.4	1.52	1.55	62.8	1.22	27.92	17.00	-0.227
[18,]	248	2/3/92	25	21.9	1.5	1.32	32.9	0.88	28.54	12.50	-0.150

[19,]	249	4/14/92	40	38.7	1.02	1.38	39.5	0.97	41.34	20.00	-0.124
[20,]	250	6/11/92	37	47.9	1.48	1.56	71	1.29	28.58	18.50	-0.190
[21,]	251	7/29/92	27	23.4	1.23	1.27	28.8	0.87	31.15	13.50	-0.077
[22,]	252	10/6/92	26	19.8	1.18	1.26	23.3	0.76	34.14	12.55	-0.146
[23,]	253	11/12/92	25	19.6	1.05	1.24	20.6	0.78	31.89	12.50	-0.102
[24,]	254	12/1/92	37	32.4	1.04	1.32	33.8	0.88	42.25	18.56	-0.186
[25,]	255	2/8/93	34	37.5	1.14	1.4	42.5	1.10	30.83	17.00	-0.210
[26,]	257	5/11/93	39	40.5	1.81	1.63	73.4	1.04	37.56	19.50	-0.105
[27,]	258	6/30/93	33	22.7	1.32	1.33	29.9	0.69	47.97	16.50	0.092
[28,]	259	8/31/93	29	17.2	0.94	1.21	16.3	0.59	48.90	15.00	0.025
[29,]	260	10/14/93	32	21.6	0.82	1.26	17.9	0.68	47.41	16.00	0.104
[30,]	261	11/30/93	33	23.3	1.18	1.29	27.6	0.71	46.74	16.50	-0.042
[31,]	262	2/2/94	39	45.4	1.66	1.6	75.3	1.16	33.50	19.50	-0.039
[32,]	263	4/8/94	42	71.6	1.72	1.89	123	1.70	24.64	21.00	-0.022
[33,]	264	6/10/94	40	35	0.95	1.32	33.4	0.88	45.71	20.00	0.029
[34,]	265	7/18/94	38	30.1	1	1.3	30	0.79	47.97	19.00	-0.001
[35,]	266	10/13/94	36	26.5	0.7	1.22	18.4	0.74	48.91	18.00	0.028
[36,]	267	11/28/94	32	26.4	0.8	1.25	21	0.83	38.79	16.00	-0.152
	Ave		32.2	34.38	1.36	1.45	50.88	1.04	33.38	16.06	-0.13
bfile22a											
[,1]	544	9/25/89	98	212	2.92	5.2	620	2.16	45.30	4.00	-0.969
[,2]	545	11/15/89	78	127	1.86	4.05	236	1.63	47.91	3.00	-0.612
[,3]	546	1/16/90	93	156	2.49	4.5	388	1.68	55.44	4.25	0.584
[,4]	547	3/23/90	90	166	2.1	4.43	348	1.84	48.80	3.00	-0.193
[,5]	548	5/1/90	93	112	2.37	4.12	265	1.20	77.22	3.00	-0.967
[,6]	549	6/18/90	88	116	1.87	3.94	217	1.32	66.76	3.75	-0.320
[,7]	558	8/29/91	65	116	1.3	3.67	151	1.78	36.42	3.00	-0.948
[,8]	562	4/14/92	79	123	1.52	3.83	187	1.56	50.74	4.00	-0.568
[,9]	564	7/28/92	83	123	1.49	3.82	183	1.48	56.01	3.75	2.883
	Ave		85.2	139	1.99	4.17	288.33	1.63	53.84	3.53	-0.123
bfile23a											
[1,]	562	87/89	70	76	1.12	2.72	85.1	1.09	64.47	35.00	-0.043
[2,]	564	11/15/89	70	84.7	1.44	2.85	122	1.21	57.85	35.00	-0.026
[3,]	565	1/10/90	70	132	1.76	3.29	232	1.89	37.12	35.00	-0.058
[4,]	566	3/19/90	75	147	2.12	3.54	312	1.96	38.27	37.50	-0.091
[5,]	567	5/1/90	69	87.6	1.4	2.86	123	1.27	54.35	34.50	-0.022
[6,]	568	6/18/90	63	97.7	0.85	2.66	82.9	1.55	40.62	31.50	-0.106
[7,]	570	9/28/90	57	79.5	0.41	2.4	32.6	1.39	40.87	28.50	-0.105
[8,]	572	12/3/90	60	90.2	0.73	2.59	65.5	1.50	39.91	30.00	-0.111
[9,]	574	3/21/91	69	124	1.65	3.19	205	1.80	38.40	35.00	-0.021
[10,]	583	6/4/94	65	110	1.11	2.84	122	1.69	38.41	32.50	-0.178
[11,]	585	10/8/92	65	58.1	0.63	2.44	36.4	0.89	72.72	32.50	-0.012
[12,]	587	2/17/93	77	140	1.44	3.18	202	1.82	42.35	38.50	0.188
[13,]	594	12/1/94	69	72.5	0.8	2.54	58.1	1.05	65.67	34.50	0.014
	Ave		67.6	99.95	1.19	2.85	129.12	1.47	48.54	33.85	-0.044
bfile24a											
[1,]	134	9/21/87	85	170	2.24	3.9	380	2.00	42.50	42.50	-0.013
[2,]	152	5/4/89	97	264	2.57	4.6	678	2.72	35.64	48.50	-0.002
[3,]	153	5/18/89	90	160	1.93	3.62	309	1.78	50.63	45.00	-0.004
[4,]	154	6/28/89	91	95.1	1.28	2.99	122	1.05	87.08	45.50	0.025
[5,]	155	8/7/89	94	98.3	1.24	3.02	122	1.05	89.89	47.00	-0.038
[6,]	156	9/25/89	88	204	2.43	4.16	495	2.32	37.96	44.00	-0.039

[7,]	157	11/15/89	88	113	1.35	3.13	153	1.28	68.53	43.50	0.028
[8,]	158	1/10/90	91	152	1.88	3.59	285	1.67	54.48	45.50	-0.017
[9,]	159	3/19/90	90	172	2.12	3.82	365	1.91	47.09	39.25	-0.058
[10,]	160	5/1/90	80	113	1.46	3.11	165	1.41	56.64	40.00	-0.011
[11,]	161	6/7/90	89	118	1.48	3.17	175	1.33	67.13	44.50	-0.012
[12,]	163	8/14/90	90	74.7	0.86	2.69	64.3	0.83	108.43	45.00	-0.040
[13,]	164	10/2/90	78	77.7	0.72	2.62	56.2	1.00	78.30	39.00	-0.037
[14,]	165	12/3/90	81	92.8	1.17	2.91	109	1.15	70.70	40.50	-0.063
[15,]	166	1/31/91	95	110	1.75	3.21	193	1.16	82.05	47.50	0.018
[16,]	167	3/28/91	91	136	1.94	3.46	263	1.49	60.89	45.50	-0.046
[17,]	168	5/16/91	81	110	1.18	2.93	130	1.36	59.65	40.50	-0.020
[18,]	169	6/18/91	90	98	0.71	2.7	71.4	1.09	82.65	45.00	-0.030
[19,]	170	6/20/91	80	117	0.63	2.68	73.7	1.46	54.70	40.00	0.046
[20,]	175	2/5/92	84	92	1.28	2.9	118	1.10	76.70	42.00	-0.086
[21,]	183	2/17/93	81	141	1.86	3.41	262	1.74	46.53	40.50	-0.036
[22,]	185	4/27/93	93	182	2.38	3.91	434	1.96	47.52	46.50	-0.097
[23,]	186	5/11/93	95	140	1.7	3.3	237	1.47	64.46	47.50	-0.066
[24,]	190	12/1/93	79	91.2	1.05	2.75	96	1.15	68.43	39.50	-0.062
[25,]	196	12/1/94	79	97.9	1.01	2.73	99	1.24	63.75	39.50	0.001
	Ave		87.2	128.8	1.53	3.25	218.22	1.47	64.09	43.35	-0.026
bfile25a											
[1,]	400	8/7/89	64	88.2	1.58	2.94	139	1.38	46.44	32.00	-0.164
[2,]	402	11/15/89	66	88	2.33	3.11	205	1.33	49.50	33.00	-0.129
[3,]	406	5/1/90	65	105	1.95	3.08	205	1.62	40.24	32.50	0.118
[4,]	408	6/19/90	63	69.7	2.02	2.92	141	1.11	56.94	31.50	-0.123
[5,]	409	8/14/90	56	46	1.66	2.67	76.3	0.82	68.17	28.00	-0.155
[6,]	410	10/2/90	51	43.8	1.64	2.65	72	0.86	59.38	25.50	-0.031
[7,]	411	12/3/90	64	80.3	1.42	2.83	114	1.25	51.01	32.00	-0.061
[8,]	412	1/31/91	67	120	1.99	3.2	239	1.79	37.41	33.50	0.094
[9,]	413	3/28/91	69	126	2.74	3.44	345	1.83	37.79	34.50	-0.057
[10,]	414	5/14/91	63	76	1.9	2.9	144	1.21	52.22	31.50	0.010
[11,]	415	6/17/91	53	47	1.73	2.7	81.4	0.89	59.77	26.50	0.069
[12,]	417	8/29/91	60	63.4	1.98	2.86	125	1.06	56.78	30.00	-0.121
[13,]	419	12/10/91	64	69	2.06	2.94	142	1.08	59.36	32.00	-0.003
[14,]	421	4/17/92	63	65.4	1.99	2.86	130	1.04	60.69	31.50	-0.108
[15,]	422	6/4/92	67	94.2	1.88	3.01	177	1.41	47.65	33.50	0.020
[16,]	423	7/28/92	65	77.4	1.42	2.89	110	1.19	54.59	32.50	0.050
[17,]	425	12/8/92	68	107	1.63	2.97	175	1.57	43.21	34.00	0.173
[18,]	426	2/11/93	65	83.7	2.09	2.95	175	1.29	50.48	32.50	0.172
	Ave		62.9	80.56	1.89	2.94	155.32	1.26	51.76	31.47	-0.014
bfile26											
[1,]	104	8/7/90	3.15	0.39	0.17	1.03	0.07	0.12	25.44	1.58	-0.022
[2,]	105	10/16/90	8.5	5.41	0.88	1.63	4.75	0.64	13.35	4.25	-0.065
[3,]	106	11/13/90	8.2	2.61	1.05	1.35	2.74	0.32	25.76	4.10	-0.142
[4,]	107	1/15/91	13	7.42	1.3	1.8	9.71	0.57	22.78	6.50	0.147
[5,]	108	3/13/91	7.6	3.65	0.56	1.45	2.04	0.48	15.82	3.80	-0.294
[6,]	109	5/22/91	2	0.49	0.26	1.03	0.13	0.25	8.16	1.00	0.122
[7,]	110	6/25/91	10.2	4.08	0.41	1.4	1.69	0.40	25.50	5.05	0.114
[8,]	112	10/10/91	0.6	0.1	0.31	0.95	0.03	0.17	3.60	0.30	0.080
[9,]	113	12/4/91	11.5	9.5	1.29	1.87	12.3	0.83	13.92	5.75	-0.053
[10,]	114	2/5/92	4.75	1.72	0.24	1.11	0.42	0.36	13.12	2.38	-0.184
[11,]	115	4/2/92	8	4.05	0.25	1.39	2.3	0.51	15.80	3.85	0.037

[12,]	116	5/27/92	6.3	3.04	0.48	1.36	1.47	0.48	13.06	3.15	-0.224
[13,]	117	7/14/92	4.4	1.12	0.22	1.09	0.24	0.25	17.29	2.20	-0.036
[14,]	118	9/4/92	4.4	1.13	0.19	1.09	0.22	0.26	17.13	2.20	-0.026
[15,]	119	10/16/92	6.3	2.67	0.73	1.41	1.96	0.42	14.87	3.15	0.105
[16,]	120	11/16/92	7.2	5.04	2.29	1.71	11.6	0.70	10.29	3.60	0.048
[17,]	121	3/22/93	9.8	8.38	1.1	1.85	9.19	0.86	11.46	4.90	-0.132
[18,]	122	4/30/93	9	4.93	0.54	1.53	2.68	0.55	16.43	4.50	-0.067
[19,]	123	6/18/93	1.6	0.329	0.43	1.08	0.14	0.21	7.62	0.80	0.156
[20,]	125	9/22/93	0.9	0.13	0.22	0.95	0.03	0.14	6.23	0.45	-0.077
[21,]	127	11/1/93	2.5	0.25	0.49	1.15	0.13	0.10	25.00	0.75	-0.040
[22,]	128	12/15/93	5.6	2.15	0.52	1.34	1.12	0.38	14.59	3.05	-0.280
[23,]	129	3/15/94	9.3	6.16	0.98	1.67	6.02	0.66	14.04	4.65	0.160
[24,]	130	5/9/94	6.7	4.16	1.02	1.62	4.26	0.62	10.79	3.35	-0.227
[25,]	132	9/8/94	3.75	0.87	0.03	1.05	0.1	0.23	16.16	1.88	-0.130
[26,]	133	11/7/94	1.25	0.15	0.28	1.08	0.04	0.12	10.42	0.63	-0.092
	Ave		6.02	3.074	0.62	1.35	2.90	0.41	14.95	2.99	-0.043
bfile27a											
[1,]	484	2/5/93	207	371	2.06	2.93	764	1.79	115.50	103.50	0.040
[2,]	486	6/2/93	210	356	1.77	2.84	631	1.70	123.88	102.50	0.000
[3,]	487	7/8/93	195	276	1.42	2.54	392	1.42	137.77	97.50	0.046
[4,]	488	8/31/93	205	272	1.07	2.55	292	1.33	154.50	102.50	0.055
[5,]	489	10/14/93	195	256	1.12	2.38	287	1.31	148.54	97.50	0.080
[6,]	490	12/14/93	217	390	1.72	2.83	671	1.80	120.74	108.50	-0.103
[7,]	491	2/7/94	216	462	2.46	3.34	1138	2.14	100.99	108.00	0.029
[8,]	493	6/7/94	210	355	1.34	2.57	474	1.69	124.23	105.00	0.133
[9,]	494	8/24/94	208	390	2.26	3.26	884	1.88	110.93	104.00	-0.015
	Ave		207	347.6	1.69	2.80	614.78	1.67	126.34	103.22	0.029
bfile28a											
[1,]	230	8/8/89	149	222	3.04	3.24	675	1.49	100.00	74.50	-0.242
[2,]	235	6/21/90	172	228	2.73	3.19	622	1.33	129.75	86.00	-0.315
[3,]	239	11/29/90	161	224	3.08	3.27	688	1.39	115.72	80.50	-0.299
[4,]	241	5/16/91	178	283	3.19	3.47	902	1.59	111.96	88.75	-0.324
[5,]	242	7/11/91	158	240	2.8	3.23	674	1.52	104.02	79.00	0.218
[6,]	243	8/28/91	153	223	2.22	3.21	494	1.46	104.97	76.50	0.226
[7,]	245	11/26/91	127	161	2.39	2.96	385	1.27	100.18	63.50	-0.116
[8,]	246	1/30/92	177	258	2.71	3.27	700	1.46	121.43	88.50	-0.369
[9,]	248	6/4/92	206	330	3.3	3.58	1090	1.60	128.59	103.00	-0.372
[10,]	249	8/3/92	167	219	2.36	3.07	517	1.31	127.35	83.50	-0.248
[11,]	250	10/15/92	171	221	2.12	3.09	469	1.29	132.31	85.50	-0.352
[12,]	251	12/3/92	210	367	3.09	3.7	1130	1.75	120.16	105.00	-0.350
[13,]	256	7/29/93	176	234	1.72	3.07	401	1.33	132.38	88.00	-0.281
[14,]	261	6/8/94	190	252	2.55	3.28	643	1.33	143.25	95.00	-0.165
[15,]	262	7/26/94	208	314	2.37	3.43	743	1.51	137.78	104.00	0.244
[16,]	264	10/6/94	185	196	1.91	2.99	374	1.06	174.62	92.50	-0.398
[17,]	265	12/9/94	199	290	2.12	3.33	615	1.46	136.56	99.50	-0.270
	Ave		176	250.7	2.57	3.26	654.24	1.42	124.77	87.84	-0.201
bfile29a											
[1,]	447	2/4/85	204	1280	2.37	3.34	3030	6.27	32.51	102.00	0.043
[2,]	449	5/8/85	201	977	1.57	2.21	1530	4.86	41.35	100.50	0.068
[3,]	451	8/5/85	190	826	0.65	1.97	536	4.35	43.70	95.00	0.073
[4,]	452	9/17/85	197	798	0.53	1.54	423	4.05	48.63	98.50	-0.068
[5,]	453	10/22/85	195	840	1.07	1.9	895	4.31	45.27	97.50	0.096

[6,]	454	11/6/85	495	12100	7.48	28.45	90500	24.44	20.25	247.50	-0.095
[7,]	455	12/17/85	194	1000	1.64	2.3	1640	5.15	37.64	97.00	-0.071
[8,]	456	2/5/86	194	848	1.32	1.76	1120	4.37	44.38	97.00	0.083
[9,]	457	3/27/86	197	965	1.5	2.14	1450	4.90	40.22	98.50	0.064
[10,]	460	8/11/86	188	654	0.46	1.03	302	3.48	54.04	94.00	0.071
[11,]	461	10/7/86	198	712	0.43	1.15	307	3.60	55.06	99.00	-0.089
[12,]	464	2/19/87	194	936	1.45	2.05	1360	4.82	40.21	97.00	0.054
[13]	465	4/23/87	215	1650	3.31	4.9	5460	7.67	28.02	107.50	-0.033
[14,]	466	7/1/87	193	808	0.8	1.61	648	4.19	46.10	96.55	0.077
[15,]	467	8/5/87	198	806	0.56	1.7	446	4.07	48.64	99.40	-0.079
[16,]	468	10/20/87	179	740	0.81	1.52	598	4.13	43.30	89.50	0.117
[17,]	469	2/23/88	198	916	1.22	1.94	1120	4.63	42.80	99.00	-0.077
[18,]	470	4/12/88	195	996	1.49	2.26	1480	5.11	38.18	97.50	0.048
[19,]	471	6/16/88	196	790	0.87	1.37	688	4.03	48.63	98.00	-0.086
[20,]	472	7/21/88	193	682	0.55	1.05	375	3.53	54.62	96.50	0.096
[21,]	473	9/13/88	199	814	0.43	1.66	352	4.09	48.65	99.50	-0.102
[22,]	474	10/13/88	197	733	0.43	1.36	316	3.72	52.95	98.50	-0.080
[23,]	475	11/15/88	197	757	0.49	1.37	372	3.84	51.27	98.40	-0.065
[24,]	476	1/5/89	197	739	0.56	1.38	417	3.75	52.52	99.75	-0.105
[25,]	477	3/20/89	198	862	1.14	1.83	984	4.35	45.48	99.00	-0.068
[26,]	478	4/12/89	198	811	1.28	1.76	1040	4.10	48.34	95.50	-0.128
[27,]	479	6/1/89	197	887	1.08	1.82	960	4.50	43.75	98.50	-0.076
[28,]	480	7/6/89	199	1010	1.14	2.37	1150	5.08	39.21	99.50	-0.073
[29,]	481	8/23/89	202	1350	2.28	3.81	3140	6.68	30.23	101.00	-0.054
[30,]	482	10/4/89	211	1650	3.24	4.9	5340	7.82	26.98	105.50	0.021
[31,]	483	11/14/89	199	884	1.21	1.78	1070	4.44	44.80	99.50	-0.074
[32,]	484	1/3/90	207	1610	3.06	4.86	4920	7.78	26.61	105.50	-0.081
[33,]	485	3/6/90	196	968	1.45	2.07	1400	4.94	39.69	98.00	-0.074
[34,]	486	4/24/90	200	997	1.52	2.16	1520	4.99	40.12	100.00	-0.082
[35,]	487	6/7/90	204	1130	1.4	2.2	1580	5.54	36.83	102.00	-0.050
[36,]	488	8/7/90	199	818	0.95	1.52	780	4.11	48.41	99.50	-0.051
[37,]	489	10/12/90	202	1070	1.62	2.68	1730	5.30	38.13	101.00	-0.051
[38,]	490	11/14/90	199	987	1.51	2.14	1490	4.96	40.12	99.50	-0.069
[39,]	491	1/10/91	205	1280	2.23	3.31	2850	6.24	32.83	102.50	-0.053
[40,]	492	3/14/91	204	1120	1.81	2.55	2030	5.49	37.16	102.00	-0.069
[41,]	493	5/9/91	199	885	1.19	1.7	1050	4.45	44.75	99.50	-0.082
[42,]	494	7/15/91	199	860	1.08	1.65	932	4.32	46.05	99.50	-0.076
[43,]	495	8/28/91	195	793	0.65	1.52	519	4.07	47.95	97.50	-0.092
[44,]	496	9/23/91	197	791	0.48	1.63	383	4.02	49.06	98.50	-0.086
[45,]	497	10/22/91	198	761	0.47	1.43	358	3.84	51.52	99.00	-0.084
[46,]	499	12/20/91	199	755	0.73	1.5	550	3.79	52.45	99.50	-0.028
[47,]	500	1/29/92	197	830	0.94	1.62	782	4.21	46.76	98.50	-0.076
[48,]	501	3/24/92	202	1090	1.73	2.51	1890	5.40	37.43	101.00	-0.071
[49,]	502	5/12/92	205	1250	2.38	3.3	2970	6.10	33.62	102.50	-0.031
[50,]	503	7/7/92	198	859	0.99	1.97	847	4.34	45.64	99.00	-0.044
[51,]	504	8/25/92	199	790	0.55	1.67	438	3.97	50.13	99.50	-0.032
[52,]	505	10/13/92	196	811	0.85	1.67	689	4.14	47.37	98.00	-0.048
[53,]	506	11/12/92	200	803	0.87	1.58	696	4.02	49.81	100.00	-0.045
[54,]	507	1/6/93	195	1089	1.86	2.64	2030	5.58	34.92	97.50	-0.052
[55,]	508	3/31/93	221	1990	4.26	6.32	8480	9.00	24.54	110.50	-0.040
[56,]	509	4/20/93	218	1660	3.33	4.87	5530	7.61	28.63	109.00	-0.024
[57,]	510	6/22/93	203	847	1.05	1.61	890	4.17	48.65	101.50	-0.021

[58,]	513	7/29/93	206	896	0.58	1.65	515	4.35	47.36	103.00	-0.094
[59,]	515	12/14/93	197	918	1.27	1.89	1170	4.66	42.28	98.50	-0.060
[60,]	516	3/17/93	205	1510	3.07	4.44	4640	7.37	27.83	102.00	-0.035
[61,]	517	6/1/94	200	848	1.09	1.59	927	4.24	47.17	100.00	-0.068
[62,]	518	6/30/94	197	776	0.97	1.44	750	3.94	50.01	98.50	-0.064
[63,]	519	8/31/94	196	802	0.91	1.52	734	4.09	47.90	98.00	-0.060
[64,]	521	12/20/94	197	797	0.77	1.44	611	4.05	48.69	93.50	-0.073
	Ave		204	1144	1.42	2.61	2902.03	5.15	42.63	101.81	-0.039
bfile30a											
[1,]	524	8/7/90	31	29	0.38	2.19	10.9	0.94	33.14	15.50	-0.006
[2,]	525	11/15/90	34	60.6	1.21	2.71	73.5	1.78	19.08	17.00	0.040
[3,]	527	2/27/91	45	70.4	0.83	2.65	58.2	1.56	28.76	22.50	-0.005
[4,]	529	7/15/91	36	42.7	1.46	2.65	62.2	1.19	30.35	18.00	0.025
[5,]	530	8/29/91	16.3	9.1	1.02	2.15	9.27	0.56	29.20	8.65	0.069
[6,]	531	9/23/91	12	5.1	0.67	2.25	3.43	0.43	28.24	6.00	0.265
[7,]	532	10/21/91	12.1	4.94	0.65	2.18	3.19	0.41	29.64	8.30	-0.600
[8,]	533	11/21/91	26	14.5	0.37	2.44	5.35	0.56	46.62	13.00	-0.024
[9,]	534	1/29/92	36	38.4	1.24	2.57	47.7	1.07	33.75	18.00	0.009
[10,]	537	7/7/92	52	67.2	0.84	2.62	56.4	1.29	40.24	26.00	-0.084
[11,]	538	8/26/92	20	9.87	0.65	2.04	6.42	0.49	40.53	10.00	-0.150
[12,]	539	9/16/92	32	25.7	1.12	2.46	28.9	0.80	39.84	16.00	-0.123
[13,]	540	10/8/92	21	12.5	0.84	2.21	10.5	0.60	35.28	10.50	-0.122
[14,]	546	8/4/93	17	5.44	0.51	1.91	2.76	0.32	53.13	8.50	0.305
[15,]	548	11/2/93	18.6	7.72	0.83	2.08	6.4	0.42	44.81	9.30	0.200
[16,]	549	12/15/93	46	57.4	1.37	2.71	78.5	1.25	36.86	23.00	-0.126
	Ave		28.4	28.79	0.87	2.36	28.98	0.85	35.59	14.39	-0.020
bfile31a											
[1,]	8	11/7/85	61	76.3	1.82	1.99	138	1.25	48.77	30.50	0.1952
[2,]	10	1/10/86	23	25.9	0.89	1.22	22.9	1.13	20.42	11.00	-0.044
[3,]	26	3/9/88	40	23.9	0.77	1.19	18.5	0.60	66.95	20.00	-0.394
[4,]	37	6/27/89	34	23.3	1.32	1.42	30.8	0.69	49.61	17.00	0.1833
[5,]	39	9/27/89	33	27.6	1.1	1.58	30.5	0.84	39.46	16.50	0.062
[6,]	41	1/16/90	31	28.6	1.09	1.32	31.3	0.92	33.60	15.50	0.1281
[7,]	42	3/22/90	34	22.4	1.14	1.17	25.5	0.66	51.61	17.00	0.0738
[8,]	46	9/4/90	31	18.6	0.75	1.22	13.9	0.60	51.67	15.50	0.0701
[9,]	60	8/3/92	28	14.7	0.62	0.95	9.05	0.53	53.33	14.00	0.0085
[10,]	71	11/22/93	30	22.8	0.33	1.33	7.5	0.76	39.47	15.00	0.0205
[11,]	72	12/2/93	30	29.2	0.97	1.36	28.3	0.97	30.82	15.00	0.1932
[12,]	75	4/12/94	36	36.2	1.86	1.63	67.2	1.01	35.80	18.00	0.0719
[13,]	76	5/17/94	37	31.8	1.52	1.47	48.4	0.86	43.05	18.50	0.0866
[14,]	78	6/16/94	35	22.3	0.84	1.15	18.7	0.64	54.93	17.50	0.166
[15,]	79	7/25/94	33	20	0.67	1.09	13.5	0.61	54.45	16.50	0.0905
[16,]	82	10/13/94	27	16.5	0.55	1.05	9.09	0.61	44.18	13.50	0.0242
[17,]	85	12/20/94	28	15.5	0.52	0.99	8.16	0.55	50.58	14.00	0.0402
	Ave		33.6	26.8	0.99	1.30	30.66	0.78	45.22	16.76	0.0574
bfile32a											
[1,]	315	8/8/89	38	31.5	0.83	1.43	26	0.83	45.84	19.00	0.000
[2,]	319	3/22/90	42	41.7	1.84	2.04	76.6	0.99	42.30	21.00	-0.041
[3,]	320	5/2/90	42	36.3	1.75	1.94	63.7	0.86	48.60	21.00	-0.030
[4l]	321	6/20/90	40	35.5	1.14	1.66	40.4	0.89	45.07	20.00	0.049
[5,]	322	8/9/90	38	26.8	0.84	1.41	22.4	0.71	53.88	19.00	0.038
[6,]	328	7/9/91	38	28.8	1.03	1.48	29.6	0.76	50.14	19.00	-0.036

[7,]	329	8/28/91	37	28.3	0.59	1.32	16.8	0.76	48.37	18.50	-0.084
[8,]	333	4/15/91	41	32	1.23	1.62	41.5	0.78	52.53	20.50	0.104
[9,]	335	8/3/91	37	39.8	0.56	1.45	22.3	1.08	34.40	18.50	-0.005
[10,]	336	10/14/92	27	20	0.71	1.4	14.2	0.74	36.45	13.50	-0.072
[11,]	337	11/23/92	39	51.8	1.06	2.05	54.9	1.33	29.36	19.50	-0.070
[12,]	338	11/30/92	40	22.6	1.3	1.62	30	0.57	70.80	20.00	0.138
[13,]	340	2/9/93	42	29.1	1.72	1.76	50.1	0.69	60.62	21.00	0.024
[14,]	342	5/19/93	42	56.6	2.67	2.54	151	1.35	31.17	21.00	0.012
[15,]	343	7/6/93	36	32.3	1.22	1.61	39.2	0.90	40.12	18.00	-0.037
[16,]	344	8/25/93	31	22.6	0.88	1.4	19.9	0.73	42.52	15.50	-0.104
[17,]	345	10/13/93	33	25.5	0.82	1.45	20.8	0.77	42.71	16.50	-0.020
[18,]	350	6/8/94	38	60.5	1.32	2.08	79.8	1.59	23.87	19.50	-0.064
[19,]	352	7/26/94	39	33.8	0.92	1.61	31	0.87	45.00	19.50	-0.045
[20,]	353	8/10/94	36	26.6	0.87	1.5	23.1	0.74	48.72	18.00	-0.017
[21,]	354	10/6/94	32	23.7	0.75	1.45	17.8	0.74	43.21	16.00	-0.041
[22,]	355	11/30/94	31	24	0.72	1.47	17.4	0.77	40.04	15.50	-0.023
	Ave		37.2	33.17	1.13	1.65	40.39	0.88	44.35	18.64	-0.015
bfile33a											
1,]	485	11/14/89	39	54.5	2.88	2.79	157	1.40	27.91	19.50	-0.037
[2,]	487	3/22/90	58	88.6	2.86	3.03	253	1.53	37.97	29.00	-0.514
[3,]	490	8/9/90	30	40.8	1.45	2.45	59	1.36	22.06	15.00	-0.074
[4,]	491	10/3/90	32	42	1.4	2.4	60.5	1.31	24.38	16.00	0.020
[5,]	492	11/29/90	38	49.2	3.2	2.74	157	1.29	29.35	19.00	0.077
[6,]	497	7/24/91	30	33.2	2.25	2.47	74.8	1.11	27.11	15.00	0.186
[7,]	498	8/23/91	28	34.8	1.49	2.38	51.8	1.24	22.53	14.00	0.022
[8,]	499	10/16/91	27	31.7	1.03	2.33	32.7	1.17	23.00	13.50	0.032
[9,]	500	11/26/91	27	28.7	1.35	2.4	38.7	1.06	25.40	13.50	-0.101
[10,]	501	2/5/92	34	34	2.89	2.55	98.3	1.00	34.00	17.00	-0.212
[11,]	503	6/2/92	40	57.2	3.76	2.9	215	1.43	27.97	20.00	-0.005
[12,]	504	8/4/92	33	37.8	2.66	2.56	100	1.15	28.81	16.50	0.108
[13,]	505	10/14/92	25	32.4	1.26	2.35	40.9	1.30	19.29	12.50	0.128
[14,]	506	1/30/92	39	65.3	3.2	2.91	209	1.67	23.29	19.50	-0.165
[15,]	510	6/2/93	36	56.6	3.16	2.82	178	1.57	22.90	18.00	0.003
[16,]	511	7/7/93	32	38.2	3.01	2.57	115	1.19	26.81	16.00	0.132
[17,]	512	8/25/93	28	28.3	1.91	2.41	53.9	1.01	27.70	13.50	0.131
[18,]	513	10/13/93	25	29.1	1.85	2.41	53.8	1.16	21.48	12.50	0.079
[19,]	518	6/7/93	33	57.5	2.96	2.81	170	1.74	18.94	16.50	0.022
[20,]	519	7/25/93	33	43.7	3.61	2.73	158	1.32	24.92	16.50	0.048
[21,]	520	10/6/93	26	34.3	1.8	2.43	61.9	1.32	19.71	13.00	0.006
[22,]	521	11/30/93	28	30	2.12	2.47	63.6	1.07	26.13	14.00	0.036
	Ave		32.8	43.09	2.37	2.59	109.18	1.29	25.53	16.36	-0.004
bfile34a											
[1,]	469	3/20/85	184	362	0.73	2.24	263	1.97	93.52	92.00	-0.030
[2,]	470	5/8/85	185	385	0.99	2.48	381	2.08	88.90	92.50	0.053
[3,]	471	6/19/85	185	377	0.69	2.26	261	2.04	90.78	92.50	-0.014
[4,]	473	9/17/85	178	258	0.25	1.73	64.8	1.45	122.81	89.00	-0.013
[5,]	475	12/17/85	181	510	1.27	2.96	666	2.82	64.24	90.50	-0.046
[6,]	476	2/4/86	184	356	0.85	2.29	282	1.93	95.10	88.03	-0.056
[7,]	477	3/27/86	186	458	1.25	2.78	557	2.46	75.54	93.00	0.042
[8,]	479	6/17/86	186	320	0.5	2	158	1.72	108.11	93.00	0.036
[9,]	481	10/7/86	184	325	0.24	1.78	78.9	1.77	104.17	92.00	0.059
[10,]	482	11/18/86	183	273	0.39	1.84	106	1.49	122.67	91.50	-0.058

[11,]	483	2/19/87	184	402	1.04	2.5	417	2.18	84.22	92.00	-0.073
[12,]	484	7/1/87	184	320	0.54	2.03	173	1.74	105.80	92.00	-0.138
[13,]	485	8/5/87	185	265	0.36	1.8	96.5	1.43	129.15	92.50	0.083
[14,]	486	10/20/87	184	304	0.49	1.97	149	1.65	111.37	92.00	-0.041
[15,]	487	2/23/88	184	390	0.88	2.41	345	2.12	86.81	92.00	-0.020
[16,]	488	6/16/88	183	348	0.7	2.17	242	1.90	96.23	91.50	-0.039
[17,]	489	7/21/88	184	310	0.48	2	150	1.68	109.21	92.00	0.073
[18,]	490	9/13/88	184	277	0.37	1.82	102	1.51	122.22	92.00	0.080
[19,]	491	10/13/88	184	271	0.25	1.75	68.3	1.47	124.93	92.00	-0.072
[20,]	492	11/15/88	179	310	0.32	1.86	99	1.73	103.36	87.00	-0.879
[21,]	493	1/5/89	184	271	0.24	1.77	65.8	1.47	124.93	92.50	0.065
[22,]	494	3/7/89	184	354	0.79	2.28	280	1.92	95.64	92.00	0.059
[23,]	496	6/1/89	179	394	0.7	2.27	275	2.20	81.32	89.50	0.229
[24,]	497	7/6/89	180	407	0.9	2.44	365	2.26	79.61	90.00	-0.020
[25,]	499	11/14/89	184	376	0.77	2.28	290	2.04	90.04	92.00	-0.018
[26,]	500	3/6/90	186	438	0.99	2.57	435	2.35	78.99	93.00	-0.031
[27,]	501	4/23/90	182	447	1.26	2.77	563	2.46	74.10	91.00	0.006
[28,]	503	8/7/90	178	380	0.44	2.12	167	2.13	83.38	89.00	-0.057
[29,]	504	10/12/90	184	360	0.62	2.26	225	1.96	94.04	92.00	-0.013
[30,]	505	11/14/90	185	413	1	2.6	414	2.23	82.87	92.50	-0.021
[31,]	506	3/14/91	185	506	1.34	2.99	676	2.74	67.64	92.00	0.034
[32,]	508	7/15/91	182	430	0.73	2.48	315	2.36	77.03	91.00	-0.104
[33,]	509	8/28/91	184	291	0.41	2.02	118	1.58	116.34	91.00	0.126
[34,]	510	9/23/91	176	328	0.31	1.91	103	1.86	94.44	88.00	-0.091
[35,]	511	10/21/91	176	347	0.24	1.94	82.6	1.97	89.27	88.00	0.099
[36,]	512	11/21/91	185	236	0.3	1.8	70.4	1.28	145.02	92.50	-0.033
[37,]	513	1/28/92	187	305	0.63	2.11	190	1.63	114.65	91.50	-0.027
[38,]	518	5/24/93	189	464	0.96	2.96	443	2.46	76.98	90.00	0.000
[39,]	519	6/22/93	187	405	0.6	2.54	242	2.17	86.34	93.50	0.054
[40,]	520	7/27/93	183	386	0.61	2.52	234	2.11	86.76	91.50	-0.048
[41,]	521	8/25/93	184	407	0.35	2.23	141	2.21	83.18	92.00	-0.084
[42,]	523	12/14/93	180	473	1.04	2.69	492	2.63	68.50	90.00	-0.067
[43,]	525	6/1/94	193	383	0.87	2.4	332	1.98	97.26	96.50	0.039
[44,]	526	6/30/94	191	329	0.78	2.22	256	1.72	110.88	96.00	0.061
[45,]	528	10/5/94	179	368	0.4	1.97	146	2.06	87.07	89.50	-0.082
	Ave		184	362.6	0.66	2.24	257.34	1.98	96.12	91.46	-0.022
bfile35a											
[1,]	541	9/27/90	58	48.8	0.65	1.69	31.8	0.84	68.93	15.00	-0.233
[2,]	555	1/25/91	30	24.1	0.29	1.59	6.94	0.80	37.34	26.50	-0.167
[3,]	556	8/27/91	30	24.8	0.3	1.61	7.53	0.83	36.29	27.53	0.012
[4,]	558	12/5/91	53	54.2	0.73	1.87	39.8	1.02	51.83	15.00	0.289
[5,]	559	1/30/92	45	46.8	0.44	1.94	20.7	1.04	43.27	22.50	-0.135
[6,]	560	4/8/92	53	52.2	1.02	1.88	53.2	0.98	53.81	26.50	-0.149
[7,]	561	6/4/92	41	37.6	0.91	1.74	34.3	0.92	44.71	20.50	-0.302
[8,]	562	7/30/92	43	37.8	0.96	1.76	36.3	0.88	48.92	21.50	0.338
[9,]	563	10/8/92	40	38.8	0.57	1.77	21.9	0.97	41.24	20.00	-0.272
[10,]	564	12/3/92	53	56.8	1.1	1.98	62.1	1.07	49.45	26.50	-0.214
[11,]	565	2/4/93	54	56.2	1.14	1.96	63.8	1.04	51.89	27.00	0.242
[12,]	566	4/8/93	55	81	2.53	2.62	205	1.47	37.35	27.50	-0.050
[13,]	567	5/20/93	53	54.2	1.28	2.01	69.2	1.02	51.83	26.50	-0.197
[14,]	570	9/30/93	38	27.6	0.5	1.55	13.7	0.73	52.32	19.00	-0.154
[15,]	571	10/21/93	32	29.1	0.67	1.71	19.5	0.91	35.19	16.00	0.265

[16,]	572	12/9/93	57	80	2	2.48	160	1.40	40.61	28.50	-0.051
[17,]	579	12/12/94	51	57.2	1.2	2.05	68.4	1.12	45.47	25.50	-0.248
Ave			46.2	47.48	0.96	1.89	53.77	1.00	46.50	23.03	-0.060
bfile36a											
[1,]	157	9/22/87	39	41.2	1.75	3.05	71.9	1.06	36.92	19.50	-0.066
[2,]	158	11/10/87	31	24.2	1.31	2.78	31.6	0.78	39.71	15.50	0.107
[3,]	159	12/10/87	54	51.8	1.25	3.07	64.5	0.96	56.29	27.00	0.405
[4,]	166	8/2/88	38	34.4	0.56	2.56	19.3	0.91	41.98	18.75	0.179
[5,]	167	9/21/88	40	39.2	0.6	2.64	23.4	0.98	40.82	20.00	0.173
[6,]	168	10/18/88	29	26.6	0.19	2.42	5.08	0.92	31.62	14.50	-0.141
[7,]	173	5/9/89	58	115	1.9	3.86	219	1.98	29.25	29.00	0.146
[8,]	176	7/12/89	41	38.2	0.6	2.62	22.8	0.93	44.01	20.50	0.092
[9,]	177	8/1/89	52	65.1	0.76	2.92	49.7	1.25	41.54	25.75	0.257
[10,]	178	9/27/89	45	49.6	0.36	2.64	17.7	1.10	40.83	22.50	0.117
[11,]	180	11/15/89	40	40.9	0.4	2.57	16.4	1.02	39.12	20.00	-0.166
[12,]	181	1/10/90	42	31.8	1.58	2.94	50.4	0.76	55.47	21.00	-0.178
[13,]	183	5/2/90	52	65.9	0.91	2.98	59.9	1.27	41.03	25.00	-0.080
[14,]	194	7/31/91	27	15.2	0.36	2.34	5.52	0.56	47.96	13.50	0.046
[15,]	195	8/13/91	19.5	9.44	0.25	2.23	2.37	0.48	40.28	9.75	0.006
[16,]	196	8/26/91	17	9.51	0.22	2.23	2.12	0.56	30.39	8.50	0.058
[17,]	198	12/4/91	51	43	0.96	2.86	41.4	0.84	60.49	25.50	0.315
Ave			39.7	41.24	0.82	2.75	41.36	0.96	42.22	19.78	0.075
bfile37a											
[1,]	231	10/26/89	73	77.7	0.64	2.75	49.7	1.06	68.58	36.50	-0.205
[2,]	245	11/28/90	76	102	0.67	2.8	68.1	1.34	56.63	38.00	0.018
[3,]	247	3/20/91	79	130	0.84	2.97	110	1.65	48.01	39.50	-0.006
[4,]	269	8/25/93	7.7	2.03	0.69	2.1	1.39	0.26	29.21	24.75	0.163
[5,]	272	12/8/93	83	162	1.22	3.5	198	1.95	42.52	41.50	0.050
[6,]	273	2/2/94	78	138	1.01	3.14	139	1.77	44.09	39.00	0.055
[7,]	274	4/6/94	84	189	1.41	3.61	267	2.25	37.33	42.00	-0.024
[8,]	275	6/2/94	78	103	0.35	2.55	36.1	1.32	59.07	39.00	-0.072
[9,]	276	7/20/94	78	101	0.26	2.48	26	1.29	60.24	39.00	0.056
[10,]	279	12/7/94	82	118	0.6	2.76	71.4	1.44	56.98	41.00	0.091
Ave			71.9	112.3	0.77	2.87	96.67	1.43	50.27	38.03	0.013
bfile38a											
[1,]	576	5/15/91	76	134	1.2	1.83	161	1.76	43.10	38.00	0.061
[2,]	577	7/10/91	43	47.2	0.53	1.1	25.2	1.10	39.17	21.50	0.367
[3,]	583	12/4/91	66	119	1.34	2.14	160	1.80	36.61	33.00	0.028
[4,]	585	4/8/92	85	146	1.09	1.79	159	1.72	49.49	42.50	0.103
[5,]	586	6/3/92	78	153	1.36	1.96	208	1.96	39.76	39.00	0.102
[6,]	587	7/29/92	77	167	1.64	2.15	274	2.17	35.50	38.50	0.086
[7,]	588	8/19/92	72	106	0.82	1.62	86.3	1.47	48.91	36.00	0.073
[8,]	589	10/7/92	62	92.3	0.85	1.58	78.5	1.49	41.65	31.00	0.235
[9,l	590	12/1/92	80	151	2.19	2.33	332	1.89	42.38	40.00	0.227
[10,]	591	2/2/93	84	165	1.57	2.15	258	1.96	42.76	42.00	0.052
[11,]	604	7/19/94	77	121	0.88	1.6	107	1.57	49.00	38.50	0.105
[12,]	605	9/6/94	73	96.8	0.57	1.39	55.3	1.33	55.05	36.50	0.155
[13,]	607	12/7/94	72	137	1.42	2	196	1.90	37.84	36.00	0.078
Ave			72.7	125.8	1.19	1.82	161.56	1.70	43.17	36.35	0.129
bfile39a											
[1,]	535	9/26/89	51	106	1.35	4.3	143	2.08	24.54	25.50	-0.030
[2,]	536	11/14/89	40	54.4	0.5	3.1	27.1	1.36	29.41	20.00	-0.119

[3,]	537	1/9/90	49	64.6	1.07	3.52	68.9	1.32	37.17	24.50	0.161
[4,]	538	3/6/90	40	58.2	0.71	3.26	41.1	1.46	27.49	20.00	-0.118
[5,]	542	10/9/90	35	38.5	0.3	2.86	11.4	1.10	31.82	17.50	-0.068
[6,]	543	11/27/90	41	52.7	0.51	3.09	27.1	1.29	31.90	20.50	-0.132
[7,]	544	1/23/91	41	66	0.8	3.39	52.9	1.61	25.47	21.00	-0.053
[8,]	545	3/19/91	46	75.6	1.02	3.62	76.7	1.64	27.99	23.00	-0.016
[9,]	546	5/14/91	41	50.9	0.57	3.12	28.8	1.24	33.03	20.50	-0.059
[10,]	547	7/9/91	40	45.9	0.77	3.19	35.2	1.15	34.86	20.00	-0.041
[11,]	548	7/31/91	36	24.8	0.72	2.91	17.7	0.69	52.26	18.00	0.040
[12,]	549	8/26/91	29	22.3	0.29	2.53	6.52	0.77	37.71	14.50	0.094
[13,]	552	1/28/92	37	45.5	0.62	3.11	28	1.23	30.09	18.50	-0.086
[14,]	556	10/6/92	36	32.8	0.64	3	21	0.91	39.51	18.00	0.072
[15,]	560	5/18/93	44	56.3	1.26	3.57	71	1.28	34.39	22.00	0.069
[16,]	572	12/6/94	41	62.9	0.88	3.42	55.3	1.53	26.72	20.50	-0.112
	Ave		40.4	53.59	0.75	3.25	44.48	1.29	32.77	20.25	-0.025
bfile40a											
[1,]	482	12/18/89	54	26.7	0.43	0.56	11.6	0.49	109.21	27.50	0.123
[2,]	483	1/29/90	69	35.8	0.67	0.65	23.9	0.52	132.99	34.50	0.394
[3,]	485	3/28/90	67	35	0.48	0.6	16.9	0.52	128.26	33.50	-0.430
[4,]	486	4/26/90	58	26.1	0.67	0.61	17.6	0.45	128.89	29.00	-0.489
[5,]	494	12/26/90	72	36.8	0.61	0.88	22.6	0.51	140.87	36.00	0.050
[6,]	495	1/29/91	70	33.4	0.61	0.79	17.1	0.48	146.71	35.00	0.183
[7,]	496	2/25/91	70	31.2	0.42	0.76	13	0.45	157.05	35.00	0.226
[8,]	497	3/27/91	75	47.4	0.75	0.99	35.6	0.63	118.67	37.50	-0.030
[9,]	498	4/25/91	71	32	0.54	0.81	17.4	0.45	157.53	35.50	0.109
[10,]	499	5/28/91	67	23.6	0.38	0.69	8.99	0.35	190.21	33.50	0.226
[11,]	500	6/26/91	70	25.8	0.34	0.67	8.72	0.37	189.92	35.00	0.248
[12,]	501	7/29/91	81	80	1.68	1.49	134	1.25	64.80	38.00	0.012
[13,]	502	8/27/91	99	78.1	1.03	1.28	80.3	0.79	125.49	49.50	-0.100
[14,]	519	2/24/93	83	57.9	0.45	0.91	25.9	0.70	118.98	41.50	0.016
[15,]	520	3/29/93	96	86.9	0.77	1.2	67.3	0.91	106.05	48.00	-0.045
[16,]	521	4/28/93	93	65.3	0.4	0.99	25.3	0.70	132.45	46.50	0.049
[17,]	522	5/25/93	91	66.5	0.33	0.98	21	0.73	124.53	45.50	-0.006
[18,]	523	6/28/93	91	56	0.09	0.84	5.12	0.62	147.88	45.50	0.055
[19,]	532	4/26/94	67	31.1	0.67	0.82	20.9	0.46	144.34	33.50	0.183
[20,]	534	6/28/94	64	25	0.44	0.72	11	0.39	163.84	32.00	0.173
[21,]	535	6/28/94	42	17.4	0.44	0.7	7.71	0.41	101.38	21.00	-0.104
[22,]	536	9/28/94	62	30.8	0.52	0.78	16.1	0.50	124.81	31.00	0.282
	Ave		73.3	43.13	0.58	0.67	27.64	0.58	134.31	36.55	0.051
bfile41a											
[1,]	430	2/27/85	28	26	0.52	1.8	13.6	0.93	30.15	13.20	0.043
[2,]	482	10/25/90	28	19.8	0.6	1.79	11.9	0.71	39.60	14.00	0.154
[3,]	484	1/23/91	30	22.6	0.59	1.83	13.4	0.75	39.82	15.00	-0.239
[4,]	485	3/19/91	28	24.6	0.88	1.97	21.7	0.88	31.87	14.00	-0.101
[5,]	488	8/5/91	7	4.4	0.35	1.44	1.54	0.63	11.14	3.50	-0.089
[6,]	499	5/18/93	31	36.5	1.07	2.28	39.1	1.18	26.33	15.50	0.018
[7,]	500	6/10/93	34	25.8	0.64	1.98	16.5	0.76	44.81	17.00	0.006
[8,]	502	8/24/93	16	5.45	0.29	1.47	1.6	0.34	46.97	8.00	-0.028
[9,]	511	10/3/94	34	22.4	0.26	1.8	5.76	0.66	51.61	17.00	-0.036
	Ave		26.2	20.84	0.58	1.82	13.90	0.76	35.81	13.02	-0.030
bfile42a											
[1,]	404	9/19/89	17	9.64	0.84	2.37	8.11	0.57	29.98	8.50	-0.062

[2,]	417	7/9/91	22	7.9	1.19	2.43	9.4	0.36	61.27	11.00	0.013
[3,]	418	8/6/91	2.8	0.57	0.94	1.97	0.54	0.20	13.75	1.40	0.140
[4,]	419	8/20/91	4.5	1.4	0.35	1.98	0.49	0.31	14.46	2.25	-0.314
[5,]	435	10/19/93	10.5	2.88	0.32	2.2	0.92	0.27	38.28	5.25	0.215
[6,]	436	12/7/93	61	115	1.63	3.72	188	1.89	32.36	30.50	0.047
[7,]	438	4/5/94	65	77.8	1.44	3.3	112	1.20	54.31	32.50	0.415
[8,]	439	6/1/94	16.2	4.98	0.95	2.25	4.72	0.31	52.70	9.23	0.233
	Ave		24.9	27.52	0.96	2.53	40.52	0.64	37.14	12.58	0.086
bfile43a											
[1,]	383	9/17/90	8.4	2.21	0.25	1.47	0.55	0.26	31.93	4.20	0.208
[2,]	384	10/26/90	12	5.28	0.47	1.7	2.46	0.44	27.27	6.00	-0.055
[3,]	388	7/22/91	1.5	0.08	0.27	1.17	0.02	0.05	28.13	0.75	0.000
[4,]	391	5/20/92	6.6	1.64	1.23	1.53	2.02	0.25	26.56	3.30	0.396
[5,]	397	6/22/93	9.2	4.54	0.22	1.47	1.16	0.49	18.64	4.60	0.277
[6,]	400	1/26/94	14	10.2	1.24	2.19	12.6	0.73	19.22	6.75	0.158
[7,]	401	3/16/94	14	8.25	1.14	1.94	9.38	0.59	23.76	7.00	0.190
[8,]	402	4/28/94	13	3.84	1.14	1.67	4.37	0.30	44.01	6.50	-0.055
[9,]	403	6/16/94	4.2	0.78	0.68	1.35	0.53	0.19	22.62	2.10	0.128
10,]	405	8/31/94	10.8	2.06	0.52	1.48	1.09	0.19	56.62	5.40	0.116
	Ave		9.37	3.888	0.72	1.60	3.42	0.35	29.87	4.66	0.136
bfile44a											
[1,]	148	8/3/87	17	8.69	0.18	1.32	1.56	0.51	33.26	8.50	0.285
[2,]	176	1/23/91	30	32.7	0.91	1.52	29.7	1.09	27.52	15.00	0.343
[3,]	177	3/19/91	38	57.5	1.36	1.86	78	1.51	25.11	19.00	0.203
[4,]	178	5/14/91	27	26	0.47	1.28	12.2	0.96	28.04	13.50	0.290
[5,]	197	7/26/93	14.7	4.02	0.22	1.09	0.9	0.27	53.75	7.35	-0.247
[6,]	200	10/19/93	15	7.05	0.28	2.05	1.98	0.47	31.91	7.50	-0.077
[7,]	205	6/1/94	23	16.2	0.46	1	7.43	0.70	32.65	11.50	0.302
[8,]	206	7/14/94	20	11.3	0.31	0.9	3.5	0.57	35.40	10.00	0.272
[9,]	208	10/4/94	18.5	12.6	0.29	1.39	3.7	0.68	27.16	9.25	0.300
[10,]	210	12/7/94	39	57.3	0.37	1.8	21.3	1.47	26.54	19.50	0.316
	Ave		24.2	23.34	0.49	1.42	16.03	0.82	32.14	12.11	0.199

APPENDIX B

ALGORITHMS FOR SUBBASIN/DRAINAGE AREA DELINEATION

<u>Process.aml</u>

```
&s sitecov [response 'Name of input site coverage in UTM']
&s elevgrid [response 'Name of output filled elevation grid']
&s shedname [response 'Name of output watershed mask grid']
&s atngrid [response 'Name of output ATN grid']
&s dirgrid [response 'Name of output direction grid']

&s i = 1
&label top
&s dem%i% [response 'Name of DEM grid']
&s i = %i% + 1
&if [query 'Additional DEMS'] &then &goto top

&do j = 1 &to [calc %i% - 1]
 arc demlattice [value dem%j%] dem%j%grid
&end

&if not [null %dem2%] &then &do
arc latticemerge commongrid
&do k = 1 &to [calc %i% - 1]
dem%k%grid
&end
end

fill commongrid %elevgrid% # # %dirgrid%

xxflowacc = flowaccumulation(%dirgrid%)

setcell %elevgrid%
setwindow %elevgrid%
xxpointgrid = pointgrid(%sitecov%)
seeds = snappour(xxpointgrid,xxflowacc,100)

%shedname% = watershed(%dirgrid%,seeds)

&r modatn %elevgrid% %dirgrid% %atngrid%

kill (! commongrid xxflowacc xxpointgrid seeds !)

&do k = 1 &to [calc %i% - 1]
```

```
kill dem%k%grid
&end

&return
```

Modpro.aml

```
&s sitecov [response 'Name of input site coverage in UTM']
&s elevgrid [response 'Name of output filled elevation grid']
&s shedname [response 'Name of output watershed mask grid']
&s atngrid [response 'Name of output ATN grid']
&s dirgrid [response 'Name of output direction grid']



xxflowacc = flowaccumulation(%dirgrid%)

setcell %elevgrid%
setwindow %elevgrid%
xxpointgrid = pointgrid(%sitecov%)
seeds = snappour(xxpointgrid,xxflowacc,100)

%shedname% = watershed(%dirgrid%,seeds)

&r modatn %elevgrid% %dirgrid% %atngrid%

kill (! xxflowacc xxpointgrid seeds !)


&return
```

Rerun.aml

```
&s sitecov [response 'Name of input site coverage in UTM']
&s tmpgrid [response 'Name of input temp elevation grid']
&s elevgrid [response 'Name of output filled elevation grid']
&s shedname [response 'Name of output watershed mask grid']
&s atngrid [response 'Name of output ATN grid']
&s dirgrid [response 'Name of output direction grid']

arc copy %tmpgrid% commongrid
/* &s i = 1
/* &label top
/* &s dem%i% [response 'Name of DEM grid']
/* &s i = %i% + 1
```

```
/* &if [query 'Additional DEMS'] &then &goto top

/* &do j = 1 &to [calc %i% - 1]
/*  arc demlattice [value dem%j%] dem%j%grid
/* &end

/* if not [null %dem2%] &then &do
/* arc latticemerge commongrid
/* &do k = 1 &to [calc %i% - 1]
/* dem%k%grid
/* end
/* end

fill commongrid %elevgrid% # # %dirgrid%

xxflowacc = flowaccumulation(%dirgrid%)

setcell %elevgrid%
setwindow %elevgrid%
xxpointgrid = pointgrid(%sitecov%)
seeds = snappour(xxpointgrid,xxflowacc,100)

%shedname% = watershed(%dirgrid%,seeds)

&r modatn %elevgrid% %dirgrid% %atngrid%

kill (! commongrid xxflowacc xxpointgrid seeds !)

/* &do k = 1 &to [calc %i% - 1]
/* kill dem%k%grid
/* &end
&return
```

APPENDIX C
WATERSHED DATA COLLECTED, CALCULATED AND/OR DERIVED

Num	Id$	Idd	b	f	m	Size
1	m10	1601500	0.1416	0.3605	0.4981	247
2	m11	1603000	0.1084	0.5349	0.3567	875
3	m19	1614500	0.0989	0.3936	0.5078	494
4	m21	1617800	0.1699	0.3841	0.4467	18.9
5	m24	1619500	0.2441	0.1891	0.5661	281
6	m26	1637500	0.3477	0.2669	0.3842	66.9
7	m29	1639140	0.225	0.2597	0.5119	31.3
8	m30	1639500	0.1121	0.3941	0.4962	102
9	m31	1640965	0.4607	0.2403	0.2895	2.14
10	m311	1640970	0.5622	0.1442	0.2976	4.01
11	m32	1640980	0.2972	0.0906	0.6336	0.38
12	m34	1643000	-0.008	0.4667	0.5736	817
13	m37	1643500	0.04	0.3581	0.6011	62.8
14	m38	1645000	0.065	0.4289	0.5113	101
15	m43	1651000	0.2741	0.2663	0.463	49.4
16	m45	1653600	0.1868	0.4474	0.3668	39.5
17	m47	1661050	0.2769	0.2784	0.4488	18.5
18	m48	1661500	0.1	0.2326	0.6684	24
19	v07	1622000	0.034	0.357	0.6072	379
20	v12	1624800	0.1302	0.4717	0.3992	70.1
21	v13	1625000	0.2286	0.2081	0.5632	375
22	v15	1626000	0.0906	0.2665	0.6411	127
23	v17	1626850	0.0507	0.3832	0.5697	149
24	v18	1627500	0.1761	0.5368	0.2872	212
25	v19	1628060	0.3773	0.2978	0.3461	1.94
26	v22	1628500	0.0573	0.3363	0.6063	1084
27	v23	1629500	0.2195	0.3008	0.4797	1377
28	v24	1631000	0.0839	0.2954	0.6208	1642
29	v25	1632000	0.339	0.416	0.2443	210
30	v26	1632082	0.1865	0.2601	0.555	45.5
31	v27	1632900	0.1437	0.2687	0.587	93.2
32	v28	1633000	0.2729	0.1612	0.5681	506
33	v29	1634000	0.0075	0.2406	0.7541	768
34	v30	1634500	0.2061	0.1703	0.6242	103
35	v36	1638480	0.2498	0.2162	0.5363	89.6
36	v38	1643700	0.4398	0.3903	0.1676	123
37	v39	1644000	0.193	0.2523	0.5559	332
38	v44	1646000	0.1671	0.3015	0.5314	57.9
39	v48	1653000	0.1374	0.3277	0.573	33.7
40	v49	1654000	0.3637	0.2618	0.3754	23.5
41	v52	1656000	0.4685	0.3194	0.2123	93.4
42	v65	1658500	0.3515	0.3744	0.2646	7.64
43	v71	1660400	0.2404	0.359	0.4032	34.9

physiogra$	phys1$	ordinary for b	ordinary for f	ordinary for m
plat (100%)	plat	5	5	2
plat (100%)	plat	5	5	2
gv/br/vr(50/10/40)	gv	2	2	5
br	br	6	6	1
br	br	6	6	1
br	br	6	6	1
pied	pied	3	3	4
pied	pied	3	3	4
br	br	6	6	1
br	br	6	6	1
br/pied (70/30)	pied	3	3	4
pied	pied	3	3	4
pied	Pied	3	3	4
pied	Pied	3	3	4
pied/coap (80/20)	coap	1	1	6
coap	coap	1	1	6
coap	coap	1	1	6
coap	coap	1	1	6
gv/vr (60/40)	gv	2	2	5
gv/br (50/50)	br	6	6	1
gv/br/vr(70/20/10)	gv	2	2	5
br/gv (80/20)	br	6	6	1
br/gv (80/20)	br	6	6	1
br	br	6	6	1
br	br	6	6	1
br/gv/vr (30/50/20)	br	6	6	1
br/gv/vr (40/40/20)	br	6	6	1
br/gv/vr (45/40/15)	br	6	6	1
vr	vr	4	4	3
gv	gv	2	2	5
gv	gv	2	2	5
vr/gv (45/55)	gv	2	2	5
vr/gv (20/80)	gv	2	2	5
vr	vr	4	4	3
br	BR	6	6	1
br	BR	6	6	1
br/pied (95/5)	pied	3	3	4
pied	pied	3	3	4
pied/coap (70/30)	coap	1	1	6
pied	pied	3	3	4
pied/br (60/40)	pied	3	3	4
pied	pied	3	3	4
pied	pied	3	3	4

piedmont	coastal	plateau	greatv_val	blue_ridge	vr
0	0	100	0	0	0
0	0	100	0	0	0
0	0	0	50	10	40
0	0	0	0	100	0
0	0	0	0	100	0
0	0	0	0	100	0
100	0	0	0	0	0
100	0	0	0	0	0
0	0	0	0	100	0
0	0	0	0	100	0
30	0	0	0	70	0
100	0	0	0	0	0
100	0	0	0	0	0
100	0	0	0	0	0
80	20	0	0	0	0
0	100	0	0	0	0
0	100	0	0	0	0
0	100	0	0	0	0
0	0	0	60	0	40
0	0	0	50	50	0
0	0	0	70	20	10
0	0	0	20	80	0
0	0	0	20	80	0
0	0	0	0	100	0
0	0	0	0	100	0
0	0	0	50	30	20
0	0	0	40	40	20
0	0	0	40	45	15
0	0	0	0	0	100
0	0	0	100	0	0
0	0	0	100	0	0
0	0	0	55	0	45
0	0	0	80	0	20
0	0	0	0	0	100
0	0	0	0	100	0
0	0	0	0	100	0
5	0	0	0	95	0
100	0	0	0	0	0
70	30	0	0	0	0
100	0	0	0	0	0
60	0	0	0	40	0
100	0	0	0	0	0
100	0	0	0	0	0

Lithology$	Litho1$	ordinary for b	ordinary for f
sili/und (70/30)	und	3	3
sili/und (70/30)	und	3	3
carb/sili/crys/und (45/40/10/5)	carb	2	2
carb	carb	2	2
carb/und/crys (70/10/20)	und	3	3
crys	crys	4	4
sili/crys (60/40)	sili	5	5
crys/sili (70/30)	crys	4	4
crys	crys	4	4
crys	crys	4	4
crys/sili (60/40)	sili	5	5
crys	crys	4	4
crys	crys	4	4
crys/sili (90/10)	sili	5	5
crys/uncon (80/20)	uncon	1	1
uncon	uncon	1	1
uncon	uncon	1	1
uncon	uncon	1	1
carb/sili (50/50)	carb	2	2
carb/sili (60/40)	sili	5	5
carb/und/sili (60/10/30)	sili	5	5
carb/und/crys (40/20/40)	und	3	3
carb/und/crys (40/20/40)	und	3	3
carb/und/crys (40/20/40)	carb	2	2
crys	crys	4	4
crys/und/carb/sili (20/10/50/20)	sili	5	5
crys/und/carb/sili (10/10/50/30)	sili	5	5
crys/und/carb/sili (25/5/50/20)	sili	5	5
sili/und (85/15)	und	3	3
carb/sili (70/30)	sili	5	5
carb/sili (50/50)	sili	5	5
sili/und/carb (45/10/45)	carb	2	2
sili/und/carb (50/10/40)	sili	5	5
sili/und (40/60)	und	3	3
crys	crys	4	4
crys	crys	4	4
crys/sili (90/10)	sili	5	5
crys	crys	4	4
crys/unc (50/50)	uncon	1	1
crys	crys	4	4
crys/sili (70/30)	sili	5	5
crys	crys	4	4
crys	crys	4	4

ordinary for m	sili1	sili_und1	carbonate1	unconsol1
3	70	30	0	0
3	70	30	0	0
4	40	5	45	0
4	0	0	100	0
3	0	10	70	0
2	0	0	0	0
1	60	0	0	0
2	30	0	0	0
2	0	0	0	0
2	0	0	0	0
1	40	0	0	0
2	0	0	0	0
2	0	0	0	0
1	10	0	0	0
5	0	0	0	20
5	0	0	0	100
5	0	0	0	100
5	0	0	0	100
4	50	0	50	0
1	40	0	60	0
1	30	10	60	0
3	0	20	40	0
3	0	20	40	0
4	0	20	40	0
2	0	0	0	0
1	20	10	50	0
1	30	10	50	0
1	20	5	50	0
3	85	15	0	0
1	30	0	70	0
1	50	0	50	0
4	45	10	45	0
1	50	10	40	0
3	40	60	0	0
2	0	0	0	0
2	0	0	0	0
1	10	0	0	0
2	0	0	0	0
5	0	0	0	50
2	0	0	0	0
1	30	0	0	0
2	0	0	0	0
2	0	0	0	0

crystalline1	Landuse$	landuse1$	ordinary for b	ordinary for f
0	f	f		
0	f	f		
10	a/f (70/30)	a		
0	a	a		
20	a/f (80/20)	f		
100	a	a		
40	a	a		
70	a	a		
100	f	f		
100	f	f		
60	f	f		
100	a	a		
100	a/f (90/10)	f		
90	a/f (90/10)	f		
80	a/u (20/80)	u		
0	a/f/u (20/50/30)	f		
0	a/f (30/70)	a		
0	f	f		
0	a/f (50/50)	a		
0	a/f (90/10)	a		
0	a	a		
40	a/f (50/50)	a		
40	a/f/u (40/50/10)	f		
40	a/f (40/60)	f		
100	f	f		
20	a/f (60/40)	f		
10	a/f (60/40)	f		
25	a/f (50/50)	f		
0	f	f		
0	a	a		
0	a/f (70/30)	a		
0	a/f (90/10)	a		
0	a/f (60/40)	a		
0	f	f		
100	a	a		
100	a	a		
90	a	a		
100	a/f/u (20/30/50)	f		
50	u	u		
100	f/u (10/90)	u		
70	a	a		
100	f	f		
100	f	f		

ordinary for m	forest2	agrric2	urban2	Bed material$
	100	0	0	c/r (50/50)
	100	0	0	g/s (50/50)
	30	70	0	r/g (90/10)
	0	100	0	r/g/si (33/33/34)
	20	80	0	g
	0	100	0	g/s (50/50)
	0	100	0	g/c (50/50)
	0	100	0	g/r (80/20)
	100	0	0	c/r (50/50)
	100	0	0	c/r (50/50)
	100	0	0	g/c (50/50)
	0	100	0	g/s (50/50)
	10	90	0	g/s/r(33/33/34)
	10	90	0	g/s (50/50)
	0	20	80	clay/s (70/30)
	50	20	30	g/s (50/50)
	70	30	0	s/si (50/50)
	100	0	0	g/s/clay (25/25/50)
	50	50	0	r/g (50/50)
	10	90	0	g/s (50/50)
	0	100	0	r
	50	50	0	r/c (50/50)
	50	40	10	g/c (50/50)
	60	40	0	r/c(50/50)
	100	0	0	r/g (80/20)
	40	60	0	r/c (50/50)
	40	60	0	r/c (50/50)
	50	50	0	r/g/s (80/10/10)
	100	0	0	r/c (50/50)
	0	100	0	r/c (50/50)
	30	70	0	c/g (50/50)
	10	90	0	r/g (50/50)
	40	60	0	r/g (50/50)
	100	0	0	g/c (50/50)
	0	100	0	c/s (50/50)
	0	100	0	s/g (50/50)
	0	100	0	g
	30	20	50	r/s (50/50)
	0	0	100	g/s (50/50)
	10	0	90	r/g (50/50)
	0	100	0	c/g (50/50)
	100	0	0	s
	100	0	0	r/c (50/50)

	ordinary for b	ordinary for f	ordinary for m	cobble3
	1.5	5.5	1.5	50
	3.5	3.5	3.5	0
	1.2	5.8	1.2	0
	3	4	3	0
	3	4	3	0
	3.5	3.5	3.5	0
	2.5	4.5	2.5	50
	2.6	4.4	2.6	0
	1.5	5.5	1.5	50
	1.5	5.5	1.5	50
	2.5	4.5	2.5	50
	3.5	3.5	3.5	0
	2.7	4.3	2.7	0
	3.5	3.5	3.5	0
	5.4	1.6	5.4	0
	3.5	3.5	3.5	0
	4.5	2.5	4.5	0
	4.75	2.25	4.75	0
	2	5	2	0
	3.5	3.5	3.5	0
	1	6	1	0
	1.5	5.5	1.5	50
	2.5	4.5	2.5	50
	1.5	5.5	1.5	50
	1.4	5.6	2	0
	1.5	5.5	1.5	50
	1.5	5.5	1.5	50
	1.5	5.5	1.5	0
	1.5	5.5	1.5	50
	1.5	5.5	1.5	50
	2.5	4.5	2.5	50
	2	5	2	0
	2	5	2	0
	2.5	4.5	2.5	50
	3	4	3	50
	3.5	3.5	3.5	0
	3	4	3	0
	3	4.5	2.5	0
	3.5	3.5	3.5	0
	2	5	2	0
	2.5	2.5	2.5	50
	4	3	4	0
	3.5	5.5	1.5	50

rock3	gravel3	sand3	silt3	clay3	bank material
50	0	0	0	0	co/rock (50/50)
0	50	50	0	0	san
90	10	0	0	0	silt
33	33	0	34	0	silt
0	100	0	0	0	silt
0	50	50	0	0	san
0	50	0	0	0	g/san (50/50)
20	80	0	0	0	silt
50	0	0	0	0	rock
50	0	0	0	0	g/san (50/50)
0	50	0	0	0	rock
0	50	50	0	0	silt
34	33	33	0	0	san/silt (50/50)
0	50	50	0	0	san/silt (50/50)
0	0	30	0	70	san/silt (50/50)
0	50	50	0	0	silt
0	0	50	50	0	san/silt (50/50)
0	25	25	0	50	san
50	50	0	0	0	rock/san (50/50)
0	50	50	0	0	san
100	0	0	0	0	co/san (50/50)
50	0	0	0	0	co/san (50/50)
0	50	0	0	0	san/clay (50/50)
50	0	0	0	0	co/san (50/50)
80	20	0	0	0	san
50	0	0	0	0	san/clay (50/50)
50	0	0	0	0	co/san (50/50)
80	10	10	0	0	silt
50	0	0	0	0	rock
50	0	0	0	0	san/co (50/50)
0	50	0	0	0	san/co (50/50)
50	50	0	0	0	co/clay (50/50)
50	50	0	0	0	san/g (50/50)
0	50	0	0	0	co/rock (50/50)
0	0	50	0	0	co/san (50/50)
0	50	50	0	0	san/clay (50/50)
0	100	0	0	0	san/rock (50/50)
50	0	50	0	0	san/rock (50/50)
0	50	50	0	0	san
50	50	0	0	0	san/co (50/50)
0	50	0	0	0	san/co (50/50)
0	0	100	0	0	san
50	0	0	0	0	rock/san (50/50)

	ordinary for b	ordinary for f	ordinary for m	cobble4	rock4
	3.5	2.5	1.5	50	50
	1	6	3	0	0
	5	5	4	0	0
	5	5	4	0	0
	5	5	4	0	0
	1	6	3	0	0
	3.5	3.5	3.5	0	0
	5	2	5	0	0
	1	6	1	0	100
	3.5	3.5	3.5	0	0
	1	6	1	0	100
	5	2	5	0	0
	4.5	2.5	4.5	0	0
	4.5	2.5	4.5	0	0
	4.5	2.5	4.5	0	0
	5	2	5	0	0
	4.5	2.5	4.5	0	0
	4	3	4	0	0
	2.5	4.5	2.5	0	50
	4	3	4	0	0
	3	4	3	50	0
	3	4	3	50	0
	5	2	5	0	0
	3	4	3	50	0
	4	3	4	0	0
	5	2	5	0	0
	3	4	3	50	0
	5	2	5	0	0
	1	6	1	0	100
	3	4	3	50	0
	3	4	3	50	0
	4	3	4	50	0
	3.5	3.5	3.5	0	0
	1.5	5.5	1.5	50	50
	3	4	3	50	0
	5	2	5	0	0
	2.5	4.5	2.5	0	50
	2.5	4.5	2.5	0	50
	4	3	4	0	0
	3	4	3	50	0
	3	4	3	50	0
	4	3	4	0	0
	2.5	4.5	2.5	0	50

sand4	silt4	gravel4	s4	clay4	grav4	ch_Pattern$
0	0	0	0	0	0	S
100	0	0	0	0	0	S
0	100	0	0	0	0	M
0	100	0	0	0	0	M
0	100	0	0	0	0	B
100	0	0	0	0	0	B
50	0	50	0	0	0	B
0	100	0	0	0	0	M
0	0	0	0	0	0	M
50	0	50	0	0	0	M
0	0	0	0	0	0	B
0	100	0	0	0	0	B
50	50	0	0	0	0	S
50	50	0	0	0	0	B
50	50	0	0	0	0	B
0	100	0	0	0	0	S
50	50	0	0	0	0	B
100	0	0	0	0	0	B
50	0	0	0	0	0	S
100	0	0	0	0	0	M
50	0	0	0	0	0	B
50	0	0	0	0	0	M
50	0	0	0	0	0	S
50	0	0	0	0	0	M
100	0	0	0	0	0	B
50	0	0	0	50	0	M
50	0	0	0	0	0	B
0	100	0	0	0	0	S
0	0	0	0	0	0	B
50	0	0	0	0	0	B
50	0	0	0	0	0	M
0	0	0	0	50	0	B
50	0	50	0	0	0	B
0	0	0	0	0	0	B
50	0	0	0	0	0	M
50	0	0	0	50	0	B
50	0	0	0	0	0	B
50	0	0	0	0	0	M
100	0	0	0	0	0	B
50	0	0	0	0	0	B
50	0	0	0	0	0	B
100	0	0	0	0	0	M
50	0	0	0	0	0	M

ordinary for b	ordinary for f	ordinary for m	ch_Shape$	ordinary for b
3	3	1	B	1
3	3	1	P	3
2	2	2	B	1
2	2	2	R	4
1	1	3	P	3
1	1	3	R	4
1	1	3	T	2
2	2	2	R	4
2	2	2	R	4
2	2	2	R	4
1	1	3	R	4
1	1	3	P	3
3	3	1	B	1
1	1	3	R	4
1	1	3	B	1
3	3	1	B	1
1	1	3	T	2
1	1	3	R	4
3	3	1	R	4
2	2	2	B	1
1	1	3	P	3
2	2	2	T	2
3	3	1	R	4
2	2	2	T	2
1	1	3	B	1
2	2	2	R	4
1	1	3	B	1
3	3	1	R	4
1	1	3	T	2
1	1	3	T	2
2	2	2	P	3
1	1	3	T	2
1	1	3	R	4
1	1	3	T	2
2	2	2	T	2
1	1	3	R	4
1	1	3	B	1
2	2	2	T	2
1	1	3	P	3
1	1	3	P	3
1	1	3	T	2
2	2	2	T	2
2	2	2	B	1

ordinary for f	ordinary for m	Asymmetry	abs_asym	topomin
4	1	-0.131	0.131	3.165
2	3	0.032	0.032	-3.578
4	1	0.089	0.089	-3.588
1	4	0.008	0.008	2.952
2	3	-0.056	0.056	4.404
1	4	0.091	0.091	4.163
3	2	-0.008	0.008	4.317
1	4	-0.023	0.023	-3.59
1	4	0.02	0.02	3.711
1	4	-0.048	0.048	3.219
1	4	0.029	0.029	-2.393
2	3	0.002	0.002	1.475
4	1	-0.012	0.012	4.995
1	4	-0.047	0.047	3.912
4	1	0.09	0.09	3.47
4	1	0.009	0.009	3.544
3	2	0.013	0.013	3.584
1	4	0.014	0.014	3.807
1	4	-0.009	0.009	2.832
4	1	-0.13	0.13	3.507
2	3	-0.123	0.123	1.2
3	2	-0.044	0.044	2.996
1	4	-0.026	0.026	2.996
3	2	-0.014	0.014	2.974
4	1	-0.043	0.043	3.551
1	4	0.029	0.029	1.2
4	1	-0.201	0.201	1.2
1	4	-0.039	0.039	1.2
3	2	-0.02	0.02	2.567
3	2	0.057	0.057	3.667
2	3	-0.015	0.015	2.742
3	2	-0.004	0.004	2.567
1	4	-0.022	0.022	2.567
3	2	-0.06	0.06	3.387
3	2	0.075	0.075	3.584
1	4	0.013	0.013	3.501
4	1	0.125	0.125	3.368
3	2	-0.025	0.025	4.002
2	3	0.051	0.051	4.099
2	3	-0.03	0.03	4.327
3	2	0.086	0.086	3.832
3	2	0.136	0.136	4.3
4	1	0.199	0.199	4.078

topomax	topomean	topostdev	topomin	tmin/size
20.624	6.828	1.991	3.165	0.013
21.89	6.965	2.023	-3.578	-0.004
21.344	7.588	2.125	-3.588	-0.007
20.754	7.427	2.168	2.952	0.156
18.557	7.935	1.994	4.404	0.016
15.878	7.112	1.722	4.163	0.062
12.207	6.812	1.434	4.317	0.138
21.695	7.644	2.075	-3.59	-0.035
19.261	7.17	2.134	3.711	1.734
19.392	7.438	2.018	3.219	0.803
19.014	7.448	2.055	-2.393	-6.297
18.789	7.325	2.181	1.475	0.002
18.315	8.212	1.809	4.995	0.080
18.035	7.548	2.177	3.912	0.039
19.321	7.087	2.076	3.47	0.070
19.745	7.463	2.1	3.544	0.090
16.491	7.277	1.96	3.584	0.194
18.009	7.04	2.148	3.807	0.159
21.033	6.868	2.143	2.832	0.007
19.403	6.967	2.309	3.507	0.050
21.033	6.997	2.287	1.2	0.003
19.954	6.923	2.286	2.996	0.024
20.13	6.934	2.288	2.996	0.020
20.467	6.982	2.285	2.974	0.014
15.779	6.048	1.801	3.551	1.830
22.093	6.998	2.236	1.2	0.001
22.335	6.982	2.236	1.2	0.001
22.509	6.972	2.239	1.2	0.001
20.46	6.396	2.128	2.567	0.012
18.922	7.173	2.18	3.667	0.081
19.663	7.158	2.137	2.742	0.029
21.251	6.867	2.182	2.567	0.005
21.761	6.964	2.186	2.567	0.003
19.701	6.885	2.078	3.387	0.033
19.61	7.406	2.136	3.584	0.040
19.88	7.096	2.087	3.501	0.028
20.897	7.284	2.11	3.368	0.010
19.17	7.343	2.078	4.002	0.069
18.643	7.592	2.035	4.099	0.122
18.284	7.567	2.008	4.327	0.184
19.65	7.635	2.082	3.832	0.041
17.148	7.539	1.966	4.3	0.563
18.676	7.551	2.062	4.078	0.117

topomax	tmax/size	topomean	tmean/size	topostdev
20.624	0.083	6.828	0.028	1.991
21.89	0.025	6.965	0.008	2.023
21.344	0.043	7.588	0.015	2.125
20.754	1.098	7.427	0.393	2.168
18.557	0.066	7.935	0.028	1.994
15.878	0.237	7.112	0.106	1.722
12.207	0.390	6.812	0.218	1.434
21.695	0.213	7.644	0.075	2.075
19.261	9.000	7.17	3.350	2.134
19.392	4.836	7.438	1.855	2.018
19.014	50.037	7.448	19.600	2.055
18.789	0.188	7.325	0.073	2.181
18.315	0.366	8.212	0.164	1.809
18.035	0.361	7.548	0.151	2.177
19.321	0.386	7.087	0.142	2.076
19.745	0.197	7.463	0.075	2.1
16.491	0.330	7.277	0.146	1.96
18.009	0.750	7.04	0.293	2.148
21.033	0.055	6.868	0.018	2.143
19.403	0.277	6.967	0.099	2.309
21.033	0.056	6.997	0.019	2.287
19.954	0.157	6.923	0.055	2.286
20.13	0.135	6.934	0.047	2.288
20.467	0.097	6.982	0.033	2.285
15.779	8.134	6.048	3.118	1.801
22.093	0.020	6.998	0.006	2.236
22.335	0.016	6.982	0.005	2.236
22.509	0.014	6.972	0.004	2.239
20.46	0.097	6.396	0.030	2.128
18.922	0.416	7.173	0.158	2.18
19.663	0.211	7.158	0.077	2.137
21.251	0.042	6.867	0.014	2.182
21.761	0.028	6.964	0.009	2.186
19.701	0.191	6.885	0.067	2.078
19.61	0.219	7.406	0.083	2.136
19.88	0.162	7.096	0.058	2.087
20.897	0.063	7.284	0.022	2.11
19.17	0.331	7.343	0.127	2.078
18.643	0.553	7.592	0.225	2.035
18.284	0.778	7.567	0.322	2.008
19.65	0.210	7.635	0.082	2.082
17.148	2.245	7.539	0.987	1.966
18.676	0.535	7.551	0.216	2.062

tsddev/size	w1/d1	w2/d2	w1/d1/w2/d2	w1	x1
0.008	90.32	45.51	1.985	44.75	l00.43
0.002	83.6	37.06	2.256	31.41	105.16
0.004	88.92	75.8	1.173	55.05	105.04
0.115	29.55	22.5	1.313	12.86	38.11
0.007	24.88	32.02	0.777	24.88	37.49
0.026	50.29	67.52	0.745	39.86	139.52
0.046	33.67	39.94	0.843	33.67	52.79
0.020	63.83	57.12	1.117	34.52	100.81
0.997	2.45	16.79	0.146	2.13	29.51
0.503	4.09	40.47	0.101	4.09	53.66
5.408	3.24	9.72	0.333	2.94	10.73
0.022	84.32	160.65	0.525	53.05	247.12
0.036	77.87	37.72	2.064	32.27	77.87
0.044	31.54	34.13	0.924	19.27	56.02
0.042	15.15	48.26	0.314	15.15	102.93
0.021	48.01	21.93	2.189	16.95	57.65
0.039	12.01	50.8	0.236	10.40	50.80
0.090	28.44	39.22	0.725	11.83	47.31
0.006	75.28	40.82	1.844	40.82	86.62
0.033	29.4	24.64	1.193	16.81	51.39
0.006	36.42	45.3	0.804	36.42	77.22
0.018	64.47	38.4	1.679	37.12	72.72
0.015	78.3	35.64	2.197	35.64	108.43
0.011	59.38	37.79	1.571	37.41	68.17
0.928	3.6	22.78	0.158	3.60	25.76
0.002	137.77	120.74	1.141	100.99	154.50
0.002	100.18	120.16	0.834	100.00	136.56
0.001	43.3	20.25	2.138	20.25	55.06
0.010	28.24	40.24	0.702	19.08	53.13
0.048	20.42	48.77	0.419	20.42	66.95
0.023	36.45	31.17	1.169	23.87	70.80
0.004	19.29	37.97	0.508	18.94	37.97
0.003	94.44	97.26	0.971	64.24	145.02
0.020	37.34	68.93	0.542	35.19	68.93
0.024	30.39	29.25	1.039	29.25	60.49
0.017	29.21	37.33	0.782	29.21	68.58
0.006	39.17	49.49	0.791	35.50	55.05
0.036	37.71	24.54	1.537	24.54	52.26
0.060	101.38	125.49	0.808	64.80	190.21
0.085	11.14	51.61	0.216	11.14	51.61
0.022	13.75	54.31	0.253	13.75	61.27
0.257	28.13	23.76	1.184	18.64	56.62
0.059	53.75	32.14	1.672	25.11	53.75

w/x	Min Elev	Max Elev	Elev diff.	Mean Elev	Std Devia	Perimeter(Mi)
2.24	214	911	697	566.213	146.317	108.090
3.35	189	1254	1065	693.802	266.490	285.080
1.91	118	749	631	268.562	123.116	248.340
2.96	107	197	90	152.000	14.038	35.550
1.51	97	660	563	248.755	106.152	137.230
3.50	113	582	469	315.581	109.402	59.690
1.57	124	260	136	177.034	27.966	44.040
2.92	111	346	235	201.412	42.433	77.580
13.84	324	582	258	471.690	57.098	9.200
13.12	302	582	280	484.572	48.147	12.070
3.65	261	509	248	417.406	56.376	2.940
4.66	38	602	564	198.272	114.934	204.180
2.41	73	387	314	167.840	37.308	56.520
2.91	66	273	207	144.432	32.859	65.540
6.79	6	179	173	99.839	52.002	59.840
3.40	4	86	82	61.018	15.538	49.740
4.88	13	177	164	109.784	31.943	29.770
4.00	3	48	45	30.120	6.955	32.120
2.12	332	1338	1006	629.720	236.035	143.040
3.06	365	677	312	482.991	65.622	63.160
2.12	315	1360	1045	503.772	130.505	138.460
1.96	396	1172	776	571.471	146.897	89.500
3.04	377	840	463	460.694	78.588	101.310
1.82	338	1027	689	498.621	138.874	131.270
7.16	457	882	425	668.902	104.118	7.710
1.53	299	1024	725	404.065	93.505	245.210
1.37	224	1180	956	467.043	173.052	323.530
2.72	140	1231	1091	379.287	187.577	394.920
2.78	320	1230	910	602.348	162.464	98.810
3.28	314	827	513	412.785	51.060	50.710
2.97	272	996	724	423.548	114.118	76.760
2.00	243	814	571	379.034	78.229	171.280
2.26	151	1006	855	370.394	152.408	229.560
1.96	204	953	749	421.646	157.441	84.240
2.07	78	514	436	175.617	58.769	63.830
2.35	105	673	568	234.813	103.924	80.560
1.55	74	537	463	159.970	49.864	137.900
2.13	45	159	114	107.311	19.523	50.750
2.94	11	150	139	82.024	24.808	41.540
4.63	59	150	91	106.284	15.970	36.290
4.45	63	416	354	131.296	43.182	68.780
3.04	73	129	57	104.479	10.967	18.070
2.14	53	136	83	94.998	16.194	40.800

perim/3.14	r	size	r square	square root r	region
34.424	17.212	247	78.662	8.869	G
90.790	45.395	875	278.662	16.693	H
79.089	39.545	494	157.325	12.543	F
11.322	5.661	18.9	6.019	2.453	G
43.704	21.852	281	89.490	9.460	A
19.010	9.505	66.9	21.306	4.616	B
14.025	7.013	31.3	9.968	3.157	F
24.707	12.354	102	32.484	5.699	G
2.930	1.465	2.14	0.682	0.826	B
3.844	1.922	4.01	1.277	1.130	B
0.936	0.468	0.38	0.121	0.348	A
65.025	32.513	817	260.191	16.130	OUT
18.000	9.000	62.8	20.000	4.472	F
20.873	10.436	101	32.166	5.671	F
19.057	9.529	49.4	15.732	3.966	B
15.841	7.920	39.5	12.580	3.547	H
9.481	4.740	18.5	5.892	2.427	G
10.229	5.115	24	7.643	2.765	F
45.554	22.777	379	120.701	10.986	F
20.115	10.057	70.1	22.325	4.725	H
44.096	22.048	375	119.427	10.928	A
28.503	14.252	127	40.446	6.360	F
32.264	16.132	149	47.452	6.889	F
41.806	20.903	212	67.516	8.217	I
2.455	1.228	1.94	0.618	0.786	B
78.092	39.046	1084	345.223	18.580	F
103.035	51.518	1377	438.535	20.941	G
125.771	62.885	1642	522.930	22.868	F
31.468	15.734	210	66.879	8.178	I
16.150	8.075	45.5	14.490	3.807	F
24.446	12.223	93.2	29.682	5.448	F
54.548	27.274	506	161.146	12.694	A
73.108	36.554	768	244.586	15.639	F
26.828	13.414	103	32.803	5.727	A
20.328	10.164	89.6	28.535	5.342	A
25.656	12.828	123	39.172	6.259	E
43.917	21.959	332	105.732	10.283	F
16.162	8.081	57.9	18.439	4.294	F
13.229	6.615	33.7	10.732	3.276	F
11.557	5.779	23.5	7.484	2.736	B
21.904	10.952	93.4	29.745	5.454	D
5.755	2.877	7.64	2.433	1.560	H
12.994	6.497	34.9	11.115	3.334	G

BIBLIOGRAPHY

Abrahams, A., 1984, Spatial dependency of hydraulic geometry exponents in a sub-alpine stream--A comment. Jour. Hydrol., vol. 75, 389-393.

Ackers, P., 1964, Experiments on small streams in alluvium. Jour. Hydraul. Div., Am. Soc. Civ. Engr., vol. 90, no. 4, 1-38.

Agnese, C., F. D'Asaro, G. Grossi and R. Rosso, 1996, Scaling properties of topologically random channel networks. Jour. Hydrol., vol. 187, 183-193.

Allen, T. F. H. and T. B. Starr, 1982, Hierarchy: Perspectives for ecological complexity. Univ. of Chicago Press, 310 pp.

Anderson, H. W., 1957, Relating sediment yield to watershed variables. Trans., Am. Geophys. Union, vol. 45, 307-321.

Anderson, M. G. and K. M. Sambles, 1988, A review of the bases of geomorphological modeling. ed. M. G. Anderson, Modelling geomorphological systems*.* New York: John Wiley & Sons, Ltd., 458 pp.

Andrews, E. D., 1979, Scour and fill in a stream channel, East Fork River, western Wyoming. U.S. Geol. Survey Prof. Pap. 1117, 49 pp.

Andrews, E. D., 1984, Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. Bull. Geol. Soc. Am., vol. 95, no. 3, 371-378.

Aron, G. and A. Miller, 1978, Adaptation of flood peaks and design hydrographs from gages to nearby ungaged watersheds. Water Resour. Bull., vol. 14, 313-321.

Azagra, E., D. R. Maidment and F. Olivera, 1999, CRWR online rep. 99-5.

Baker, V. R. and C. R. Twidale, 1991, The reenchantment of geomorphology. Geomorphology, vol. 4, 73-100.

Band, L. E., 1986, Topographic partition of watersheds with digital elevation models. Water Resour. Res., vol. 22, no. 1, 15-24.

Barrett, E. C. and L. F. Curtis, 1992, Introduction to environmental remote sensing (3rd ed.). London: Chapman & Hall, 426 pp.

Bates, B. C., 1990, A statistical log piecewise linear model of at-a-station hydraulic geometry. Water Resour. Res., vol. 26, no. 1, 109-118.

Bathurst, J. C., 1993, Flow resistance through the channel network. eds. K. Beven and M. J. Kirkby, Channel network hydrology, New York: John Wiley, 69-98.

Beer, T. and P. C. Young, 1983, Longitudinal dispersion in natural streams. Jour. Environ. Eng., vol. 109, no. 5, 1049-1067.

Beven, K. J., 1995, Grid ATB sink: Program to identify and correct sink values from gridded elevation data, version 95.01. Centre for Research on Environmental Systems and Statistics. Lancaster, UK: Lancaster Univ.

Beven, K. J., 1986b, Runoff production and flood frequency in catchments of order n: An alternative approach. eds. V. K. Gupta, I. Rodriquez-Iturbe, E. F. Wood, Scale problems in hydrology. Norwell, Mass: Reidel, 107-131.

Beven, K. J. and M. J. Kirkby, 1979, A physically-based variable contributing area model of basin hydrology. Hydrol. Sci. Bull., vol. 24, no. 1, 43-69.

Beven, K. J. and E. F. Wood, 1983, Catchment geomorphology and the dynamics of runoff contributing areas. Jour. Hydrol., vol. 65, 139-158.

Beven, K. J., E. F. Wood and M. Sivapalan, 1988, On hydrological heterogeneity-catchment morphology and catchment response. Jour. Hydrol., vol. 100, 353-375.

Bhowmik, N. G., 1984, Hydraulic geometry of flood plains. Jour. Hydrol., vol. 68, 369-401.

Blench, T., 1969, Mobile-bed fluviology. Edmonton, Alberta, Canada: Univ. of Alberta Press, 168 pp.

Blomquist, J. D., G. T. Fisher, J. M. Denis, J. W. Brakebill and W. H. Berkheiser, 1996, Water-quality assessment of the Potomac River basin: Basin description and analysis of available nutrient data, 1970-90. U.S. Geol. Survey Water-Resour. Invest. Rep. 95-4221, 88 pp.

Bloschl, G., D. Gutknecht and R. Kimbauer, 1991, Distributed snow melt simulations in an alpine catchment. Water Resour. Res., vol. 27, 3181-3188.

Broeren, S. M. and K. P. Singh, 1990, Environmentally acceptable morphologic channel design of streams with small- to medium-sized drainage areas. Illinois State Water Survey, Contr. Rep. 495, 93 pp.

Brown, D. A., 1971, Stream channels and flow relations. Water Resour. Res., vol. 7, no. 2, 304-310.

Brunsden, D., 1990, Tablets of stone: Toward the ten commandments of geomorphology. Zeitschrift fur Geomorphologie, Supp. Bd. 79, 1-37.

Brunsden, D. and J. B. Thornes, 1979, Landscape sensitivity and change. Trans., Inst. Brit. Geograph., vol. 4, no. 4, 463-484.

Brush, L. M., Jr., 1961, Drainage basins, channels, and flow characteristics of selected streams in central Pennsylvania. U.S. Geol. Survey Prof. Pap. 282-F, F145-F181.

Buchanan, T. J. and W. P. Somers, 1969, Discharge measurements at gaging stations: Techniques of water resource investigation. U.S. Geol. Survey Water-Resour. Invest., bk. 3, chap. A8, 65 pp.

Burkham, D. E., 1972, Channel changes of the Gila River in Safford Valley, Arizona, 1846-1970. U.S. Geol. Survey Prof. Pap. 655-G, Gl-G24.

Burt, T. P. and D. P. Butcher, 1985, Topographic controls of soil moisture distributions. Jour. Soil Sci., vol. 36, 469-486.

Butakov, G. P., 1970, Experiment in the mathematical description of the form of longitudinal river profiles. Geomorphology, vol. 1, 336-340.

Camacho, R., 1989, Potomac River basin land use data: Evaluation and methodology to determine basin land use from non-digitized county land use data. Interst. Comm. on the Potomac River Basin, ICPRB-89-8, 45 pp.

Cambers, G., 1976, Temporal scales in coastal erosion systems. Trans., Inst. Brit. Geograph., vol. 1, no. 2, 246-256.

Carling, P. A. and N. Wood, 1994, Simulation of flow over pool-riffle topography: A consideration of the velocity reversal hypothesis. Earth Surf. Process. & Landfms., vol. 19, no. 4, 319-332.

Carlston, C. W., 1965, The relation of free meander geometry to stream discharge and its geomorphic implications. Am. Jour. Sci., vol., 263, 864-885.

Caroni, E., R. Rosso and F. Siccardi, 1986, Nonlinearity and time-variance of the hydrologic response of a small mountain creek. eds. V. K. Gupta, I. Rodriguez-Iturbe and E. Wood, Scale problems in hydrology: Runoff generation and basin response. D. Reidel Pub. Co., 19-37.

Carpenter, D. H., 1990, Floods in West Virginia, Virginia, Pennsylvania, and Maryland, November 1985. U.S. Geol. Survey Water-Resour. Invest. Rep. 88-4213, 86 pp.

Carswell, L. D. and G. D. Bennett, 1963, Geology and hydrology of the Neshannock quadrangle, Mercer and Lawrence counties, Pennsylvania. Penn. Geol. Survey Water Resour. Rep. 15, 90 pp.

Carter, R. W. and I. E. Anderson, 1963, Accuracy of current-meter measurements. Proceeds., Am. Soc. of Civ. Eng., vol. 89, no. HY4, 105-115.

Casman, E. A., 1990, Monocacy river watershed modeling project hydrometeorological data report. Interst. Comm. on the Potomac River Basin, ICPRB-90-8, 149 pp.

Chang, T. P. and G. H. Toebes, 1970, A statistical comparison of meander planforms in the Wabash basin. Water Resour. Res., vol. 6, 557-577.

Chong, S. E., 1970, The width, depth and velocity of the Sungei Kimla, Perak. Geographica, vol. 6, 72-88.

Chorley, R. J., 1978, Bases for theory in geomorphology. eds. C. Embleton, D. Brunsden and D.K.C. Jones, Geomorphology: Present problems and future prospects. Oxford: Oxford University Press, 1-13.

Clark, W. A. V. and P. L. Hosking, 1986, Statistical methods for geographers. New York: John Wiley & Sons, Inc., 528 pp.

Cleaves, E. T., J. Edwards Jr. and J. D. Glaser, 1968, Geologic map of Maryland. Maryland Geol. Survey, 1 sheet, scale 1:250,000.

Cronin, L. E., 1973, The Chesapeake Bay, in The Chesapeake Bay in Maryland: An atlas of natural resources. ed. J. Lippson, Baltimore, Maryland: The Johns Hopkins Univ. Press, 2-3.

Culling, W. E. H. and M. Datko, 1987, The fractal geometry of the soil-covered landscape. Earth Surf. Process. & Landfms., vol. 12, no. 4, 369-385.

Davis, R. W., D. S. Schimel, M. A. Friedl, J. C. Michaelsen, T. G. F. Kittel, R. Dubayah and J. Dozier, 1992, Covariance of biophysical data with digital topographic and land use maps over the FIFE site. Jour. Geophys. Res., vol. 97, no. D17, 19009-19021.

DeBoer, D. H., 1992, Hierarchies and spatial scale in process geomorphology: A review. Geomorphology, vol. 4, no. 5, 303-318.

Denis, J. M. and J. D. Blomquist, 1995, Nitrate in streams in the Great Valley carbonate subunit of the Potomac River Basin. U.S. Geol. Survey fact sheet 161-95, 4 pp.

Department of Environmental Programs, 1984, Potomac River water quality-1983: Conditions and trends in metropolitan Washington. Water Resour. Planning Board - Washington Council of Governments, 113 pp.

DeWalle, D. R. and A. Rango, 1972, Water resources applications of stream channel characteristics on small forested basins. Water Resour. Bull., vol. 8, no. 4, 697-703.

Dietrich, W. E., 1987, Mechanics of flow and sediment transport in river bends. ed. K. S. Richards, River Channels: Environment and Process. Inst. Brit. Geograph., Spec. Pub. 18, Oxford: Basil Blackwell, Inc. 179-227.

Douglas, I., 1982, The unfulfilled promise: Earth surface processes as a key to landform evolution. Earth Surf. Process. & Landfms., vol., 7, 101 pp.

Dubayah, R., 1992, Estimating net solar radiation using Landsat Thematic Mapper and digital elevation data. Water Resour. Res, vol. 28, 2469-2484.

Duigon, M. T., 1991, Water resources of Washington County, Maryland. Mary. Geol. Surv. Bull. 36, 109 pp.

Duigon, M. T. and J. R. Dine, 1987, Water resources of Frederick County, Maryland. Mary. Geol. Survey Bull. 33, 106 pp.

Dunne, T. and L. B. Leopold, 1978, Water in environmental planning. New York: W. H. Freeman Co., 818 pp.

Dunne, T., T. R. Moore and C. H. Taylor, 1975, Recognition and prediction of runoff-producing zones in humid regions. Hyrol. Sci. Bull., vol 20, no. 3, 305-327.

Eastman, P. W., 1985, The state of the Potomac River Basin-1985. Interst. Comm. on the Potomac River Basin, ICPRB-M-8, 8 pp.

Elliott, J. and K. Cartier, 1986, Hydraulic geometry and streamflow of channels in the Piceance Basin, Rio Blanco and Garfield counties, Colorado. U.S. Geol. Survey Water-Resour. Invest. Rep. 85-4118, 28 pp.

Embleton, C. and J. Thornes, eds., 1979, Process in Geomorphology. New York: John Wiley & Sons, 436 pp.

Emmett, W. W., 1975, The channels and waters of the upper Salmon River area, Idaho. U.S. Geol. Survey Prof. Pap. 870-A, 116 pp.

Emmett, W. W., 1972, The hydraulic geometry of some Alaskan streams south of the Yukon River. U.S. Geol. Survey Op. File Rep. 72-08, 102 pp.

Emmett, W. W., 1965, The Vigil network: Methods of measurement and a sampling of data collected. Intl. Assoc. Sci. Hydrol. Pub. 66, 89-106.

Emmett, W. W. and R. F. Hafley, 1968, The Vigil network: Preservation and access of data. U.S. Geol. Survey Circ. 460-C, 21 pp.

Endreny, T. A., E. F. Wood and D. P. Lettenmaier, 2000, Satellite-derived digital elevation model accuracy: Hydrogeomorphological analysis requirements. Hydrol. Process., vol. 14, no. 2, 177-194.

Engel, B. R., 1993, Methodologies for development of hydrologic response units based on terrain, land cover, and soils data. 2nd Intl. Conf/Wkshp on Integrating GIS and Environmental Modeling, Breckenridge, CO.

Engelund, F. and E. Hansen, 1967, A monograph on sediment transport in alluvial streams. Copenhagen: Teknisk Forlag, 62 pp.

Eschner, T. R., 1982, At-a-station hydraulic geometry of the Platte River in south-central Nebraska. U.S. Geol. Survey Op. File Rep. 82-436, 59 pp.

Fahnestock, R. K., 1963, Morphology and hydrology of a glacial stream: White River, Mount Ranier, Washington. U.S. Geol. Survey Prof. Pap. 422-A, 70 pp.

Fairfield, J. and P. Leymarie, 1991, Drainage networks from grid digital elevation models. Water Resour. Res., vol. 27, no. 5, 709-717.

Famiglietti, J. S. and E. F. Wood, 1995, Effects of spatial variability and scale on areal-average evapotranspiration. Water Resour. Res., vol. 31, no. 3, 699-712.

Famiglietti, J. S. and E. F. Wood, 1994a, Multi-scale modeling of spatially variable water and energy processes. Water Resour. Res., vol. 30, no. 11, 3061-3078.

Famiglietti, J. S. and E. F. Wood, 1994b, Applications of multi-scale water and energy balance models on a tall grass prairie. Water Resour. Res., vol. 30, 3079-3093.

Fedra, K., 1993, GIS and environmental modelling. eds. M. F. Goodchild, B. O. Parks and L. T. Staeyert, Environmental modeling with GIS. New York: Oxford University Press, 35-50.

Fedra, K., 1993, Integrated information systems for water resources management. Proceeds., WATERCOMP 93, Melbourne, Australia, 30th Mar - 1st Apr 1993, Inst. Engs. Australia, National Conf. Pub. 93, no. 2, 277-289.

Federal Energy Regulatory Commission, Office of Electric Power Regulation, New York Regional Office, 1980, Potomac River Basin, Pennsylvania, Maryland, West Virginia, Virginia, and District of Columbia: Planning Status Report, 13 pp.

Fenneman and Johnson, 1946, Physical division of the United States, U.S. Geol. Survey map, scale 1:7,000,000.

Ferguson, R. I., 1986, Hydraulics and hydraulic geometry. Prog. Phys. Geog., vol. 10, 1-31.

Ferrari, M. J. and J. M. Denis, 1999, Water quality assessment of the Potomac River Basin: Occurrences of pesticides in the Great Valley carbonate subunit. U.S. Geol. Survey Water Resour. Invest. Rep. 98-4054, 35 pp.

Fields, F. K., 1975, Estimating streamflow characteristics for streams in Utah using selected channel-geometry parameters. U.S. Geol. Survey Water-Resour. Invest. Rep. 34-74, 19 pp.

Foley, M. G., 1978, Scour and fill in steep, sand-bed ephemeral streams. Bull. Geol. Soc. Am., vol. 89, 559-570.

French, N. R., 1986, Hierarchical conceptional model of the alpine geosystem. Arctic and Alpine Res., vol. 18, no. 2, 133-146.

Friedkin, J. F., 1945, A laboratory study of the meandering of alluvial rivers: Vicksburg, Miss. U.S. Army Corps. of Engrs., Mississippi River Comm., Water-ways Ext. Sta., 40 pp.

Gerhart, J. M. and J. W. Brakebill, 1996, Design and implementation of a sampling strategy for a water-quality assessment of the Potomac River basin. U.S. Geol. Survey Water-Resour. Invest. Rep. 96-4034, 31 pp.

Giere, R. N., 1988, Explaining science: A cognitive approach. Univ. of Chicago Press, 313 pp.

Glazzard, C. F., 1981, Streamflow characteristics related to channel geometry of selected streams on the Cumberland Plateau, Tennessee. Univ. of Tenn., unpub. MS thesis, 132 pp.

Goodchild, M. F., 1988, A spatial analytical perspective on GIS. Intl. Jour. Geograph. Info. Sys., vol. 1, 327-334.

Goodchild, M. F., R. Haining and S. Wise, 1992, Integrating GIS and spatial data analysis: Problems and possibilities. Intl. Jour. Geograph. Info. Sys. vol. 6, no. 5, 407-423.

Gordon, N. D., T. A. McMahon and B. L. Finlayson, 1992, Stream Hydrology: An introduction for ecologist. New York: John Wiley & Sons, 526 pp.

Graf, W. L., 1988, Fluvial processes in dryland rivers. Berlin: Springer-Verlag, 246 pp.

Gregory, K. J., A. M. Gurnell, C. T. Hill and S. Tooth., 1994, Stability of the pool-riffle sequence in changing river channels. Regulated Rivers: Res. and Managem., vol. 9, 35-43.

Griffiths, G. A., 2003, Downstream hydraulic geometry and hydraulic similitude. Water Resour. Res., vol. 39, no. 4, ESG 3-1-3-6.

Gruessner, B. (1997), Dissolved and particulate transport of chemical contaminants in the Northeast and Northwest Branch of the Anacostia River, Interst. Comm. Potomac River Basin, ICPRB 97-10, 97 pp.

Gupta, V. K. and E. Waymire, 1990, Multiscaling properties of spatial rainfall and river flow distributions. Jour. Geophys. Res., vol. 95, no. D3, 1999-2009.

Gupta, V. K., O. Mesa, and D. Dawdy, 1994, Multiscaling theory of flood peaks: Regional quartile analysis. Water Resour. Res., vol. 30, no. 12, 3405-3421.

Gurnell, A. M., P. G. Angold and P. J. Edwards, 1996, Extracting information from river corridor surveys. Appl. Geography, vol. 16, no. 1, 1-19.

Gyasi-Agyei, Y., G. Willgoose and F. P. DeTroch, 1995, Effects of vertical resolution and map scale of digital elevation models on geomorphological parameters used in hydrology. Hydrol. Process., vol. 9, 363-382.

Hack, J. T., 1960, Interpretation of erosional topography in humid temperate regions. Am. Jour. Sci., vol. 258A, 80-97.

Hack, J. T., 1957, Studies of longitudinal stream profiles in Virginia and Maryland. U.S. Geol Survey Prof. Pap. 294-B, 45-97.

Hadley, R. F., 1961, Influence of riparian vegetation on channel shape, northeastern Arizona. U.S. Geol. Survey Prof. Pap. 424-C, 30-31.

Haigh, M. J., 1987, The holon: Hierarchy theory and landscape research. ed. F. Ahnert, Geomorphological Models: Theoretical and Empirical Aspects. Catena Suppl. 10, 181-192.

Haines-Young, R. H. and J. R. Petch, 1986, Physical geography: Its nature and methods. London: Harper and Row, 230 pp.

Haining, R. P., 1990, Spatial Data Analysis in the Social and Environmental Sciences. Cambridge: Cambridge Univ. Press.

Haining, R. P. and S. Wise, 1991, GIS and spatial analysis: Report on the Sheffield workshop, Regional research laboratory initiative discussion paper 11, Univ. of Sheffield.

Harenberg, W. C., 1980, Using channel-geometry measurements to estimate flood flows at ungaged sites in Idaho. U.S. Geol. Survey Water-Resour. Invest. Rep. 80-32, 39 pp.

Hart, M. G., 1986, Geomorphology: Pure and applied. London: Allen and Unwin, 228 pp.

Harvey, D. W., 1968, Pattern, process, and the scale problem in geographical research. Trans., Inst. Brit. Geograph., vol. 45, 71-78.

Harvey, A. M., 1975, Some aspects of the relations between channel characteristics and riffle spacing in meandering streams. Am. Jour. Sci., vol. 275, 470-478.

Hatfield, T., A. Lewis and D. Ohlson, 2003, Development of instream flow thresholds for fish and fish habitat as guidelines for reviewing proposed water uses. BC Ministry of Sustainable Resource Management and BC Ministry of Water, Land and Air Protection.

Haywood, C. and S. S. Schwartz, 1991, The Potomac River model: Data report. Interst. Comm. on the Potomac River Basin, ICPRB-90-9, 213 pp.

Hedman, E. R., 1970, Mean annual runoff as related to channel geometry in selected streams in California. U.S. Geol Survey Water-Supply Pap. l999-E, 17 pp.

Hedman, E. R., W. M. Kastner, and H. R. Hejl Jr., 1974, Selected streamflow characteristics as related to active-channel geometry of streams in Kansas. Kansas Water Resour. Bd. Tech. Rep. 10, 21 pp.

Hedman, E. R., and W. M. Kastner, 1972, Mean annual runoff as related to channel geometry of selected streams in Kansas. Kansas Water Resources Bd. Tech. Rep. 9, 25 pp.

Hedman, E. R., D. O. Moore, and R. K. Livingston, 1972, Selected streamflow characteristics as related to channel geometry of perennial streams in Colorado. U.S. Geol. Survey Op. File Rep. 72-160, 24 pp.

Hedman, E. R., and W. R. Osterkamp, 1982, Streamflow characteristics related to channel geometry of streams in the western United States. U.S. Geol. Survey Water-Supply Pap. 2193, 17 pp.

Hey, R. D., 1988, Mathematical models of channel morphology. ed., M. G. Anderson, Modelling geomorphic systems. Chichester: John Wiley & Sons Ltd., 99-125.

Hickin, E. J., 1983, River channel changes retrospect and prospect. eds., J. D. Rollins and J. Lewin, Modern and Ancient Fluvial Systems. Intl. Assoc. Sedimentol. Spec. Pub. 6, 61-83.

Hobba, W. A., E. A. Friel, and J. L. Chisholm, 1972, Water resources of the Potomac River Basin, West Virginia. West Virginia Geol. and Econ. Surv., River Basin Bull. 3, 110 pp.

Hogan, D. L. and M. Church, 1989, Hydraulic geometry in small, coastal systems: Progress toward quantification of salmonid habitat. Canad. Jour. Fisheries and Aquatic Sciences, vol. 46, 844-852.

Hornberger, G. M, and E. W. Boyer, 1995, Recent advances in watershed modeling. Reviews of Geophysics. National Rep. to Intl. Union of Geodesy and Geophysics, 1991-1994, 949-957.

Hornberger, G. M., K. J. Beven, B. J. Cosby and D. E. Sappington, 1985, Shenandoah watershed study: Calibration of a topography-based variable contributing area hydrological model to a small forested catchment. Water Resour. Res., vol. 21, no. 12, 1841-1850.

Horton, R. E., 1945, Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology. Geol. Soc. Am. Bull. 56, 275-370.

Jackson, R. G., II, 1975, Hierarchical attributes and a unifying model of bedforms composed of cohesionless material and produced by shearing flow. Geol. Soc. Am. Bull. 86, 1523-1533.

Jarvis, R. S., 1976, Drainage network analysis. Prog. Phys. Geograph., 1, 271-295.

Jensen, J. R., 1996. Introductory digital image processing: A remote sensing perspective (2nd ed.), N.J.: Prentice Hall, 316 pp.

Jenson, S. K. and J. O. Domingue, 1988, Extracting topographic structure from digital elevation data for geographic information system analysis. Photogramm. Eng. and Remote Sens., vol. 54, no. 11, 1593-1600.

Jet Propulsion Laboratory (JPL), 1997, Shuttle Radar Topography Mission, JPL 400-713, National Aeronautics and Space Administration. Pasadena, California.

Joering, E. A., and H. C. Preul, 1973, A set of regime equations for indirectly estimating streamflow characteristics. Proceeds., Intl. Water Resour. Assoc., September 24-28, 411-426.

Johnson, A. R., 1993, Spatiotemporal hierarchies in ecological theory and modeling. 2nd Intl. Conf./wkshp on Integrating GIS and Environmental Modeling, Breckenridge, CO.

Johnston, P.M., 1964, Geology and ground-water resources of Washington, D.C., and vicinity. U.S. Geol. Survey Water-Supply Pap. 1776, 97 pp.

Judd, H. E. and D. F. Peterson, 1969, Hydraulics of large bed element channels. PRWG Rep. 17-16, Logan, UT: Utah State Univ.

Kellerhals, R., 1967, Stable channels with gravel-paved beds. Jour. Waterways Harbor Div., Am. Soc. Civ. Engrs., vol. 93, no. 1, 63-84.

Kellerhals, R., C. R. Neill, and D. I. Bray, 1972, Hydraulic and geomorphic characteristics of rivers in Alberta. Research Council of Alberta, River Engineering and Surface Hydrology Rep. 72-1. 52 pp.

Kemp, K. K., 1992, Spatial models for environmental modeling with GIS. eds. E. Breshanan, E. Corwin and D. Cowen, Proceeds., 5th Intl. Symp. on Spatial Data Handling, Charleston, South Carolina, 524-533.

Kennedy, B. A., 1977, A question of scale? Prog. Phys. Geog., no. 1, 154-157.

Kennedy, R. G., 1895, Prevention of silting in irrigation canals. Proceeds., Inst. Civ. Eng., vol. 119, 281-290.

Kesseli, J. E., 1950, Geomorphic landscapes. Yearbook, Assoc. Pacific Geogr., 12, 3-10.

Kilpatrick, F. A., and H. H. Barnes Jr., 1964, Channel geometry of piedmont streams as related to frequency of floods. U.S. Geol Survey Prof. Pap. 422-E, El-E10.

King, A. W., 1990, Translating models across scales in the landscape. eds. M. G. Turner and R. H. Gardner, Quantitative methods in landscape ecology, ecological studies. vol. 82, New York: Springer-Verlag, 479-517.

Kirkby, M. J., 1985, A model for the evolution of regolith-mantled slopes. ed., M. J. Woldenberg, Models in geomorphology. Boston: Allen and Unwin, 213-237.

Kikby, M. J. and D. R. Weyman, 1974, Measurement of contributing area in very small drainage basins. Seminar Pap. Series B, no. 3, Dep. Geogr. Univ. Bristol.

Kirkby, M. J. and R. J. Chorley, 1967, Through flow, overland flow and erosion. Bull. Intl. Assoc. Sci. Hydrol., vol. 12, 5-21.

Knighton, A. D., 1984, Fluvial forms and processes. London: Edward Arnold, 218 pp.

Knighton, A. D., 1975, Variations in at-a-station hydraulic geometry. Am. Jour. Sci., vol. 275, 186-218.

Knighton, A. D., 1974, Variation in width-discharge relation and some implications for hydraulic geometry. Geol. Soc. Am. Bull., vol. 85, 1069-1076.

Knighton, A. D. 1981, Channel form and flow characteristics of supraglacial streams, Austre Okstindbreen, Norway. Arctic and Alpine Res., vol. 13, 295-306.

Kondrat'ev, N. E., and others, 1962, River flow and river channel formation: Ruslouoiprotsess, Translated by Israel Project for Scientific Translations, Ltd., 172 pp.

Kopaliani, Z. D., and V V. Romashin, 1970, Channel dynamics of mountain rivers. Soviet Hydrol. Selected Paps., vol. 183, 81-97.

Lamberti, A., 1988, About extremal hypotheses and river regime. ed., W. R. White, Intl. Conf. opn River Regime, 121-134.

Lane, E. W., 1935, Stable channels in erodible material. Am. Soc. Civ. Eng., Trans., vol. 63, 123-142.

Langbein, W. B., 1965, Closure of "geometry of river channels." Jour. Hydraul. Div., Am. Soc. Civ. Eng., vol. 91, HY3, 297-313.

Langbein, W. B., 1964, Geometry of river channels. Jour. Hydraul. Div., Am. Soc. Civ. Eng., vol. 90, no. HY2, 301-312.

Langbein, W. B., 1960, Hydrologic data networks and methods of extrapolating or extending available hydrologic data, hydrologic networks and methods, flood control series no. 15, United Nations Economic Commission for Asia and the Far East, Bangkok, Thailand.

Langbein, W. B., 1947, Topographic characteristics of drainage basins. U.S. Geol. Survey Water Supply Pap. 968-C, 125-157.

Langran, G., 1993, Issues of implementing a spatiotemporal system. Intl. Jour. Geograph. Info. Sys., vol. 7, no. 4, 305-314.

Larsen, J. E., M. Sivapalan, N. A. Coles and P. E. Linnet, 1994, Similarity analysis of runoff generation processes in real-world catchments. Water Resour. Res., vol. 30, no. 6, 1641-1652.

Laurini, R. and D. Thompson, 1992, Fundamentals of spatial information systems. London: Academic Press, 680 pp.

Leliavsky, S., 1955, An introduction to fluvial hydraulics. New York: Dover Pubs., Inc., 257 pp.

Leopold, L. B., 1994, A view of the river. Harvard Univ. Press, 298 pp.

Leopold, L. B. and T. Maddock, 1953, The hydraulic geometry of stream channels and some physiographic implications. U.S. Geol. Survey Prof. Pap. 252, 57 pp.

Leopold, L. B., M. G. Wolman and J. P. Miller, 1964, Fluvial processes in geomorphology. San Francisco: W. H. Freeman & Co., 522 pp.

Leopold, L. B., and W. B. Langbein, 1962, The concept of entropy in landscape evolution. U.S. Geol. Survey Prof. Pap. 500-A, 20 pp.

Leopold, L. B. and J. P. Miller, 1956, Ephemeral streams: Hydraulic factors and their relation to the drainage net. U.S. Geol. Survey Prof. Pap. 282-A, 36 pp.

Lewis, L. A., 1966, The adjustment of some hydraulic variables at discharges less than 1 cfs. Prof. Geographer, vol. 18, 230-234.

Li, R. M., D. B. Simons and M. A. Stevens, 1976, Morphology of cobble streams in small watersheds. Jour. Hydraul. Div., Am. Soc. Civ. Eng., vol. 102, HY8, 1101-1117.

Lindley, E. S., 1919, Regime channels. Proceeds., Punjab Eng. Congress, vol. 7.

Lippson, A. J., M. S. Haire, A. F. Holland, F. Jacobs, J. Jensen, R. L. Moran Johnson, T. T. Polgar and W. A. Richkus, 1979, Environmental atlas of the Potomac estuary. Martin Marietta Env. Ctr., 130 pp.

Lowham, H. W., 1982, Streamflows and channels of the Green River basin, Wyoming. U.S. Geol. Survey Water-Resour. Invest. Rep. 81-71, 73 pp.

Lowham, H. W., 1976, Techniques for estimating flow characteristics of Wyoming streams. U.S. Geol. Survey Water-Resour. Invest. Rep. 76-112, 83 pp.

Mackin, J. H., 1963, Rational and empirical methods of investigation in geology. ed., C. C. Albritton, The fabric of geology. Reading, Mass: Addison-Wesley, 135-163.

Maddock, T., 1970, Indeterminate hydraulics of alluvial channels. Jour. Hydraul. Div., Am. Soc. Civ. Eng., vol. 96, 2309-2323.

Maddock, T., 1969, The behavior of straight open channels with movable beds. U.S. Geol. Survey Prof. Pap. 622-A, A1-A70.

Mahmood, K. and H.W. Shen, 1971, The regime concept of sediment-transporting canals and rivers. ed. H. W. Shen, River mechanics. vol. 2, ch. 30, Fort Collins, CO: Colorado State Univ. 39 pp.

Maidment, D. R., 1994, Geographic information systems and hydrologic modeling. Proceeds., Scientific assessment and strategy team workshop on hydrology, ecology and hydraulics, Sioux Falls, SD.

Maizels, J., 1988, Paleochannels: Plio-Pleistocene raised channel systems of the western Sharqiyah. in, The scientific results of the Royal Geograph. Society's Oman Wahiba Sands project, 1985-1987. Jour. Oman Studies, 95-112.

Mark, D. M., 1989, Cognitive image-schema for geographic information systems: Relations of user views and GIS interfaces. Proceeds., GIS/LIS '89, 26-30 November 1989, Orlando FL, 551-560.

Martz, L.W. and J. Garbrecht, 1993, Automated extraction of drainage networks and watershed data from digital elevation models. Water Resour. Bull. 29, no. 6, 901-908.

Mason, D. and D. R. Maidment, 2000, An analysis of a methodology for generating watershed parameters using GIS. Center for Research in Water Resources, CRWR Online Report 00-3, Austin, TX: The University of Texas, 191 pp.

Mason, W. T. ed., 1977, Potomac River Basin baseline water quality monitoring network. Interst. Comm. on the Potomac River Basin, Rockville, MD., Tech Pub. 77-1, 40 pp.

McConkey, S. A., R. Larson and K. Singh, 1992, Pilot study: Riffle-pool geometry in the Fox river below Algonquin and aquatic habitat assessment. Illinois State Water Survey, ISWS CR-542, 60 pp.

Mesa, O. J. and V. K. Gupta, 1987, On the main channel length-area relationships for channel networks. Water Resour. Res., vol. 23, no. 11, 2119-2122.

Milici, R. C., 1963, Geologic map of Virginia. Virginia Dep. Min. Resour., 1 map sheet, scale 1:500,000.

Miller, J. P., 1958, Effects of geology on channel characteristics and bed material. New Mexico Bur. Geol. and Min. Resour., Memoir 4, 53 pp.

Miller, H. J., 1991, Modelling accessibility using space-time prism concepts within geographic information systems. Intl. Jour. Geograph. Info. Sys., vol. 5, no. 3, 287-301.

Miller, K. M. and L. J. Onesti, 1977, Multivariate empirical test of the Leopold and Miller stream order – hydraulic geometry hypothesis. Geol. Soc. Am. Bull. 88, 85-88.

Miller, S. N., D. P. Guertin and D. C. Goodrich, 1996, Investigating stream channel morphology using a geographic information system. Proceeds. of the 1996 ESRI user conference, Palm Springs, CA.

Moberg, R. M., K. C. Rice and E. D. Powell, 1995, Measuring streamflow in Virginia. U.S. Geol. Survey Op. File Rep. 95-713, 9 pp.

Moglen, G. E. and J. A. Berger, 1998, Quantifying the effect of land use change on channel hydraulic geometry. Present., Am. Geophys. Union, Spring Conf., Boston, MA.

Moglen, G. E. and R. E. Beighley, 2000, Using GIS to determine the extent of gauged streams in a region. Jour. Hydrol. Eng., vol. 5, no. 2, 190-196.

Moglen, G. E. and R. L. Bras, 1995, The effect of spatial heterogeneities on geomorphic expression in a model of basin evolution. Water Resour. Res., vol. 31, no.10, 2613-2623.

Montgomery, D. R. and W. E. Dietrich, 1992, Channel initiation and the problem of landscape scale. Science, vol. 255, 826-830.

Moore, D. O., 1974, Estimating flood discharges in Nevada using channel-geometry measurements. Nevada Highway Dept. Hydrol. Rep. no.1, 43 pp.

Moore, D. O., 1968, Estimating mean runoff in ungaged semiarid areas. Intl. Assoc. Hydrol. Sci. Bull., vol. 13, no. 1, 28-39.

Moore, I. D., R. B Grayson and A. R. Ladson, 1991, Digital terrain modelling: A review of hydrological, geomorphological, and biological applications. Hydrol. Process., vol. 5, 3-30.

Morisawa, M., 1968, Streams: Their dynamics and morphology. New York: McGraw Hill, 175 pp.

Mueller, J. E., 1973, Re-evaluation of the relationship of master streams and drainage basins: Reply. Geol. Soc. Am. Bull., vol. 84, 3127-3130.

Nash, J. E., 1959, Discussion of "A study of bankfull discharge of rivers in England and Wales" by M. Nixon: London, Inst. Civ. Engrs., Proceeds., vol. 14, 395-425.

Nebert, D. D., 1995, Process aml for delineation of watershed, E-mail commun. fr. author.

Nixon, M., 1959, A study of the bankfull discharges of rivers in England and Wales. Proceeds., Inst. Civ. Engrs., vol. 12, 157-174.

Nyerges, T. L., 1993, Understanding the scope of GIS: Its relationship to environmental modeling. eds. M. F. Goodchild, B. O. Parks and L. T. Steyaert, New York: Oxford: Oxford Univ. Press, 75-93.

Nyerges, T. L., 1992a, Coupling spatial analytical models and GIS. Proceeds., 5th Intl. Symp. Spatial Data Handling, Charleston, SC. eds., Intl. Gegraph. Union.

O'Callaghan, J. F. and D. M. Mark, 1984, The extraction of drainage networks from digital elevation data. Comp. Vision Graphics Image Process., vol. 28, 328-344.

O'Loughlin, E. M., 1981, Saturation regions in catchments and their relation to soil and topographic properties. Jour. Hydrol., vol. 53., 229-246.

O'Loughlin, E. M., 1986, Prediction of surface saturation zones in natural catchments by topographic analysis. Water Resour. Res., vol. 22, 794-804.

Omang, R. J., C. Parrett and J. A. Hull, 1983, Mean annual runoff and peak flow estimates based on channel geometry of streams in southeastern Montana. U.S. Geol. Survey Water-Resour. Invest. Rep. 82-4092, 33 pp.

O'Neill, R. V., 1988, Hierarchy theory and global change. eds., T. Roswall, R. G. Woodmansee and P. G. Risser, Scales and global change - spatial and temporal variability in biospheric and geospheric processes. Chichester, NY: John Wiley, 29-45.

O'Neill, R. V., R. H. Gardner, B. T. Milne, M. G. Turner and B. Jackson, 1991, Heterogeneity and spatial hierarchies eds., J. Kolasa and S. T.A. Pickett, Ecological heterogeneity. New York: Springer-Verlag, 85-96.

Openshaw, S., 1991, Developing appropriate spatial analysis methods for GIS. eds., D. Maguire, M. F. Goodchild and D. Rhind, GIS principles and applications. vol. 1, London: Longman Scientific & Technical Pub., 389-402.

Orsborn, J. F., 1981, The development of new methods for hydrologic analysis in the Siuslaw National Forest in the mid-coast of Oregon. file notes, Siuslaw National Forest. Corvallis, Oregon.

Orsborn, J. F. and J. M. Stypula, 1987, New models of hydrological and stream channel relationships. Proceeds., Corvallis Symp., Erosion and Sedimentation in the Pacific Rim, Intl. Assn. Hydrol. Sci., no. 165, 375-384.

Osterkamp, W. R. and E. R. Hedman, 1982, Perennial-streamflow characteristics related to channel geometry and sediment in the Missouri River basin. U.S. Geol. Survey Prof. Pap. 1242, 37 pp.

Osterkamp, W. R. and E. R. Hedman, 1977, Variation of width and discharge for natural high-gradient stream channels. Water Resour. Res., vol. 13, no. 2, 256-258.

Osterkamp, W. R. and E. R. Hedman, 1981, Channel geometry of regulated streams in Kansas as related to mean discharge, 1970-80. Kansas Water Office Tech. Rep. no. 15, 56 pp.

Osterkamp, W. R., L. J. Lane and G. R. Foster, 1983, An analytical treatment of channel-morphology relations. U.S. Geol. Survey Prof. Pap. 1288, 21 pp.

Osterkamp, W. R., W. W. Emmett and L. B. Leopold, 1990, The Vigil Network: A reviving of interest. Trans., Am. Geophys. Union, no. 71, 338 pp.

Park, C. C., 1977, World-wide variations in hydraulic geometry exponents of stream channels: An analysis and some observations. Jour. Hydrol., vol. 33, 133-146.

Parker, G., S. Dhamotharan and H. Stefan, 1982, Model experiments on mobile, paved gravel-bed streams. Water Resour. Res., vol. 18, no. 5, 1395-1408.

Parker, G. and P. Klingeman, 1982, On why gravel bed streams are paved. Water Resour. Res., vol. 18, no. 5, 1409-1423.

Parrett, C., R. J. Omang and J. A. Hull, 1983, Mean annual runoff and peak flow estimates based on channel geometry of streams in northeastern and western Montana. U.S. Geol. Survey Water-Resour. Invest. Rep. 83-4046, 53 pp.

Penning-Rowsell, E. C. and J. R. G. Townshend, 1978, The influence of scale on the factors affecting stream channel slope. Trans., Inst. Brit. Geograph., New Series 3, 395-415.

Pettis, C. R., 1937, Discussion of "Stable channels in erodible material" by E. W. Lane. Trans. Am. Soc. Civ. Eng. vol. 102, 149-152.

Pfleiderer, S. and G. L. Moltyaner, 1993, The use of velocity and conductivity data for the quantification of heterogeneity: A comparison. Water Resour. Res., vol. 29, no. 12, 4151-4156.

Phillips, J. D., 1995, Self-organization and landscape evolution. Prog. Phys. Geog. vol. 19, no. 3, 309-321.

Phillips, J. D., 1991, Multiple modes of adjustment in unstable river channel-sections. Jour. Hydrol., vol. 123, 39-49.

Phillips, J. D., 1990, The instability of hydraulic geometry. Water Resour. Res., vol. 26, no. 4, 739-744.

Phillips, P. J. and J. M. Harlin, 1984, Spatial dependency of hydraulic geometry exponents in a sub-alpine stream. Jour. Hydrol., vol. 71, 277-283.

Pilgrim, D. H., 1983, Some problems in transferring hydrological relationships between small and large drainage basins and between regions. Jour. Hydrol., vol. 65, 49-72.

Potter, W. D., F. K. Stovicek and D.C. Woo, 1968, Flood frequency and channel cross-section of a small natural stream. Intl. Assoc. Sci. Hydrol. Bull. vol. 13, no. 3, 66-76.

Prestegaard, K. L., 1983, Bar resistance in gravel bed streams at bankfull stage. Water Resour. Res. vol. 19, no. 2, 472-476.

Prugh, B. J., Jr., and C. G. Humphrey, 1993, Compilation of surface-water and water-quality data-collection sites on selected streams in Virginia. U.S. Geol. Survey Op. File Rep. 93-462, 645 pp.

Quinn, P. F. and K. J. Beven, 1993, Spatial and temporal predictions of soil moisture dynamics, runoff, variable source areas and evapotranspiration for Plynlimon, Mid-Wales. Hydrol Process., vol. 7, 425-448.

Rhoads, B. L., 1994, Fluvial geomorphology. Prog. Phys. Geog., vol 18. no. 1, 103-123.

Rhoads, B. L. and C. E. Thorn, 1993, Geomorphology as science: The role of theory. Geomorphology, 6, 287-307.

Rhodes, D. D., 1978, World-wide variations in hydraulic geometry exponents of stream channels: An analysis and some observations, comments. Jour. Hydrol., vol. 33, 133-146.

Rhodes, D. D., 1977, The b-f-m diagram: Graphical representation and interpretation of at-a-station hydraulic geometry. Am. Jour. Sci., vol. 277, 73-96.

Richards, K. S., 1982, Rivers: Form and process in alluvial channels. London: Methuen, 361.

Richards, K. S., 1977, Channel and flow geometry: A geomorphological perspective. Prog. in Phys. Geog., vol. 1, 65-103.

Richards, K. S., 1976, Complex width-discharge relations in natural river sections. Geol. Soc. Am. Bull., vol. 87, no. 2, 199-206

Richards, K. S., 1973, Hydraulic geometry and channel roughness: A non-linear system. Am. Jour. Sci., vol. 273, 877-896.

Ridenour, G. S., 1999, Compositional data analysis of the influence of drainage area and stream order on hydraulic geometry. 4th Intl. Conf. of GeoComputation, Mary Washington College, Federicksburg, VA.

Ridenour, G. S. and J. R. Giardino, 1991, The statistical study of hydraulic geometry: A new direction for compositional data analysis. Mathematical Geology, vol. 23, no. 3, 349-366.

Riggs, H.C., 1978, Streamflow characteristics from channel size. Jour. Hydraul. Div., Proceeds. Am. Soc. Civ. Engrs., vol. 104, 87-96.

Riggs, H. C., 1974, Flash flood potential from channel measurements. Proceeds. of Paris Symp., Assoc. Sci. Hydrol., Pub. 112, 52-56.

Riggs, H. C., and Harenberg, W. A., 1976, Flood characteristics of streams in Owyhee County, Idaho. U.S. Geol. Survey Water-Resour. Invest. Rep. 76-88, 14 pp.

Rigon, R., I. Rodriguez-Iturbe, A. Maritan, A. Giacometti, D. G. Tarboton, and A. Rinaldo, 1996, On Hack's Law. Water Resour. Res., vol. 32, no. 11, 3367-3374.

Ritchie, J. C., M. Menenti and M.A. Weltz, 1996, Measurements of land surface features using an airborne laser altimeter: the HAPEX-Sahel experiment. Intl. Jour. Rem. Sens., vol. 17, 3705-3724.

Rosgen, D., 1994, A classification of natural rivers. Catena, vol. 22, 169-199.

Roswall, T., R. G. Woodmansee and P. G. Risser, 1988, Preface. eds. T. Roswall, R. G. Woodmansee and P. G. Risser, Scales and global changes - spatial and temporal variability in Biospheric and Geospheric Processes, Wiley, Chichester, xi-xii.

Roy, A., R. Roy, and N. Bergeron, 1988, Hydraulic geometry and changes in flow velocity at a river confluence with coarse bed material. Earth Surf. Process. & Landfms., vol. 13, 583-598.

Roy, A., 1981, Optimality and its relationship to the hydraulic and angular geometry of rivers and lungs, Ph.D. dissertation, University of New York at Buffalo.

Rubey, W. W., 1933, Equilibrium conditions in debris-laden streams. Am. Geophys. Union Trans., vol. 14, 497-505.

Scheidegger, A. E., 1970, Theoretical Geomorphology (2d ed.), Englewood Cliffs, NJ: Prentice-Hall, 435 pp.

Schubel, J. R. and R. H. Meade, 1977, Man's impact on estuarine sedimentation. Estuarine pollution control and assessment, Proceedings of a Conference, vol. 1, U. S. Environmental Protection Agency, Office of Water Planning and Standards, Washington, D.C., 193-209.

Schumm, S. A., 1991, To Interpret the Earth: Ten ways to be wrong. Cambridge Univ. Press, 143 pp.

Schumm, S. A., 1985, Explanation and extrapolation in geomorphology: Seven reasons for geologic uncertainty. Trans., Jour. Geomorph. Union, 6, 1-18.

Schumm, S. A., 1960, The shape of alluvial channels in relation to sediment type. U.S. Geol. Survey Prof. Pap. 352-B, 17-30.

Schumm, S. A., M. P. Mosley and W. E. Weaver, 1987, Experimental fluvial geomorphology, New York: John Wiley & Sons, 413 pp.

Schumm, S. A. and R. W. Lichty, 1965, Time, space, and causality in geomorphology. Am. Jour. Sci., vol. 263, 110-119.

Schwartz, S. S., 1987, A Conceptual model of sediment transport and delivery for the Monocacy River sub-basin of the Potomac River basin. Interst. Comm. on the Potomac River Basin, ICPRB-87-11, 45 pp.

Scott, A. G., and J. L. Kunkler, 1976, Flood discharges of streams in New Mexico as related to channel geometry. U.S. Geol. Survey Op. File Rep. 76-414, 29 pp.

Seyfried, M. S. and B. P. Wilcox, 1995, Scale and the nature of spatial variability: Field examples having implications for hydrologic modeling. Water Resour. Res., vol. 31, no. 1, 173-184.

Shen, R., 2005, A constrained joint equation estimation of at-a-station hydraulic geometry. M. S. Thesis, Simon Fraser Univ.

Shepard, F. P., 1954, Nomenclature based on sand-silt-clay ratios. Jour. Sediment. Petrol., vol. 24, 151-158.

Shepherd, R. H., 1985, Regression analysis of river profile. Jour. Geol., vol. 93, no. 3, 377-384.

Shimer, J. A., 1972, Field guide to landforms in the United States. New York: The MacMillan Co., 272 pp.

Shreve, R. L., 1966, Statistical law of stream numbers. Jour. Geol., vol. 74, 17-37.

Simons, D. B., E. V. Richardson and C. F. Nordin, Jr., 1965, Bedload equations for ripples and dunes. U.S. Geol. Survey Prof. Pap. 462-H, 9 pp.

Singh, K. P., and S. M. Broeren, 1989, Hydraulic geometry of streams and stream habitat assessment. Jour. Water Resour. Plann. and Managem, vol. 115, no. 5, 583-597.

Sivapalan, M., K. J. Beven and E. F. Wood, 1987, On hydrological similarity: A scaled model of storm runoff production. Water Resour. Res., vol. 23, no 12, 2266-2278.

Slaymaker, H. O., 1972, Patterns of present sub-aerial erosion and landforms in mid-Wales. Trans. Inst. Brit. Geograph., 55, 47-68.

Smith, D. G., 1993, Fluvial geomorphology: Where do we go from here? Geomorphology, vol. 7, 251-262.

Smith, J. A., 1992, Representation of basin scale in flood peak distributions. Water Resour. Res., vol. 28, no. 11, 2993-2999.

Snell, J. D. and M. Sivapalan, 1994, On geomorphological dispersion in natural catchments and the geomorphological unit hydrograph. Water Resour. Res., vol. 30, no. 7, 2311-2323.

Snell, J. D. and M. Sivapalan, 1995, Application of the meta-channel concept: Construction of the meta-channel hydraulic geometry for a natural catchment. Hydrol. Process., vol. 9, 485-505.

Snow, R. S. and R. L. Slingerland, 1987, Mathematical modeling of graded river profiles. Jour. Geol., vol. 95, no. 1, 15-33.

Smith, T. R., 1974, A derivation of the hydraulic geometry of steady state channels from conservation principles and sediment transport laws. Jour. Geol., vol. 82, 98-104.

Southworth, C. S., D. K. Brezinski, R. C. Orndorf, P. G. Chirico and K. M. Lageux, 2001, Geology of the Chesapeake and Ohio Canal National Historical Park and Potomac River Corridor, District of Columbia, Maryland, West Virginia, and Virginia. U.S. Geol. Survey Op. File Rep. 102 pp.

Stall, J. B. and C. T. Yang, 1970, Hydraulic geometry of 12 selected stream systems of the United States. Illinois State Water Survey Res. Rep. 32, 73 pp.

Stall, J. B. and Y., S., Fok, 1968, Hydraulic geometry of Illinois streams. Illinois State Water Survey Research Report 15, 47 pp.

Stevens, M. A., D. B. Simons and E. V. Richardson, 1975, Nonequilibrium river form. Trans., Hydraul. Div., Am. Soc. Civil Engrs., vol. HY5, 557-566.

Strahler, A. N., 1964, Quantitative geomorphology of drainage basins and channel networks. ed., V. T. Chow, Handb. Appl. Hydrol., sec. 4-II., New York: McGraw Hill, 4-39.

Strahler, A. N., 1960, Physical Geography. New York: John Wiley & Sons, 534 pp.

Stypula, J. M., 1986, An investigation of several streamflow and channel form relationships. M.S. thesis. Dep. Civil & Environ. Engr., Pullman WA: Washington State Univ.

Subcommittee on Hydrology, 1951, Inter-Agency Coordination of Drainage Area Data, Bull. 4, 49 pp.

Sugden, D. and P. Hamilton, 1971, Scale, system and regional geography, Area, Vol. 3, No. 3, 139-144.

Swain, L. A., E. F. Hollyday, C.C. Daniel III and O.S. Zapecza, 1991, Plan of study for the regional aquifer-system analysis of the Appalachian Valley and Ridge, Piedmont, and Blue Ridge physiographic provinces of the eastern and southeastern United States, with a description of study area geology and hydrology. U.S. Geol. Survey Water-Resour. Invest. Rep. 91-4066, 44 pp.

Tarboton, D. G., 1997, A new method for the determination of flow directions and upslope areas in grid digital elevation models. Water Resour. Res., vol. 33, 309-319.

Tarboton, D G., Bras. R. L., and I. Rodriguez-Iturbe, 1991, On the extraction of channel networks from digital elevation data. Hydrol. Process., 5, 81-100.

Thornes, J. B., 1970, Hydraulic geometry of stream channels in the Xingu-Araguaia headwaters. Jour. Geog., vol. 136, 376-382.

Thornes, J. B., 1978, The character and problems of theory in contemporary geomorphology. eds. C. Embleton, D. Brunsden and D. K. C. Jones , Geomorphology: present problems and future prospects. Oxford Univ. Press, 14-24.

Thornes, J. B. and D. Brunsden, 1977, Geomorphology and time. London: Methuen, 208 pp.

Tinkler, K. J., 1985, A short history of geomorphology. Totowa, NJ: Barnes and Noble, 317 pp.

Todd, D. K., ed., 1970, The water encyclopedia. Water Information Center, Port Washington, N.Y., 559 pp.

Toutin, T. and M. Beaudoin, 1995, Real-time extraction of planimetric and altimetric features from digital stereo SPOT data using a digital video plotter. Photogramm. Engr. & Rem. Sens., vol. 61, 63-68.

Trainer, F. W. and F. A. Watkins, 1975, Geohydrologic reconnaissance of the upper Potomac River basin. U.S. Geol. Survey Water-Supply Pap. 2035, 68 pp.

Trimble, S. W. and R. U. Cooke, 1991, Historical sources for geomorphological research in the United States. Professional Geographer, vol. 43, no. 212-228.

Trimble, S. W. and S. W. Lund, 1982, Soil conservation and the reduction of erosion and sedimentation in the Coon Creek Basin, Wisconsin. U.S. Geol. Survey Prof. Pap. 1234, 35 pp.

Trudgill, S. T., 1976, Rock weathering and climate: Quantitative and experimental aspects. ed. E. Derbyshire, Geomorphology and Climate, London: John Wiley & Sons, 59-99.

Unwin, D., 1981, Introductory spatial analysis, Methuen & Co. Ltd., 212 pp.

U. S. Department of Agriculture, 1981, WRC Hydrologic Unit Boundaries Correlated with Oklahoma CNI, Watersheds, and Other Sub-state Resource Unit Delineations. Rep. no. 6-81, Soil Conservation Service, Stillwater, Oklahoma.

U. S. Department of the Army, 1973, Chesapeake Bay Existing County Report, Baltimore District Corps of Engineers, Baltimore MD, Appendices A, B, C, and D.

U. S. Environmental Protection Agency, 1994, EPA Reach File Version 3.0 Alpha Release Technical Reference, Contract No. 68-C3-0303. Office of Wetlands, Oceans, and Watersheds, Office of Water, USEPA. Washington, D.C.

U.S. Geol. Survey, 1993, Digital Elevation Models: Data User's Guide 5, National Mapping Program Technical Instructions, Department of the Interior, Reston, Virginia.

U.S. Geol. Survey, 1996, Global 30-arc Second Elevation Data Set, Eros Data Center, Department of the Interior, Sioux Falls, South Dakota.

U.S. Geol. Survey, 1997, Standards for Digital Elevation Models, National Mapping Program Technical Instructions, Department of the Interior, Reston, Virginia.

U.S. Geol. Survey, 1993, Data Users Guide for Digital Elevation Models, 109 pp.

Vanoni, V. A., 1941, Some experiments on the transportation of suspended load. Trans., AGU, Washington, D.C., 608-621.

Vokes, H. E. 1968, Geography and Geology of Maryland. Mary. Geol. Surv., Bull.19, 243 pp.

Vokes, H. E. and J. Edwards, 1974, Geography and geology of Maryland. Baltimore.

Wahl, K. L., 1976, Accuracy of channel measurements and the implications in estimating streamflow characteristics. Proceeds. of the intl. seminar, Modern Developments in Hydrometry. Padua, Italy, World Meteorological Organization, no. 427, vol. 2, 311-319.

Wahl, K. L., 1984, Evolution of the use of channel cross-section properties for estimating streamflow characteristics. ed. E. L. Meyer, Selected papers in the hydrologic sciences. U. S. Geol. Survey Water Supply Pap. 2262, 53-66.

Walker, H. J., 1993, Geomorphology: the research frontier and beyond-Introduction, Geomorphology Special Issue. Proceeds., 24th Binghamton Symp. in Geomorphology, Aug 25, 1993, 1-8.

Webber, E. E. and H. W. Roberts, 1981, Floodflow characteristics related to channel geometry in Ohio. U.S. Geol. Survey Op. File Rep. 81-1105, 28 pp.

Weissel, J. K., L. F. Pratson and A. Malinverno, 1994, The length-scale properties of topography. Jour. Geophys, Res., vol. 99, no. B7, 13997-14012.

Wilcock, D., 1971, Investigation into the relations between bedload transport and channel shape. Geol. Soc. Am. Bull. 82, 2159-2176.

Wiley, J. B., M. L. Hunt and D. K. Stewart, 1995, Drainage areas of the Potomac River basin, West Virginia. U.S. Geol. Survey Op. File Rep. 95-292, 60 pp.

Willgoose, G. R., R. L. Bras and I. Rodriguez-Iturbe, 1991, Results from a new model of river basin evolution. Earth Surf. Process. & Landfms., 16, 237-254.

Williams, G. P., 1978 (a), Hydraulic geometry of river cross-sections-Theory of minimum variance. U.S. Geol. Survey Prof. Pap. 1029, 47 pp.

Williams, G. P., 1978 (b), Bankfull discharge of rivers. Water Resour. Res., vol. 14, no. 6, 1141-1154.

Williams, G. P. and J. E. Costa, 1988, Geomorphic measurements after a flood. eds. V. R. Baker, R. C. Kochel and P. C. Patton, Flood Geomorphology, New York: John Wiley & Sons, 65-80.

Williams, R. P., I. O'Dell and W. F. Megahan, 1989, Hydraulic geometry and sediment data for the South Fork Salmon River, Idaho, 1985-1986. U.S. Geol. Survey Prof. Pap. 89-233, 22 pp.

Wolman, M. G., 1955, The natural channel of Brandywine Creek, Pennsylvania. U.S. Geol. Survey Prof. Pap. 271, 56 pp.

Wolman, M. G. and W. P. Miller, 1960, Magnitude and frequency of forces in geomorphic processes. Jour. Nat. Resour. Baltimore, MD: Johns Hopkins Univ. Press.

Wolman, M. G. and L. M. Brush, Jr., 1961, Factors controlling the size and shape of stream channels in coarse non-cohesive sands. U.S. Geol. Survey Prof. Pap. 282-G, 191-210.

Wolock, D. M., 1995, "quikatn" for ln(a/tanB) code, Arc Macro Language, E-mail comm. fr. author.

Wolock, D. M., G. M. Hornberger and T. J. Musgrove, 1990, Topographic effects on flow path and surface water chemistry of the Llyn Branne catchments in Wales. Jour. Hydrol., vol. 115, 243-259.

Wolock, D. M. and C.V. Price, 1994, Effects of digital elevation model map scale and data resolution on a topography-based watershed model. Water Resour. Res., vol. 30, 3041-3052.

Wolock, D. M. and G. J. McCabe, 1995, Comparison of single and multiple-flow direction algorithms for computing topographic parameters on TOPMODEL. Water Resour. Res., vol. 31, 1315-1324.

Wolock, D. M., J. Fan and G. B. Lawrence, 1997, Effects of basin size on low-flow stream chemistry and subsurface contact time in the Neversink River watershed, New York. Hydrol. Process., vol. 11, 1273-1286.

Wood, J. D., Visualizing contour interpolation accuracy in digital elevation models. eds. H. M. Hearnshaw and D. J. Unwin, Visualization in Geograph. Info. Sys., Wiley Chichester, 168-180.

Wood, E. F., M. Sivapalan and K. J. Beven, 1990, Similarity and scale in catchment storm response. Reviews of Geophysics, vol. 28, issue 1, 1-18.

Wood, E. F., M. Sivapalan, K. J. Beven and L. Band, 1988, Effects of spatial variability and scale with implications to hydrologic modeling. Jour. Hydrol., vol. 102, no. 1-4, 29-47.

Woodford, A. O., 1951, Stream gradients and Monterey sea valley. Geol. Soc. Am. Bull., vol. 62, no. 7, 799-852.

Woodyer, K. D., 1968, Bankfull frequency of rivers. Jour. Hydrol., vol. 6, no. 2, 114-142.

Yang, C. T., C. C. S. Song, and M. J. Woldenburg, 1981, Hydraulic geometry and minimum rate of energy dissipation. Water Resour. Res., vol. 17, no. 4, 1014-1018.

Yatsu, E., 1955, On the longitudinal profile of the graded river. Am. Geophys. Union Trans., vol. 36, 655-663.

Zhang, W., and D. R. Montgomery, 1994, Digital elevation model grid size, landscape representation, and hydrologic simulation. Water Resour. Res., vol. 30, issue 4, 1019-1028.

Zimmerman, R. C., J. C. Goodlett and G. H. Comer, 1967, The influence of vegetation on channel form of small streams. Symp. of River Morphology, Intl. Assoc. of Sci. Hydrol., pub. no. 75, 255-274.