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Comparison of Hydrologic Responses at Different Watershed Scales

By

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Notice

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Abstract

Land surface hydrology controls runoff production and the associated transport of sediments, and a wide variety of anthropogenic organic chemicals, and nutrients from upland landscape areas and hillslopes to streams and other water bodies. Based on interactions between landscape characteristics and precipitation inputs, watersheds respond differently to different climatic inputs (e.g. precipitation and solar radiation). This study compares the hydrologic responses of the Mid-Atlantic watersheds, and identifies the landscape and climatic descriptors that control those responses. Our approach was to select representative watersheds from the Mid-Atlantic region, group the watersheds by physiographic province and ecoregion, and then collect landscape, climate, and hydrologic response descriptor data for each selected watershed. For example, we extracted extensive landscape descriptor data from soil, land use and land cover, and digital elevation model geographic information system (GIS) databases. After sufficient data was collected, we conducted a variety of studies to determine how different landscape and climatic descriptors influence the hydrologic response of Mid-Atlantic watersheds.

This report is comprised of four main parts. Part I describes the selection of the representative study watersheds and the determination of representative physical landscape descriptors for each watershed using geographic information system analysis tools. Part II characterizes the climate and associated hydrologic responses of the study watersheds. To select climate descriptors that are good predictors of hydrologic response, we examined a large number of candidate descriptors. Based on our examination, we selected dryness index and mean monthly rainfall as the best hydrologic response predictors. In Part II, we also present the results of our study hydrologic response comparisons of the study watersheds using a water balance approach. The water balance approach was based on comparisons of precipitation, streamflow, and evapotranspiration at annual, monthly, and daily time scales. These comparisons revealed that elevation and latitudinal position strongly influence hydrologic response. The results also showed that mountainous watersheds of the Appalachian Plateau, Ridge and Valley, and Blue Ridge Physiographic Provinces have more streamflow and less evapotranspiration than watersheds located in the Piedmont Province, and that snowmelt contributes a large portion of streamflow.

Part III presents relationships we derived between landscape-climatic descriptors and the hydrologic response descriptors. Flow duration indices (Q1…Q95) were used to represent the hydrologic responses of the study watersheds. In Part III, we also present comparisons of the hydrologic responses of the study watersheds at high flow condition, represented by the Q1 index, medium flow condition represented by the Q50 index, and low flow condition represented by the Q95 index. These comparisons revealed that: the Appalachian Plateau, ridge-dominated Ridge and Valley, and Blue Ridge watersheds have the highest Q1 and Q50 indices; the valley-dominated Ridge and Valley watersheds have the lowest Q50 index, and the Piedmont watersheds have the lowest Q1 index and a relatively high Q95 index.

Finally, Part IV discusses some of the implications of the study results for watershed management. We also present applications of the research for hydrologic modeling and watershed assessment.

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1 Introduction

The hydrologic response of a watershed is influenced by many soil property descriptors (e.g., infiltration capacity, soil depth, and porosity), geomorphologic descriptors (e.g., drainage area, lake/pond areas, slope, channel length, drainage density, and relief ratio), geologic descriptors (e.g., lithologic and structural geologic properties), and land cover and land use descriptors (e.g., percent forest, agricultural, and urban cover). Many investigators have developed regression equations to relate landscape descriptors to hydrologic response variables, such as low flows or peak flow rates.

Some of the widely used landscape descriptors in hydrology include drainage area, channel slope, channel length, forested area, drainage density, and relief ratio. Because landscape descriptors influence the hydrologic response of a watershed, landscape descriptors have been the foundation of many widely used empirical and statistical hydrologic response equations, such as the rational method (Kuichling,1889) that relates the peak flow rate to the drainage area of a watershed. Other important empirical equations that use landscape descriptors include the Soil Conservation Service Method (SCS, 1972) that uses an arbitrary "curve number" to determine direct runoff. The "curve number" represents the cumulative effects of landscape descriptors that control initial abstractions or water losses that usually correspond to that fraction of precipitation not translated into direct runoff. Such initial abstractions include surface depression storage (controlled by land use and land cover, soil, and micro-topography), interception (controlled by land use and land cover type), and infiltration losses, controlled by soil characteristics.

As high-speed computers became available and as more models were used for regulatory purposes, the need for physically-based hydrologic models increased. In recent years, resource managers and policy makers have demanded models that can be easily parameterized and that can accurately simulate both hydrology and water quality processes at the watershed scale. Unfortunately, these models need parameter values that reflect the effect of soil, geology, topography, land use and land cover on the hydrologic response. The transition from simple empirical models to physically based hydrologic models has to date met with limited success. One limitation to developing and testing physically-based models is the lack of ways to represent the relationships between landscape descriptors and hydrologic response. Without a clear understanding of these relationships, it is difficult to identify how soil, vegetation, geology, and the geomorphologic parameters influence hydrologic processes at different spatial and temporal scales. Moreover, measured data is essential to process understanding, but it is not logistically feasible to obtain measured landscape and hydrologic descriptor data for many large watersheds.

There are also a number of climate and hydrologic factors that influence the hydrologic response of a watershed. These factors include precipitation input (e.g., rainfall and snow), including its temporal and spatial distribution over the watershed (Singh 1997), antecedent soil moisture conditions (Hawley et al. 1983; Montgomery and Dietrich, 2002), and available soil and groundwater storage (Troch et el. 1993; Wittenberg and Sivapalan, 1999). A watershed's hydrologic response is an indicator of how a watershed processes precipitation inputs, based on its unique set of landscape descriptors. Many investigators have examined the relationship between landscape descriptors and observed hydrologic response variables (Zecharias and Brutsaert, 1988;

Nathan and McMahon, 1988; Lacey and Grayson, 1998). Other researchers have examined the relationship between landscape descriptors and simulated hydrologic response variables (Sefton and Howarth, 1998; Berger and Entekhabi, 2001). The focus of most of these cited studies was, however, to examine relationships between landscape descriptors and low flow hydrologic conditions.

Lacey and Grayson (1998) examined the relationship between baseflow index and landscape descriptors that included a set of qualitative geology-vegetation parameters and dimensionless topographic and climatic indices. They found no trends between plots of baseflow index against any dimensionless topographic parameter within the geology-vegetation groups. Although most landscape and hydrologic relationship studies have focused on baseflow or peak flow conditions, some investigators examined long-term hydrologic responses. Berger and Entekhabi (2001) demonstrated that long-term hydrologic response of a watershed could be determined from physiographic and climatic descriptors. These investigators used the annual runoff ratio (ratio between annual streamflow to annual precipitation) to represent the long-term hydrologic response of a basin. They also have examined a number of other potential hydrologic response predictors, but found that runoff ratio was also the most closely related to climate that they represented by the wetness ratio (ratio between annual precipitation and annual potential evapotranspiration).

Although landscape descriptors and precipitation inputs influence the hydrologic response of a watershed, scale also plays an important role because scale introduces heterogeneity in the landscape descriptors. As the drainage area of a watershed increases, the soil, bedrock geology, land use and land cover, and topographic features become more variable. As the variability in landscape descriptors increases, different landscape characteristics can interact and possibly initiate a different hydrologic response than could have been produced by any single set of descriptors without the interaction. Unlike large watersheds, small headwater watersheds show a high degree of homogeneity in landscape descriptors and, in some cases, can have: a single soil unit, and land use and land cover type; homogeneous bedrock geology, and uniform topography. Small watersheds also tend to receive a more evenly distributed rainfall, and thus their hydrologic response reflects that uniformity in rainfall distribution (Singh, 1997). On the other hand, large watersheds experience uneven rainfall distribution that often leads to an uneven runoff distribution.

Different processes become important at different spatial scales and processes that are important at small scales may not be important at large scales (Meentemeyer and Box, 1987). Wood et al. (1988) conducted an empirical study on the impact of scale on runoff. Wood (1994) later repeated the same experiment on runoff ratio and Famiglietti and Wood (1995) repeated the same experiment on evaporation. These studies found that both runoff and evaporation have large variability, controlled by the variability in soils and topography.

The water balance equation is a fundamental hydrology equation that is valid for all temporal and spatial scales. At large time scales, some terms of the water balance equation become negligible while other terms transform themselves and become part of another water balance term. For example, interception is a part of evaporation, while depending on the time scale, infiltration is a part of soil moisture storage, subsurface runoff or groundwater recharge. For time scales that are equal to or longer than one day, process aggregation occurs and infiltration and interception processes that are important at short temporal scales are no longer important; other processes, such as evapotranspiration, that are negligible and are often ignored at short time scales become important at large time scales.

Although considerable research has been conducted examining the relationship between landscape descriptors and hydrologic responses, many past studies were based on field plot or small experimental watersheds where landscape descriptors are nearly homogeneous and the heterogeneities that exist in large watersheds are missing. Observations and insights gained from these small-scale field studies are often used to build physically-based models. A critical limitation of such single site studies is how to extrapolate knowledge gained from a small-scale area with nearly homogeneous landscape descriptors to larger watersheds with variable size and variable landscape descriptors.

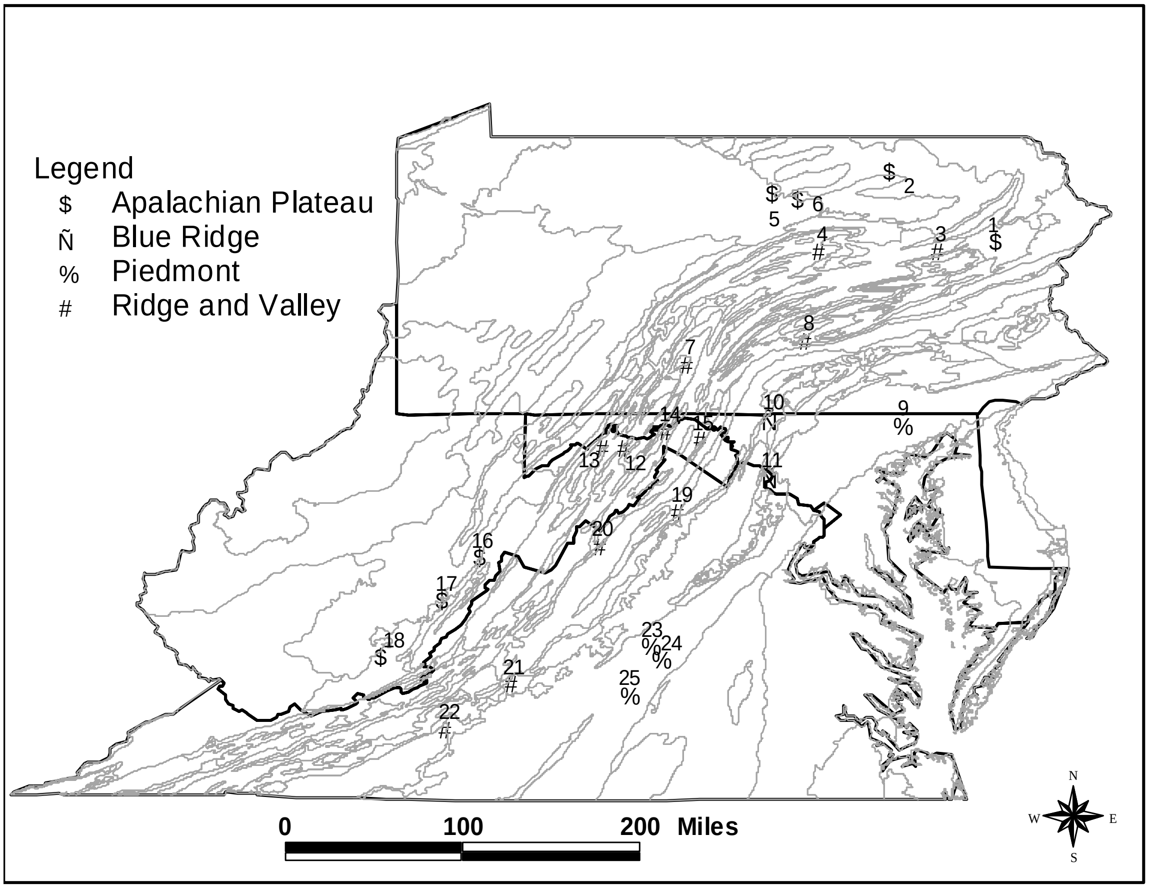
In the past, to develop relationships between landscape descriptors and hydrologic response, researchers used only a few landscape variables (e.g., drainage density, relief ratio, drainage area, etc.) and only one hydrologic response variable at a time (e.g., baseflow index or peak flow rate). The present effort differs from earlier studies in a number of ways. First, this study uses an extensive array of landscape descriptors that incorporate soil, geology, topography, vegetation, and climate data. The availability of geographic information system (GIS) analysis tools combined with spatial databases, such as the digital elevation model (DEM) data, and soil databases, e.g., the digital State Soil Geographic Database (STATSGO) provided the opportunity to easily and rapidly obtain extensive soil and topographic parameters for our selected study watersheds. Second, unlike other studies that focused on either low flow (baseflow) or peak flow conditions, this study uses multiple hydrologic response representations that reflect a wide range of hydrologic conditions.

The objectives of this study were: (1) to compare hydrologic responses and identify the dominant landscape descriptors that control the hydrologic responses of Mid-Atlantic watersheds; (2) to develop relationships between landscape and climatic descriptors and hydrologic response variables; and (3) to make recommendations on how to use the results of this study for resource management and modeling purposes.

2 Description of Study Area

The United States Geological Survey (USGS) has classified the nation's water resources into 21 hydrologic regions. According to their regional classification, Region 2 covers the Mid-Atlantic States from Maine to Virginia. Our study area covers four physiographic provinces: Appalachian Plateaus, Ridge and Valley, Blue Ridge, and Piedmont. A physiographic province is a landform characterized by similar elevation, relief, geologic structure, and climate. In general, physiographic provinces are subdivided into ecoregions (Woods et al. 1999). Woods et al. (1999) defined ecoregions as areas of relative homogeneity in ecological systems (e.g., soils, vegetation, geology, and physiography) and their components. They also stated that, because of their similar landscape descriptors, ecoregions could be an effective framework for inventorying and assessing regional environmental resources and setting regional resources management goals.

Using physiographic provinces and ecoregions as a selection framework, we selected 25 watersheds from the Appalachian Plateaus, Ridge and Valley, Blue Ridge, and the Piedmont Physiographic Provinces of Maryland, Pennsylvania, Virginia, and West Virginia (Figure 1). Note that different physiographic provinces have different numbers of ecoregions. For instance, there are 12 ecoregions in the Appalachian Plateaus, nine ecoregions in the Ridge and Valley, five ecoregions in the Blue Ridge, and eight ecoregions in the Piedmont. Our 25 study watersheds represent about 80 percent of the Ridge and Valley ecoregions, 50 percent of the Appalachian Plateau ecoregions, 40 percent of the Blue Ridge ecoregions, and 35 percent of the Piedmont ecoregions. In other words, we selected six watersheds from the 12 ecoregions of the Appalachian Plateau, seven watersheds from the nine ecoregions of the Ridge and Valley, two watersheds from the five ecoregions of the Blue Ridge, and three watersheds from the eight ecoregions of the Piedmont. While some Mid-Atlantic ecoregions are not represented in this study, others are represented more than once. The use of ecoregions as a selection framework facilitates the extrapolation of our results to all watersheds within Mid-Atlantic region.



West Virginia

12-South Branch Potomac
13-Patterson Creek
14-Cacapon River
15-Back Creek
16-Greenbier at Durban
17-Greenbrier River Buckeye
18-Greenbrier River at Alderson

Virginia

19-SF Shenandoah River
20-NF Shenandoah River
21-Bullpasture Creek
22-Johns Creek
23-Hardware Creek
24-Slate River
25-Holiday Creek

Pennsylvania

1-Lehigh River
2-Towanda River
3-Wapwallopen
4-Marsh Creek
5-Pine River
6-Blockhouse Creek
7-L. Juniata River
8-Sherman Creek

Maryland

9- Deer Creek
10-Owens Creek
11-Fishing Creek

Figure 1. Location of Study Watersheds.

Part I

3 Physical Landscape Descriptors Controlling Hydrologic Responses

When comparing hydrologic responses, we assumed that watersheds located in the same or similar ecoregions within a physiographic province have closely related landscape descriptors and, may therefore, have comparable hydrologic responses. A list of the selected watersheds, their drainage areas, latitudinal and longitudinal positions, and the major river system to which each belongs is shown in Table 1. The study watersheds have drainage areas that range from 15 to 4250 km^2 (variable spatial scale) and all have a long record of climatic and hydrologic data. Most of the watersheds have a high percentage of forest cover and limited impacts of human-induced watershed disturbances such as urbanization, flow regulation, and/or agricultural land use. To ensure that the study watersheds had long records of good-quality streamflow data, we selected all 25 watersheds from the U.S. Geological Survey's Hydro-climatic Data Network (HCDN) (Slack and Landwehr, 1992). The HCDN data consists of a list of about 1659 gaging sites with good-quality streamflow data.

As stated before, in order to examine the relationships between landscape descriptors and hydrologic response variables, one must obtain coincident landscape, climate, and hydrologic response descriptor data. In this study, we denoted landscape descriptor data as that extracted from soils, geology, land use and land cover, and topography databases using geographic information systems (GIS) tools. We denoted climate and hydrologic response descriptors or variables as climate and streamflow time series data (See Table 2). We used surrogate descriptors when quantitative measures of landscape descriptors were not available. A more detailed description of some of the descriptors is given in the following sections of this report. All landscape descriptor data extracted from the GIS databases were considered as potential predictors of hydrologic response.

Table 1. List of Study Watersheds, Their Location, Drainage Area, and Major River System.

Watershed	Major River Basin	Drainage Area (km^2)	Latitude	Longitude
		Appalachian Plateaus		
Lehigh River at Stoddarsville, PA	Delaware	237.40	41:07:49N	075:37:33W
Towanda Creek, Monroetown, PA	Susquehanna	556.61	41:42:25N	076:29:06W
Pine Creek at Cedar Run, PA	Susquehanna	563.68	41:31:18N	077:26:52W
Blockhouse Creek Near English, PA	Susquehanna	97.60	41:28:25N	077:13:52W
Greenbrier River at Durbin, WV	Ohio	344.32	38:32:37N	079:50:00W
Greenbrier River at Buckeye, WV	Ohio	1398.00	38:11:09N	080:07:51W
Greenbrier River at Alderson, WV	Ohio	3531.23	37:43:27N	080:38:30W
		Ridge and Valley		
Wapwallopen Creek Near Wap., PA	Susquehanna	113.39	41:03:33N	076:05:38W
Marsh Creek at Blanchard, PA	Susquehanna	114.17	41:03:34N	077:36:22W
Little Juniata River at Spruce, PA	Susquehanna	569.55	40:36:45N	078:08:27W
Sherman Creek, Shermans Dale, PA	Susquehanna	517.78	40:19:24N	077:10:09W
Patterson Creek, Headsville, WV	Potomac	566.96	39:26:35N	078:49:20W
South Branch Potomac Sprinfield, WV	Potomac	3808.24	39:26:49N	078:39:16W
Cacapon River Great Capapon, WV	Potomac	1752.67	39:34:43N	078:18:34W
Back Creek Near Jones Spring, WV	Potomac	629.10	39:30:43N	078:02:15W
S F Shenandoah River at Front, VA	Potomac	4250.94	38:54:50N	078:12:40W
N F Shenandoah River at Cootes, VA	Potomac	543.67	38:38:13N	078:51:11W
Bullpasture River, Williamsville, VA	James	284.78	38:11:43N	079:34:14W
Johns Creek at New Castle, VA	James	269.24	37:30:22N	080:06:25W
		Blue Ridge		
Owens Creek at Lantz, MD	Potomac	15.35	39:40:36N	077:27:50W
Fishing Creek Near Lewistown, MD	Potomac	18.87	39:31:35N	077:28:00W
		Piedmont		
Deer Creek at Rocks, MD	Susquehanna	244.39	39:37:49N	076:24:13W
Slate River Near Arvonia, VA	James	585.09	37:42:10N	078:22:40W
Hardware River Near Scottsville, VA	James	300.31	37:48:45N	078:27:20W
Holiday Creek, Andersonville, VA	James	23.30	37:24:55N	078:38:10W

Table 2. List of landscape descriptors

Symbol	Variable description	Units
Land use and land cover		
AGRC	Agriculture	(%)
URBN	Urban	(%)
FRSD	Decidiuous forest	(%)
FRST	Mixed forest	(%)
FRSE	Evergreen forest	(%)
Geomorphologic		
HMIN	Minimum elevation	(m)
HMAX	Maximum elevation	(m)
HAVG	Average elevation	(m)
HMED	Median elevation	(m)
HSTD	Standard deviation of elevation	(m)
BREL	Basin relief	(m)
RRAT	Relief ratio	(m)
SAVG	Average slope	(m/m)
SMED	Median slope	(m/m)
SSTD	Slope standard deviation	(m/m)
MCHL	Main stream channel length	(km)
TCHL	Total length of streams	(km)
MCHS	Main channel slope	(m/m)
DDEN	Drainage density	(km/km^2)
DARE	Drainage area	km^2
HPC10	Hypsometric curve elevation corresponding to 10% of area	(%)
Soil (top two layers)		
SOLD	Total soil depth	(mm)
AWC12	Plant available water content	(mm)
KSAT12	Saturated hydraulic conductivity	(mm/hr)
ORGC12	Soil organic carbon	(%)
CLAYl12	Percent clay	(%)
SILT12	Percent silt	(%)
SAND12	Percent sand	(%)
ROCK12	Percent rock fragment	(%)
STOR	Available moisture storage	mm
DRATIO	Depth ratio (layer 2/layer 1)	-
KRATIO	Depth weighted ratio of saturated hydraulic conductivity for layers 1 and 2	-
Geology		
DLIT	Dominant lithology (qualitative)	-
BFI	Baseflow index (daily)	-

3.1 Soil Descriptors

The underlying bedrock geology (Lacey and Grayson, 1998) and topographic position in the landscape of an area often influence the rate of formation and properties of its soils. The topographic position determines important soil properties that influence the hydrologic response of a watershed (England et al. 1968). For example, soil depth decreases with an increase in elevation, and elevation has both direct and indirect influence on hydrologic response. Specifically, watersheds with shallow soils and steep slopes retain less precipitation in the soil, that is they have low moisture storage capacity. When precipitation fills the available storage capacity of a soil, the soil becomes highly responsive and quickly releases a high fraction of the incident precipitation as quickflow runoff (Carey and Woo, 2001). The geographic information system analysis tools available within the U.S. EPA BASINS3 Modeling System were used to extract soil characteristics for the dominant soil of each study watershed. We extracted all the soil parameters from the digital State Soil Geographic Database (STATSGO) (NRCS, 1991). The extracted soil parameters for the 25 study watersheds are shown in Table 3.

3.1.1 Dominant Soils of the Study Watersheds

The properties of the soils of the Ridge and Valley Province clearly vary with the topographic position in the landscape and the underlying bedrock geology. For example, colluvial soils derived from sandstone and shale bedrock are found on the ridge slopes, while the valley soils are formed from limestone and shale. Limestone-derived soils are generally deep and fertile. In many valley-dominated watersheds of the Ridge and Valley Province, these deep and fertile soils are under intensive agricultural use. The dominant Ridge and Valley Province soils include Berks, Dekalb, Lehew, and Wallen soil series (Table 3).

The Appalachian Plateau watersheds have deep soils with high rock fragments. These soils formed in residuum or from glacial till deposits. The soils are classified as Ultisols, Inceptisols, and Alfisols. Some Appalachian Plateau soils have a flow-impeding subsoil layer known as fragipan. The fragipan occurs at a depth of 43 to 91 cm below the surface, where it restricts root penetration and controls the flow of water and solutes. Norris and Volusia soils are two dominant soils that are commonly found in our study watersheds located in the Appalachian Plateau Physiographic Province (Table 3).

Only four out of our 25 study watersheds are found in the Piedmont Physiographic Province. These watersheds are Deer Creek located in Hartford County, Maryland, and the Hardware, Slate, and Holiday watersheds located in Albemarle, Buckingham, and Appomattox counties, respectively, of Virginia. Chester soil series is the dominant soil type for the Deer Creek watershed in Maryland while Georgeville is the dominant soil type for the Hardware, Slate, and Holiday watersheds in Virginia (Table 3). In general, soils of the Piedmont Province are derived from metamorphic rocks and are relatively deep with a low rock fragment content and a thick, saprolite layer.

Table 3. Soil Physical Properties Extracted from STATSGO Database for the Top Layers of the Dominant Soils of each Watershed

Watershed	Soil Series	Soil Depth[1] (mm)	Soil Depth[2] (mm)	AWC mm/mm	KS mm/hr	SOC %	Clay %	Silt %	Sand %
		Appalachian Plateau							
Lehigh (62a)	Morris	1524	292	0.18	5.40	2.0	21	53	26
Towanda (60a/62c	Morris	1524	304	0.16	4.85	2.0	21	53	26
Pine (62c/62d)	Volusia	1778	174	0.14	8.52	1.0	20	45	35
Blockhouse (60a)	Morris	1524	381	0.17	2.90	1.0	21	53	27
Greenbrier (69a/69c)	Berks	863	212	0.13	22.32	1.6	17	45	38
		Ridge and Valley							
Wapwallopen (67b)	Morris	1524	332	0.16	4.01	1.5	20	53	27
Marsh (67d)	Lechkill	1295	207	0.12	14.84	1.4	14	49	37
L. Juniata (67c)	Hazelton	1447	206	0.10	23.74	1.6	13	44	43
Sherman (67f)	Hazelton	1447	199	0.11	17.65	1.4	14	46	40
South Branch (67d)	Berks	863	216	0.11	70.69	1.9	12	39	49
Patterson (67b/67c)	Berks	863	238	0.11	33.07	1.8	14	41	45
Cacapon (67b/67c)	Lehew	838	198	0.11	81.10	1.7	12	33	55
Back (67a/67b)	Berks	863	240	0.13	26.36	1.7	17	44	39
S.F. Shenan (67a/67b)	Frederick	1828	197	0.14	16.89	0.9	17	44	39
N.F. Shenand. (67d)	Berks	863	228	0.10	35.00	1.4	14	36	50
Bullpasture (67b/67c)	Wallen	736	148	0.07	39.54	0.7	15	19	66
Johns (67g/67h)	Wallen	736	148	0.07	39.54	0.7	15	19	66
		Blue Ridge							
Owens (66a)	Fauquier	1524	152	0.13	15.00	1.2	18	39	43
Fishing (66b)	Fauquier	1524	152	0.13	15.00	1.2	18	39	43
		Piedmont							
Deer (64c)	Chester	1574	226	0.17	9.95	1.2	17	47	36
Hardware (45e)	Georgeville	1600	163	0.14	25.19	0.8	17	40	43
Slate (45e)	Georgeville	1600	163	0.14	25.19	0.8	17	40	43
Holiday (45f)	Georgeville	1600	152	0.14	27.00	0.7	16	40	44

Numbers in parenthesis refer to the eco-region of each watershed within each physiographic province. The superscripts 1 and 2 refer to total profile soil depth and depth of the top soil layer, respectively, in each watershed.

The Blue Ridge Province consists of narrow, mountain ridges that run parallel to the Ridge and Valley Province. Out of our 25 study watersheds, only Owens Creek and Fishing Creek watersheds in Frederick County, Maryland are located in the Blue Ridge Physiographic Province (Table 3). In both of those watersheds, Fauquier soil type covers the entire watershed. This soil is derived from igneous and metamorphic rocks. It contains significant amounts of rock fragments and is often found on areas with steep slopes. In some areas, the Blue Ridge Province soils are nearly identical to the soils of the Piedmont Province. One difference between the soils of these two provinces is that the Blue Ridge soils have a high percent of rock fragments whereas the Piedmont Province soils have a low percent.

Figure 2 shows an inverse relationship between saturated hydraulic conductivity (KS) - a soil descriptor - and the monthly runoff ratio- a hydrologic response descriptor. Soils of our study watersheds vary from province to province and from watershed to watershed. Figure 2 shows that, as a group, the Ridge and Valley Province soils have the highest saturated hydraulic conductivity while the Appalachian Plateau soils have the lowest. Saturated hydraulic conductivity of some Ridge and Valley soils can be as high as 81 mm/hr (Table 3). Wilson and Luxmore (1988) conducted infiltration experiments on forested watersheds in the Ridge and Valley Province. They reported that infiltration rates could reach 72 mm/hr and could exceed the rainfall intensity during storm events, thus eliminating the occurrence of infiltration-excess runoff.

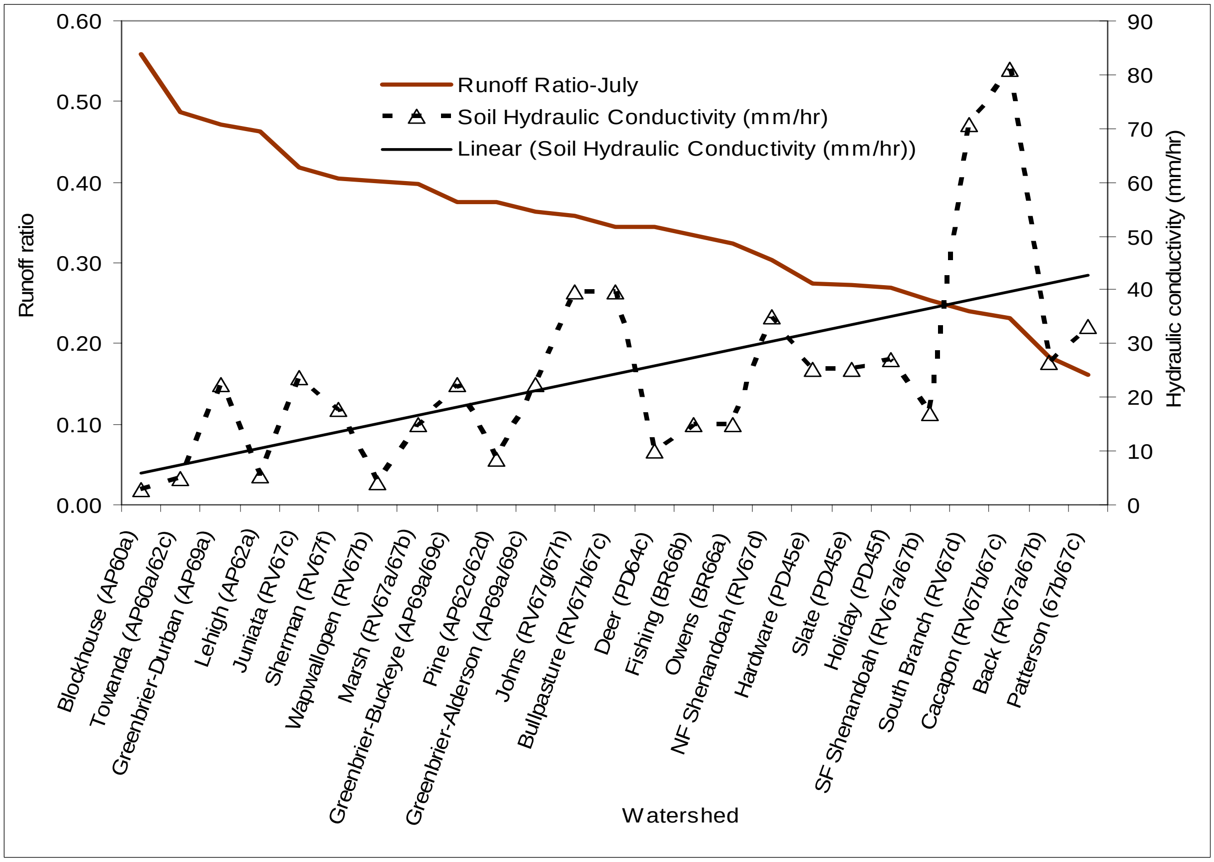


Figure 2. Relationship Between Hydraulic Conductivity and Runoff Ratio of Study Watersheds.

Figure 2 also shows that valley-dominated Ridge and Valley watersheds and Piedmont and Blue Ridge watersheds have the lowest runoff and, therefore, have the highest hydraulic conductivities. Note that the use of runoff ratio and the selection of the month of July improved hydrologic response comparisons because the use of runoff ratio removed two factors that normally complicate hydrologic response comparisons. First, by dividing the monthly runoff by monthly precipitation, we removed the effect of different precipitation inputs on the hydrologic response of different watersheds. Second, if all other factors remain the same, watersheds that have larger drainage areas tend to have greater runoff. To address this scale factor problem, we normalized runoff as depth of water instead of a flow rate. Third, because differences in elevation result in differences in hydrologic response, we excluded the months when elevation influence on hydrologic response was high i.e., when elevation would likely confound the influences of other landscape descriptors. In this study, we limited hydrologic comparisons to when elevation influence was negligible. For this reason, for both the monthly and daily comparisons, we used only the months of June, July, August, and September. By selecting July for the comparison shown in Figure 2, we assume that most of the runoff in July is from rainfall since the snowmelt period has ended and groundwater storage and baseflow are receding during the summer months.

3.1.2 Soil Descriptors as Potential Hydrologic Response Predictors

Soil characteristics control hydrologic processes such as rainfall infiltration, percolation, and moisture storage. Some soil properties, e.g., saturated hydraulic conductivity, control entry of precipitation inputs into the soil, and consequently the generation of infiltration-excess runoff. Other soil properties control soil moisture storage. These latter soil descriptors include soil depth, porosity, plant-available water content and depth to bedrock or the water table. Soils normally retain water by capillary forces and release water through gravity, evaporation from the soil surface and transpiration from plant stomata.

The importance of soil descriptors as hydrologic response predictors is well documented and is evidenced by the inclusion of soil parameter values in many hydrologic models. Although the importance of soil descriptors as hydrologic response predictors is widely recognized, what is not known is how to identify and quantify the specific soil descriptors that control hydrologic responses at different spatial and temporal scales. For instance, at short time scales, particularly during storm events, parameters such as saturated hydraulic conductivity that control processes such as infiltration capacity are important. At longer time scales, such as days or months, however, processes that control moisture storage and internal soil drainage are more important and so are the soil properties that influence these processes (e.g., soil depth and porosity).

Although soil-controlled hydrologic processes are represented in current hydrologic models, there are some limitations in the identification and quantification of the relevant soil parameters at the watershed scale. As an example, depending on its topography, watersheds can have different soils at different topographic positions in the landscape. Some soils are deep and permeable, others are shallow and may have a flow-impeding layer at some depth below the soil surface. Soil characteristics clearly vary across the landscape and within the soil profile, and unfortunately methodologies to combine the effects of all these diverse soil characteristics for reliable model use are not currently available.

In this study, we used the dominant soil unit of each watershed, as if a single soil, to cover the entire watershed. For small watersheds, the dominant soil may indeed be the only soil unit in the watershed. However, for large watersheds, using only the dominant soil may not entirely reflect all the combinations of soil influences on the hydrologic response of the watershed. In other words, depending on a particular soil type’s topographic position on the landscape and its relative contribution to the overall hydrologic response of a watershed, the dominant soil type by area of coverage may not sometimes be the hydrologically dominant soil in a large watershed.

3.2 Characterization of Bedrock Geology

Two major rock types cover the study area, consolidated crystalline and consolidated to unconsolidated sedimentary. The crystalline rocks, found in the Piedmont and the Blue Ridge Physiographic Provinces, consist of igneous and metamorphic rocks. By contrast, the consolidated to unconsolidated sedimentary rocks, found in the Appalachian Plateau and Ridge and Valley Provinces, consist of sandstone, siltstone, and shale (United States Geological Survey, 1992-1997). Both lithologic and structural geologic properties influence the watershed hydrologic response, but no quantitative geologic descriptors were used in this study. We have, however, made some inferences about the geologic descriptors of each watershed from qualitative measures such as dominant rock type, and surrogate quantitative measures, such as baseflow index. The qualitative bedrock geology data were extracted from digital United States Geological Survey maps (Shruben, 1998).

3.2.1 Bedrock Geology of the Study Watersheds

The bedrock geology of the Appalachian Plateau watersheds consists of shale, siltstone, sandstone, and carbonates. Sandstone and some erosion-resistant carbonates are found in the upland areas, while shale is usually found in the valleys. These watersheds have very limited recharge and most of the precipitation that falls on the ground may run rapidly off the slopes. Except for some springs that occur in areas where stream channels intersect the water table, there are no major regional groundwater aquifers in the Appalachian Plateau Province (United States Geological Survey, 1992-1997).

Unlike the Appalachian Plateau province, the Ridge and Valley Province has distinct landforms characterized by sequences of ridges and valleys that reflect folded and faulted bedrock geologic formations (Table 4). The valleys and the ridges are shaped by differential erosion of rocks with different erosion resistance. For example, erosion-resistant sandstone bedrock forms the ridges while less erosion resistant rocks, such as shale and limestone form the valleys. In some valley areas, the bedrock is covered by a thick regolith. For most of the Ridge and Valley Province watersheds, aquifer rocks are mainly low porosity and low permeability sandstone and shale bedrock material. Secondary porosity and permeability caused by fracturing and dissolution often create increased water storage and transmission properties yielding groundwater movement along fractures and bedding planes.

In the Piedmont and Blue Ridge watersheds, the bedrock is covered by regolith and precipitation enters the aquifer through this porous regolith. Unlike the overlying regolith, the bedrock has very low porosity and limited capacity to store water. Most of the Piedmont and Blue Ridge Physiographic Provinces are underlain by dense and nearly impermeable bedrock that yields water primarily from secondary porosity and permeability provided by fractures. Water stored in the porous regolith normally moves through the regolith laterally until it discharges into a nearby stream.

Table 4. Study Watersheds Arranged by Physiographic Province and Ecoregion, and Dominant bedrock Geology

Watershed	Dominant eco-region	lithology and dominant formations
	Appalachian Plateaus	
Lehigh (AP)	Pocono High Plateau (62a)	Sandstone-siltstone-mudstone Duncannon member of Catskill
Towanda (AP)	Glaciated high (62c) and low plateau (60a)	Mudstone-siltstone-sandstone Lock haven/Burgoon
Pine (AP)	Glaciated high (62c)/unglaciated plateau (62d)	Sandstone-siltstone-shale Catskill/Pottsville
Blockhouse (AP)	Glaciated low plateau (60a)	Sandstone-siltstone-shale Catskill/Huntley
Greenbrier (AP)	Forested hills (69a); Greenbrier Karst (69c)	Shale-Limestone Chemung/Greenbrier
	Ridge and Valley	
Wapwallopen (RV)	Northern shale valleys (67b)	Shale-siltstone-sandstone Pottsville
Marsh (RV)	Northern dissected ridges (67d)	Sandstone-siltstone-shale Catskill/Lock haven
Little Juniata (RV)	Northern shale valleys/sandstone ridges (67c)	Siltstone-shale-dolomite Brallier/Harrel/Lock haven
Sherman (RV)	Northern limestone/sandstone ridges (67f)	Quarzite-Shale-limestone Tuscarora/bloomsburg
South B. Potomac (RV)	Northern dissected ridges and valleys (67d)	Shale-sandstone-limestone Chemung/Oriskony
Patterson (RV)	Northern shale valleys/sandstone ridges (67bc)	Shale-sandstone Brallier/Harrel/Chemung
Cacapon (RV)	Northern shale valleys/sandstone ridges (67bc)	Shale-sandstone Chemung/Hampshire
Back (RV)	Northern shale/limestone valleys (67ba)	Shale-limestone Martinsburg
S.F. Shenandoah (RV)	Northern shale/limestone valleys (67ba)	Sandstone-shale
N.F. Shenandoah (RV)	Northern dissected ridges (67d)	Sandstone-shale
Bullpasture (RV)	Northern sandstone ridges/shale valleys (67cb)	Sandstone
Johns (RV)	Southern sandstone ridge/shale valleys (67hg)	Sandstone-shale
	Blue Ridge	
Owens (BR)	Northern igneous ridges (66a)	Greenstone schist
Fishing (BR)	Northern sedimentary and Metased.,ridges (66b)	Greenstone schist
	Piedmont	
Deer (PD)	Piedmont uplands (64c)	Albite-Phylite-chlorite schists Octoraro formation
Hardware (PD)	Northern inner piedmont (45e)	Igneous and metamorphic
Slate (PD)	Northern inner piedmont (45e)	Igneous and metamorphic
Holiday (PD)	Northern outer piedmont (45f)	Igneous and metamorphic

Source: Eco-region numbers were obtained from Woods et al.(1999).

3.2.3 Bedrock Geology Descriptors as Potential Hydrologic Response Predictors

In the absence of quantitative measures of bedrock geologic descriptors, we used baseflow index as a surrogate variable to represent the geologic properties that control groundwater storage and discharge (e.g., porosity and permeability). Baseflow index is defined as the volume of baseflow divided by the total volume of streamflow. To separate streamflow into baseflow and quickflow, we used a baseflow index method developed by the Institute of Hydrology (Gustard et al. 1992). Quickflow is defined as the rapid runoff component of a streamflow hydrograph that is observed during or after a rainfall event. Baseflow is one of the most important low flow hydrologic characteristics of a catchment (Lacey and Grayson, 1998; Smakhtin 2001). Theoretically, soil and geologic properties control baseflow. Specifically, soil properties control initial entry of precipitation into the soil, and the soil and the underlying aquifer properties combine to control storage and release of that water to nearby streams. Farvolden (1963) stated that the streamflow hydrograph during dry weather flows represents depletion of the groundwater reservoir, and that baseflow can be used as an indirect indication of soil moisture deficiency.

To compare the baseflow indices of our study watersheds, we ranked the watersheds in the order of increasing baseflow index (Figure 3). In addition to the baseflow index rankings, Figure 3 also displays the fraction of the total annual streamflow that is baseflow and the fraction of total annual streamflow that is quickflow. Note that some watersheds have low total streamflow (e.g., the South Fork Shenandoah River) while other watersheds have high total streamflow (e.g., the Lehigh River). An analysis of Figure 3 reveals that Appalachian Plateau watersheds generally have high total streamflows, but their baseflow indices are not very high. In general, watersheds located in the mountainous areas of the Appalachian Plateau and the ridge-dominated watersheds of the Ridge and Valley Province show high total annual streamflow. This high annual total streamflow is a result of generally high precipitation and low evapotranspiration rates (Hartley and Dingman, 1993). Among all study watersheds, those located in the Blue Ridge Physiographic Province had the highest total annual streamflow and baseflow indices. By contrast, the Piedmont watersheds had the lowest total annual streamflows, but had relatively high baseflow indices. The valley-dominated Ridge and Valley watersheds, such as Back, Patterson, Cacapon, and South Branch Potomac had both low total streamflows and low baseflow indices. The relative baseflow and quickflow contributions to total annual streamflow have important implications for water resources management.

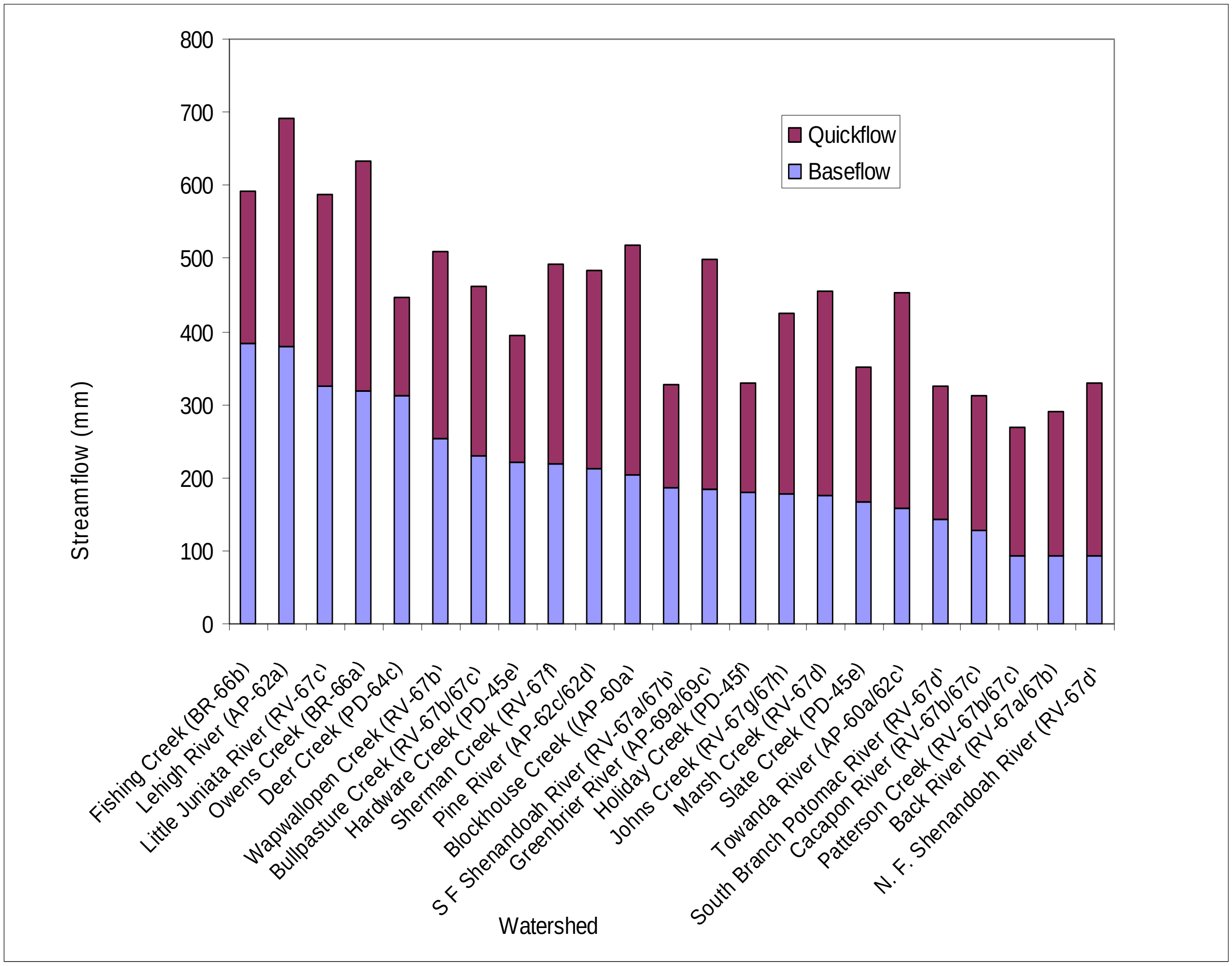


Figure 3. Study Watersheds Ranked in the Order of Increasing Baseflow Index.

3.3 Land Use and Land Cover Descriptors

The land use and land cover data used in this study were obtained from U.S. EPA's Better Assessment Science Integrating Point and Non-point Source (BASINS) GIRAS databases. The data is based on the Anderson land use and land cover classification system (Anderson et al. 1976) and has a scale of 1:250,000. The data reflects land cover conditions from the mid 1970s to the early 1980s. More information about land use and land cover data can be found at the following website http://www.epa.gov/waterscience/basins/metadata/giras.htm.

3.3.1 Dominant Land Use and Cover Types of the Study Watersheds

In the Mid-Atlantic Highlands Region, vegetation type varies from one province to another and, within each; vegetation type varies from one ecoregion to another. Much of the variability in vegetation type depends on differences in soil and topography. In mountainous watersheds of the Appalachian, Ridge and Valley, and Blue Ridge provinces, deciduous forest cover is dominant. Figure 4 ranks the study watersheds in order of increasing deciduous forest cover. Some of the mountainous watersheds with high deciduous forest cover are Bullpasture and Johns Creek in Virginia, Fishing and Owens Creek in Maryland, South Branch Potomac in West Virginia, and Pine River and Blockhouse Creek in Pennsylvania (Figure 4). Normally, the low-lying valley areas of the Ridge and Valley Province are covered by mixed forest type, while the deciduous forest type covers the ridge-dominated watersheds and high elevation areas, such as the ridge tops. Because low valley areas are relatively flat and suitable for agriculture, in some low valley areas of the Ridge and Valley Province forest cover has been converted to agriculture. On the contrary, mountainous areas not suitable for agriculture remain covered by deciduous forest. The dominant species in mountainous areas of the Appalachian Plateau and Ridge and Valley Provinces are mainly oaks, maples, and other hardwood trees.

Vegetation in the Piedmont Province is significantly different than that found in the mountainous areas of the Appalachian Plateau and Ridge and Valley Provinces. In the Piedmont Province, evergreen forest cover is dominant. For example, the dominant vegetation types in the Hardware, Holiday, and Slate watersheds located in the Northern Inner Piedmont ecoregion (45e) of Virginia are hickory (*Carya spp*.), loblolly pine (*Pinus taeda*), and Shortleaf Pine (*Pinus echinata*), respectively. Within the Piedmont province, vegetation type also varies; virgin chestnut oak (*Quercus pinus*), hemlock (*Tsuga Canadensis*), and Beech (*Fagus grandifolia*) dominate the watersheds in the Piedmont Uplands ecoregion (64c) of Maryland.

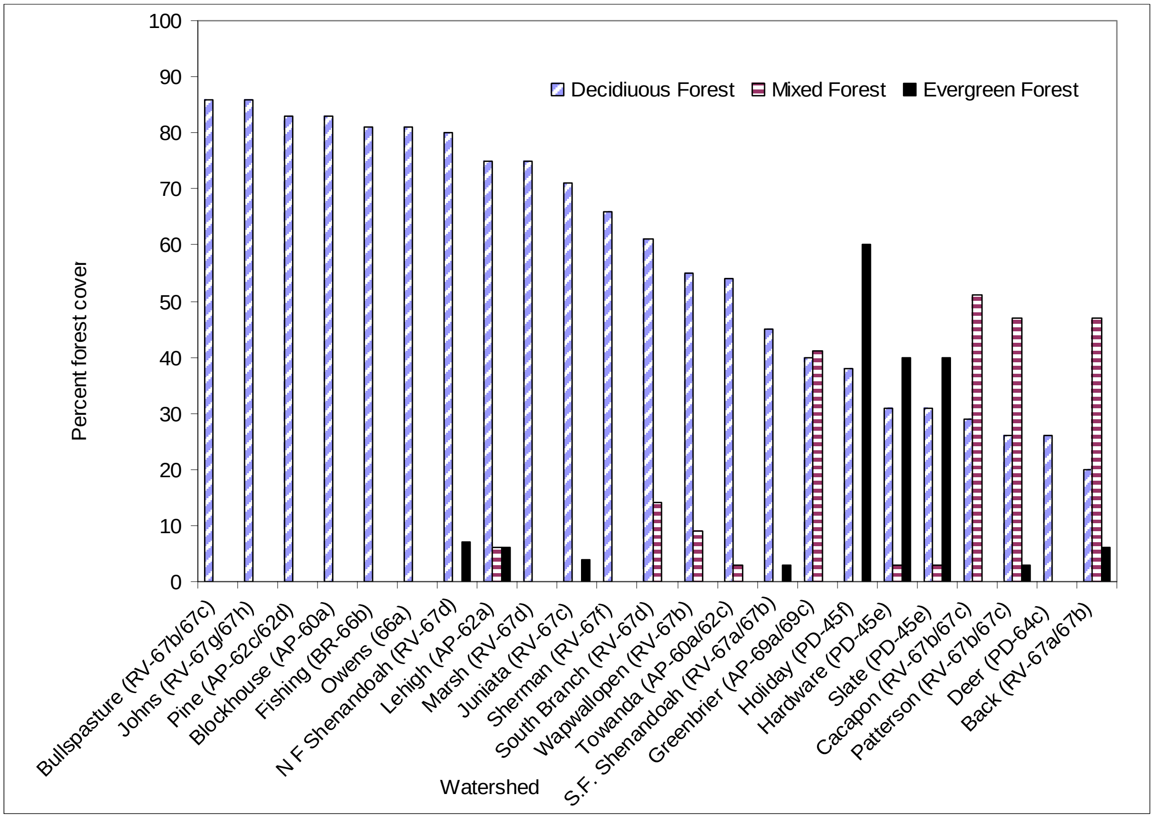


Figure 4. Study Watersheds Ranked in the Order of Increasing Deciduous Cover.

3.3.2 Land Use and Land Cover Descriptors as Potential Hydrologic Response Predictors

Many investigators have studied the relationship between vegetative cover and hydrologic response. Forest cover is critical to the hydrology of the Mid-Atlantic watersheds because the forest stabilizes the thin residuum soils and prevents landslides and excessive soil erosion from occurring on steep hillslopes. Forest cover also influences hydrologic response in a number of other ways. For example, forest cover directly affects such hydrologic processes as interception (Swank et al. 1972), rainfall infiltration, evaporation from plant canopy, and transpiration through plant stomata (Fujieda, 1997). For most of our study watersheds, the deciduous forests are leafless about half the year and evapotranspiration is high only during the summer months (i.e., June, July, August, and September) (Patric, 1973). Therefore, it is during the summer when the differential role of vegetation on hydrologic response can be best evaluated because the snow season has ended and the effect of elevation on hydrologic response is negligible.

Vegetation is widely recognized as an indicator of climatic conditions within a watershed (Lacey and Grayson, 1998). In this study, the land use and land cover descriptors used are percent of forest land, percent of agricultural land, and percent of urban land of each watershed. In addition to land use type, we further classified forest cover into deciduous forest, mixed forest, and evergreen forest. Because deciduous forest is closely related to elevation, we hypothesized that the percent of deciduous forest cover of a watershed could be a useful predictor of watershed hydrologic response.

3.4 Geomorphologic Descriptors

Geomorphologic descriptors of each watershed were extracted from 30 m by 30 m grid resolution Digital Elevation Model (DEM) data. Geographic Information System tools, such as those available from the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) (USEPA, 1998) Modeling System and MicroDEM (Guth, 1989), were used to extract quantitative measures of geomorphologic descriptors from digital elevation model data obtained from the United States Geological Survey Website (http://edc.usgs.gov/geodata). For large watersheds, we merged several 1:24000 digital elevation model databases to achieve full coverage. The extracted topographic parameters were elevation (minimum, maximum, average, median, and standard deviation) and slope (maximum, average, median, and standard deviation) (Table 5). Other important geomorphologic descriptors extracted include stream network parameters such as total stream length, average channel slope, and main channel length. While most of the topographic parameters were directly measured, there were also a number of parameters calculated from the measured parameters. These calculated parameters included drainage density and relief ratio. A brief description of each geomorphologic descriptor and symbol was listed in Table 2.

3.4.1 Elevation Parameters

Table 5 displays the elevation parameter values extracted for each watershed; a brief description of each parameter is given in the following section. Note that some elevation parameters may not have any direct influence on hydrologic response, but can be useful for estimating other geomorphologic parameters.

Maximum elevation (HMAX). Maximum elevation of a basin is the highest watershed elevation. A high maximum elevation indicates the presence of mountain summits in the watershed. Although maximum elevation was used to estimate other parameters, such as basin relief and relief ratio, maximum elevation had very limited hydrologic significance.

Minimum elevation (HMIN). Minimum elevation is the lowest elevation point of a watershed. A low minimum elevation indicates the presence of low valley areas in a watershed. Although minimum elevation was used for the determination of basin relief and relief ratio, minimum elevation also had very limited hydrologic significance.

Table 5. Geomorphologic Descriptors of the Study Watersheds by Physiographic Province

Watershed	HMIN	HMAX	HAVG	HMED	HSTD	BREL	SMAX	SMED	SAVG	SSTD	HPC10
			Appalachian Plateau								
Lehigh	443	692	543	537	40	249	52	4	6	5	60
Towanda	235	745	495	470	120	510	1973	12	15	16	88
Pine	244	773	562	557	100	529	118	8	12	11	85
Blockhouse	314	722	541	540	79	407	110	15	21	16	83
GreenbrierD	826	1371	1067	1062	96	545	3564	26	27	33	88
GreenbrieB	633	1461	957	927	153	828	3909	27	30	86	80
GreenbrierA	470	1390	830	805	159	920	3830	27	28	79	78
			Ridge and Valley								
Wapwallopen	157	632	398	390	100	475	79	13	11	8	86
Marsh	195	669	397	372	115	474	60	12	14	10	78
Little Juniata	231	813	496	457	149	582	206	15	17	12	85
Sherman	115	694	310	264	127	579	103	16	18	15	75
Patterson	190	1070	404	353	147	880	140	19	20	13	58
South Branch	170	1490	618	595	252	872	430	23	27	16	70
Cacapon	170	1026	495	470	158	856	1910	17	21	36	70
Back	135	785	279	261	87	650	1143	13	16	35	48
NF Shenand.	327	1228	611	576	168	900	264	29	31	19	68
SF Shenand.	150	1321	468	392	182	1171	8575	12	21	115	55
Bullpasture	510	1335	801	766	151	825	161	24	26	16	75
			Blue Ridge								
Johns	430	1318	702	649	169	888	4087	23	25	20	73
Fishing	222	562	457	466	64	340	70	13	15	10	90
			Piedmont								
Owens	302	543	454	459	50	241	55	11	13	8	90
Deer	88	322	201	197	43	234	45	9	10	6	78
Hardware	95	726	207	182	83	531	820	10	14	18	45
Slate	72	340	156	150	33	274	80	6	9	6	56
Holiday	145	290	210	206	22	145	40	10	11	6	65

* Normalized elevation that corresponds to 1% of the normalized area on the hypsometric curve.

Average elevation (HAVG). The average elevation is the arithmetic mean of all the digital elevation model (DEM) data points within a watershed. The average elevation has important hydrologic and climatic influence because elevation influences soil, geology, vegetation, and microclimate of a watershed that, in turn, influence the hydrologic response. Average elevation is a reasonable measure of the overall watershed elevation, but it can be indirectly influenced by the presence of very low or very high elevation points.

Median elevation (HMED). The median elevation of a basin is that elevation where half of the watershed elevation data is higher and the other half is lower. Unlike average elevation, median elevation is more representative of the watershed elevation because it provides more information on the elevation distribution within a watershed.

Standard deviation of elevation (HSTD). The elevation standard deviation is a measure of the variability in watershed elevation. For example, Ridge and Valley watersheds usually have high standard deviations because the ridge areas are rugged with great elevation differences and the valley areas are nearly uniform (Table 5).

Basin relief (BREL). Basin relief is measured as the difference between the maximum and minimum watershed elevations. Normally, the lowest watershed elevation is found at the watershed outlet and the highest elevation is found in the headwater area. Basin relief is an indicator of the potential energy of the water being drained from the system (Bras, 1990). It is also highly correlated to drainage area and is an indicator of the overall watershed gradient. High relief may also indicate the presence of high elevation summits, thus high precipitation inputs and large recharge and discharge areas within a watershed (Farvolden, 1963).

Relief ratio (RRAT). The relief ratio is defined as basin relief divided by a representative basin length, usually selected as the distance between the furthest watershed boundary and the watershed outlet. Among the geomorphologic descriptors, relief ratio is often considered as a good predictor of the hydrologic response of a watershed.

3.4.2 Slope Parameters

The slope of a watershed determines the direction of flow and flow velocity, and controls soil erosion from hillslopes and channel areas. Some slope indices used to represent the slope of a watershed are given in Table 5. A brief description of each slope parameter is also given in the following.

Maximum slope (SMAX). Maximum slope is a measure of the greatest watershed slope. Watersheds with very high maximum slopes may indicate the presence of escarpments in the watershed. For example, watersheds in the Appalachian Plateau and the Ridge and Valley Provinces have very high maximum slopes (Table 5). Among our study watersheds, the South Branch Potomac, South Fork Shenandoah, North Fork Shenandoah, Greenbrier, Bullpasture, and Johns Creek all have very high maximum slopes. Because a maximum slope may correspond to a single point (e.g., an outlier), this parameter has very limited utility in predicting the hydrologic response of a watershed.

Average slope (SAVG). Average slope is the arithmetic average of the measured watershed slopes. It contains very limited information on slope distribution over a watershed since the presence of a few very high slopes or a few very low slopes can shift the average slope higher or lower.

Median slope (SMED). The median watershed slope is that slope value where 50 percent of the measured watershed slopes are higher and the other 50 percent are lower. Median slope is more representative than the average slope because it is based on the distribution of watershed slope values. Although it represents the overall slope of a watershed, it does not differentiate between hillslope and stream channel slope.

Standard deviation of slope (SSTD). The standard deviation of slope is the square root of the variance of all the measured watershed slopes. In general, watersheds with high slope standard deviation reflect rugged topography while watersheds with low standard deviation reflect watersheds with more uniform slopes.

3.4.3 Channel Network and Other Parameters

The landscape of a watershed normally consists of upland, hillslope, and channel segments. Channel parameter values extracted from the digital elevation model (DEM) databases include total channel length, main channel length, and main channel slope. A brief discussion of each channel parameter follows. Other geomorphologic descriptors, including drainage area, drainage density and hypsometric curve are also described. In addition, Figures 5, 6, 7, and 8 present color-coded digital elevation contours for four selected study watersheds. Figures 5 and 6 show Appalachian and Ridge and Valley watersheds with deeply dissected valleys and steep slopes whereas Figures 7 and 8 show Blue Ridge and Piedmont watersheds that have less dissected valleys and gently sloping hills.

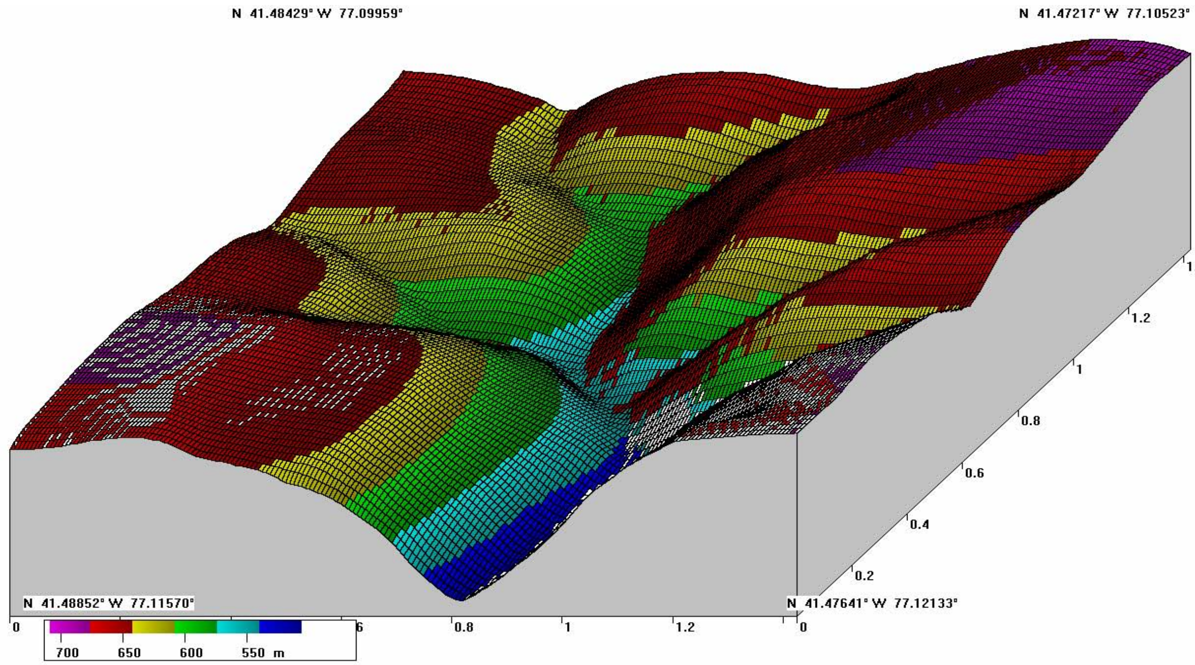


Figure 5. A color-coded digital elevation contour of a headwater stream of Blockhouse Creek in Pennsylvania showing geomorphologic features of the glaciated low plateau ecoregion (60a) of the Appalachian Plateau Province.

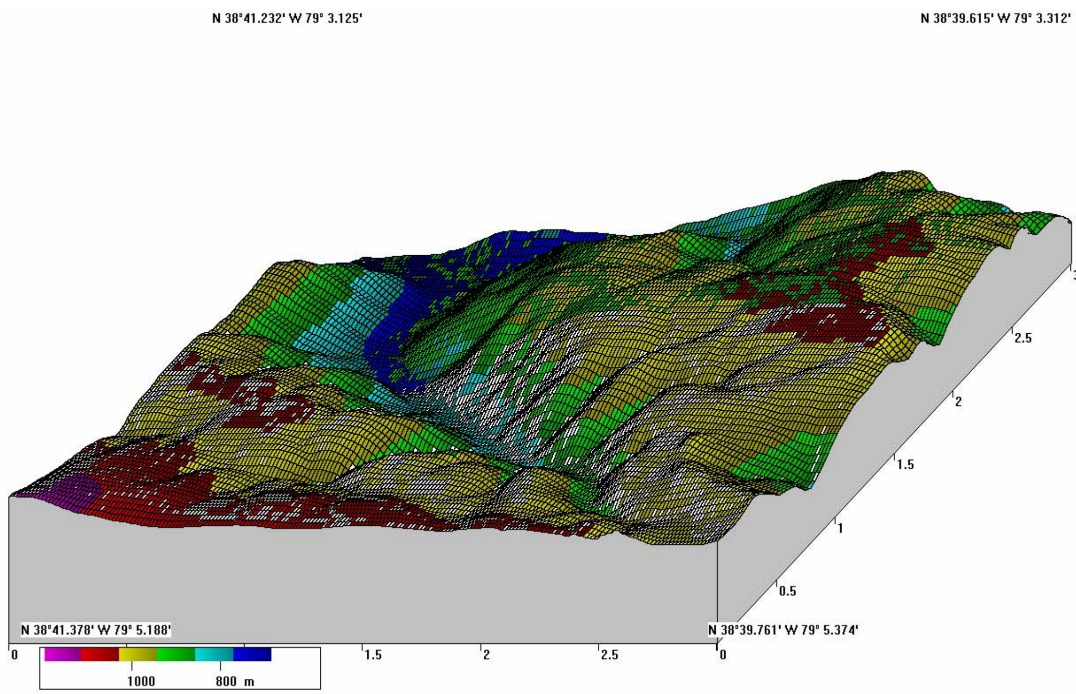


Figure 6. A color-coded digital elevation contour of a headwater stream of South Branch Potomac River in West Virginia showing geomorphologic features of the northern dissected ridges and valleys ecoregion (67d) of the Ridge and Valley Province.

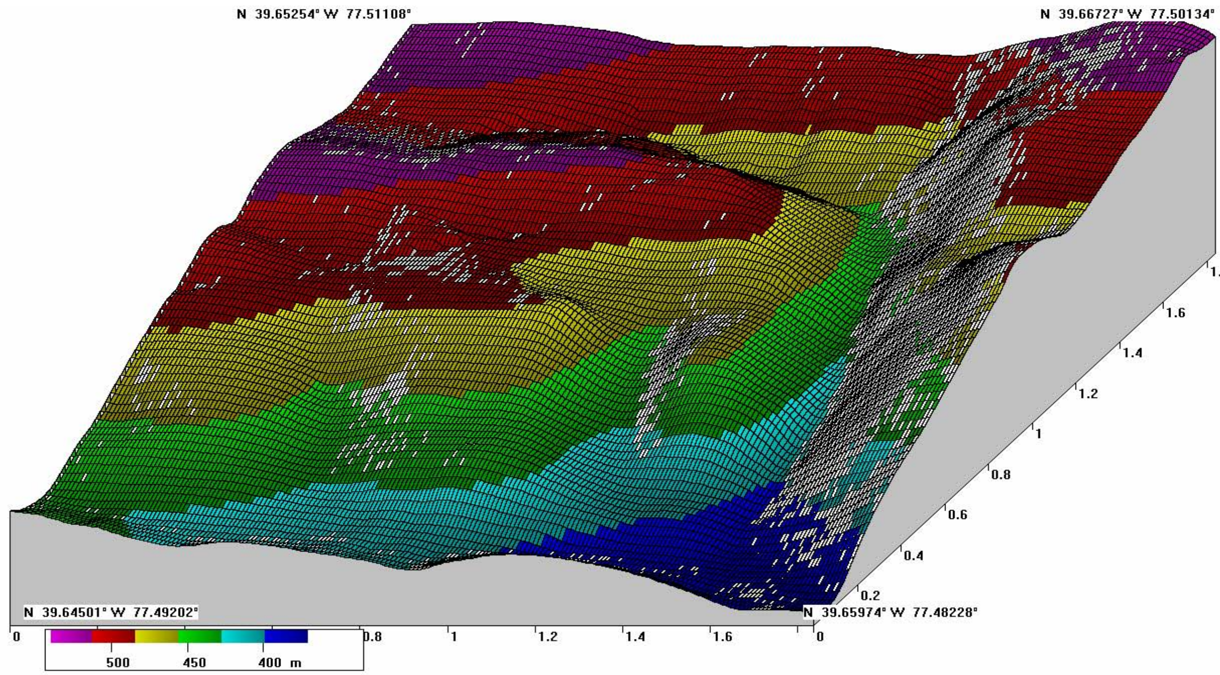


Figure 7. A color-coded digital elevation contour of a headwater stream of Owens Creek in Maryland showing geomorphologic features of northern igneous ridges ecoregion (66a) of the Blue Ridge Province.

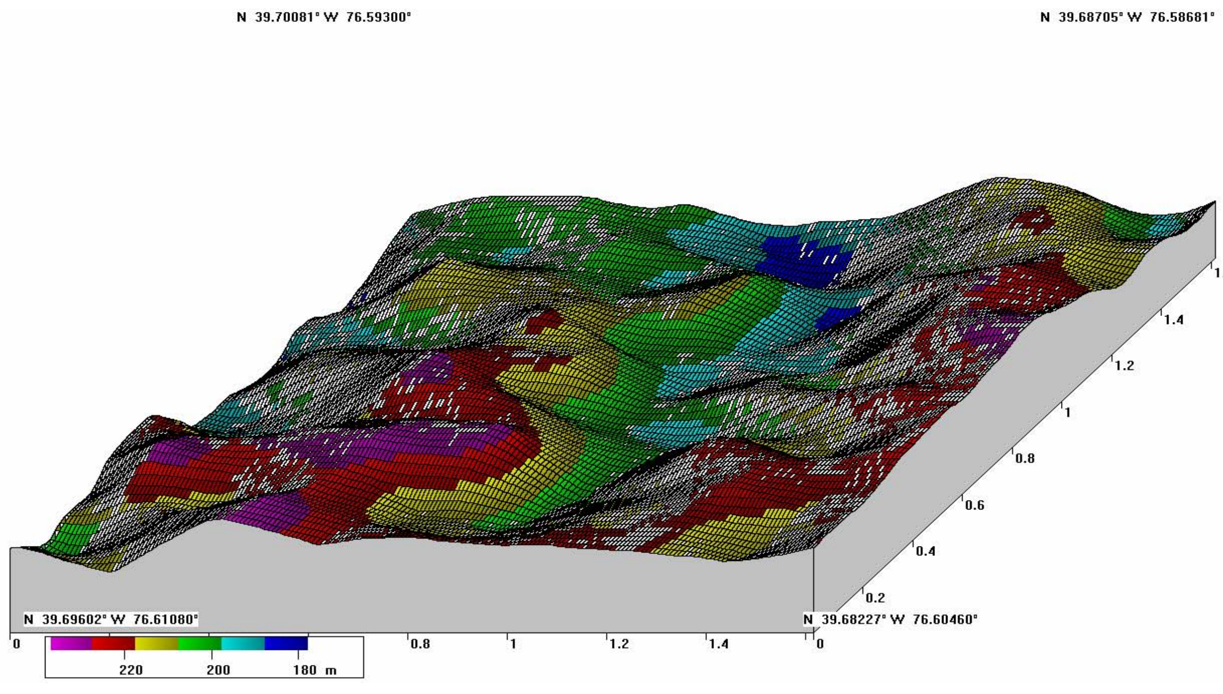


Figure 8. A color-coded digital elevation contour of a headwater stream of Deer Creek watershed in Maryland showing geomorphologic features of the Piedmont upland ecoregion (64c) of the Piedmont Province.

Main channel length (MCHL). Main channel length is the centerline length of the main channel of the watershed. It is the distance between where the channel begins at the headwater areas to the watershed outlet where the channel arbitrarily ends. Main channel length is closely correlated to drainage area and is an indicator of flow travel time. Channel length usually affects the shape of runoff hydrographs because large watersheds tend to have longer times of concentration, hydrographs with lower rising limb slope, and hydrographs with longer recession periods.

Main channel slope (MCHS). Main channel slope is a measure of the slope of the main stream channel. It is determined by subtracting the elevation at the watershed outlet from the elevation at the headwater end and then dividing the difference by the distance between the two points. Main channel slope also controls flow velocity and travel time.

Total Channel Length (TCHL). Total length of all the channels of a watershed is determined by adding the length of all the perennial channels within each watershed. In this study, we used Geographical Information System (GIS) tools to determine total channel length from data obtained from the National Hydrography Datasets at the website (http://nhd.usgs.gov/data.html).

Drainage area (DARE). Drainage area is the area of a watershed as determined from the topography of the surrounding watershed divide. The drainage area is an indicator widely used to develop relationships between watershed characteristics and hydrologic response variables (e.g., peak flow and/or low flow rates). Drainage area is a scale factor that introduces heterogeneity in landscape descriptors when watersheds have different drainage areas. Variable landscape descriptors would then introduce variability in hydrologic responses. When comparing hydrologic responses of watersheds with different drainage areas, normalizing the hydrologic response variable is often desirable. Normalization adjusts hydrologic response differences introduced by variability in watershed size. In this study, we normalized the hydrologic response variables by dividing the daily streamflow by the drainage area of each watershed (e.g., cfs/sq. mile).

Drainage density (DDEN). Drainage density is measured by dividing the total length of channels of the watershed by its total drainage area. Harlin (1984) reported that drainage density is related to time-to-hydrograph peak, but Berger and Enthekhabi (2001) and Dingman (1978) found no significant relationship between drainage density and hydrologic response variables. A high drainage density generally indicates a dense stream network throughout a watershed, whereas low drainage density indicates a sparse stream network and a watershed with large upland and hillslope areas relative to its channel areas. Drainage density has some influence on hydrologic response because it reflects the distance that water has to travel along a hillslope before reaching a nearby stream. A short hillslope length may not, however, lead to a short travel time because, in humid regions, subsurface flow is usually controlled by soil and geologic properties of the hillslope segments (Buttle and McDonald, 2002). Our hypothesis is that, over time, watershed systems have evolved into efficient water and sediment delivery systems and that their hydrologic response is well adjusted to the interactions between landscape descriptors (e.g., soil, bedrock geology, topography, and vegetation) and precipitation input characteristics of each watershed (Troch, 1995). In other words, as an efficient system, the watershed creates only the channel network needed to transfer the precipitation incident upon it to streamflow at the watershed outlet.

Hypsometric curve (HPC10): The hypsometric is an area-elevation relationship curve that plots normalized elevation against normalized area of a watershed (Langbein et al. 1947; Strahler, 1952). In this study, the normalized elevation of the hypsometric curve that corresponds to 10 percent of the normalized area was determined for each watershed and this point is shown in the watersheds plotted in Figure 9. The hypsometric curves shown in Figure 9 represent four physiographic provinces and watersheds with variable drainage areas. The hypsometric curves shown in Figure 9 illustrate watersheds with different levels of geomorphic maturity as influenced by various forcing factors such as tectonics, climate and lithology. The Owens Creek and the Blockhouse watersheds exhibit low geomorphic maturity level while the Deer Creek and South Branch Potomac watersheds exhibit high geomorphic maturity level.

3.4.4 Geomorphologic Descriptors as Potential Hydrologic Response Predictors

Dingman (1981) reported that, in the mountainous areas of New Hampshire and Vermont, an increase in elevation resulted in an increase in precipitation, and snow depth, snow water equivalents, and a decrease in temperature. Boyer (1984) also reported that most of the spatial variability of daily temperature means in the central Appalachian region can be accounted for by differences in elevation and latitude. Elevation, therefore, influences precipitation and temperature. Changes in precipitation and temperature then influence streamflow and evapotranspiration. As Dingman (1981) concluded, in the mountainous areas of Vermont and New Hampshire, elevation could be used as the single, independent variable for predicting streamflow.

Many researchers have reported the influence of the hypsometric curve on the hydrologic response of a watershed. Harlin (1984) concluded that the hypsometric curve characteristics might have some predictive power that can enhance rainfall-runoff modeling. Our hypothesis is that the HPC10 may be related to headwater drainage development, and that a high HPC10 value may be an indicator of a watershed that has a high headwater elevation. The shape of the hypsometric curve may be related to the shape of the longitudinal profile of the main stream channel of a watershed.

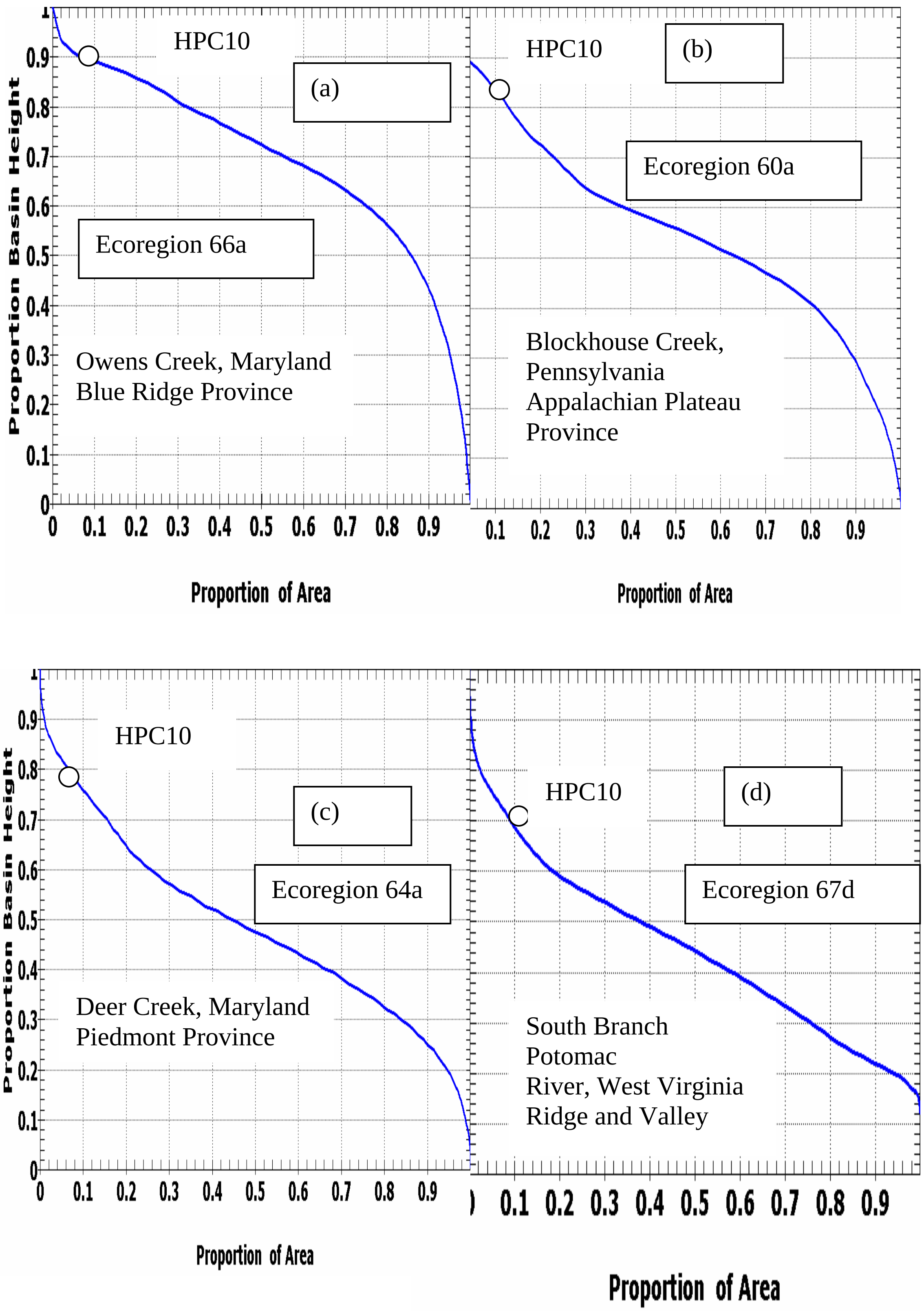


Figure 9. Hypsometric curves of four study watersheds arranged in the order of decreasing HPC10 ((a) having the highest HPC10 and (d) having the lowest HPC10).

Part II

4 Climate Characterization

The climate of the Mid-Atlantic Region is classified as humid to semi-humid continental because the region has relatively evenly distributed precipitation throughout the year and marked temperature contrasts between summer and winter. However, within the study area, both precipitation and temperature vary with elevation and latitudinal position. Elevation has a strong influence on the climate of the Mid-Atlantic Region. Specifically, the climate of the mountainous watersheds in the Appalachian Plateau, the Blue Ridge, and the ridge-dominated Ridge and Valley watersheds differs significantly from the climate of the Piedmont and the valley-dominated Ridge and Valley watersheds.

4.1 Precipitation

Table 6 presents mean annual precipitation, minimum January temperature, mean watershed elevation, and latitude and longitude of each study watershed. Mean annual precipitation of the study area ranges from 889 to 1207 mm (Table 6). In general, precipitation increases with elevation and even within a physiographic province, some watersheds, depending on their elevation, receive more precipitation than others. Among the four physiographic provinces of the study area, the valley-dominated Ridge and Valley watersheds have the lowest mean annual precipitation. Watersheds with high mean annual precipitation include the Greenbrier Watershed in West Virginia, the Little Juniata Watershed in Pennsylvania, and the Owens Creek Watershed in Maryland. These watersheds also receive more precipitation in the form of snow. Depending on their elevation, some watersheds may receive up to 30 % of their annual precipitation as snow.

4.2 Temperature

The mean annual temperature of the study watersheds varies across physiographic provinces. Within a physiographic province, temperature also varies with the elevation and latitudinal position of a watershed. The mean annual temperature of the study area ranged from 39 to 64^{o}F and the minimum temperature in January from 16 to 27 ^{o}F. The Appalachian Plateau watersheds had the lowest minimum January temperature while Piedmont watersheds had the highest (Table 6). Watersheds located in mountainous areas of the Appalachian Plateau, Ridge and Valley, and Blue Ridge Provinces usually have low temperatures. Where the temperature is relatively low, evapotranspiration may also be low and streamflow may be high. To the contrary, watersheds with relatively high temperature may exhibit high evapotranspiration and low streamflow. The Piedmont watersheds belong to the high temperature, high evapotranspiration, and low streamflow category.

Table 6.Long-term Mean Annual Precipiation, Minimum Januray Temperature, Mean Elevation, and Latitude and Longitude of Study Watersheds

Watershed	Mean annual Precipitation (mm)	Jan. minimum Temp. Deg F.	Mean Elevation meter a.s.l	Latitude degrees	Longitude degrees
Appalachian Plateaus					
Lehigh (AP)	1143	16	543	41:07:49N	075:37:33W
Towanda (AP)	970	18	495	41:42:25N	076:29:06W
Pine (AP)	1021	17	562	41:31:18N	077:26:52W
Blockhouse (AP)	1036	19	541	41:28:25N	077:13:52W
Greenbrier(AP)	1067	19	1103	38:32:37N	079:50:00W
Greenbrier (AP)	1067	19	957	38:11:09N	080:07:51W
Greenbrier (AP)	1041	20	830	37:43:27N	080:38:30W
Ridge and Valley					
Wapwallopen (RV)	1057	18	398	41:03:33N	076:05:38W
Marsh (RV)	970	21	397	41:03:34N	077:36:22W
Little Juniata (RV)	1123	19	496	40:36:45N	078:08:27W
Sherman (RV)	1077	23	310	40:19:24N	077:10:09W
Bullpasture (RV)	1018	22	801	38:11:43N	079:34:14W
Johns Creek (RV)	970	24	702	37:30:22N	080:06:25W
South Branch (RV)	889	20	618	39:26:49N	078:39:16W
Cacapon (RV)	914	22	495	39:34:43N	078:18:34W
Patterson (RV)	914	20	404	39:26:35N	078:49:20W
Back (RV)	991	23	279	39:30:43N	078:02:15W
S.F. Shenandoah (RV)	1057	24	468	38:54:50N	078:12:40W
N.F. Shenandoah (RV)	909	21	611	38:38:13N	078:51:11W
Blue Ridge					
Owens (BR)	1207	26	454	39:40:36N	077:27:50W
Fishing (BR)	1181	23	457	39:31:35N	077:28:00W
Piedmont					
Deer (PD)	1130	24	201	39:37:49N	076:24:13W
Hardware (PD)	1120	27	207	37:48:45N	078:27:20W
Slate (PD)	1072	27	156	37:42:10N	078:22:40W
Holiday (PD)	1054	27	210	37:24:55N	078:38:10W

4.3 Influence of Elevation on Climate and Hydrology

The elevation trend lines shown in Figure 10 illustrate an appropriately linear relationship between elevation and runoff ratio recorded in March and April. Since elevation influences temperature and precipitation (Dingman, 1981; Boyer, 1984), it also influences evapotranspiration and streamflow. For most of the study watersheds, March has the highest runoff ratio because, in March, the snow that accumulates during the winter melts and generates high streamflow. Figure 10 ranks the study watersheds in the order of increasing runoff ratio for March. The watersheds ranked toward the left side of Figure 10 had strong elevation influence, whereas the watersheds ranked toward the right side of Figure 10 had only limited elevation influence. For example, watersheds with high elevation or latitudinal position influence included the Towanda, Little

Juniata, Sherman, and the Greenbrier watersheds. Conversely, watersheds with low elevation influence were the four Piedmont watersheds shown on the right side of Figure 10. As the spring and summer seasons progressed, the influence of elevation on runoff ratio decreased until it became negligible in July, August, and September (Figure 10).

Because elevation has such a strong influence on hydrologic response, we hypothesize that elevation influences may dominate for most of the year except during the summer months. For some watersheds, the elevation influence may mask the influences of all the other landscape descriptors. To moderate the dominance of elevation influences over other landscape descriptors, i.e. soil descriptors, hydrologic response comparisons were also conducted during the summer months when the elevation influence was negligible (Figure 10). During the summer period, soil, vegetation, and geology influences on hydrologic response were less masked by the elevation effects.

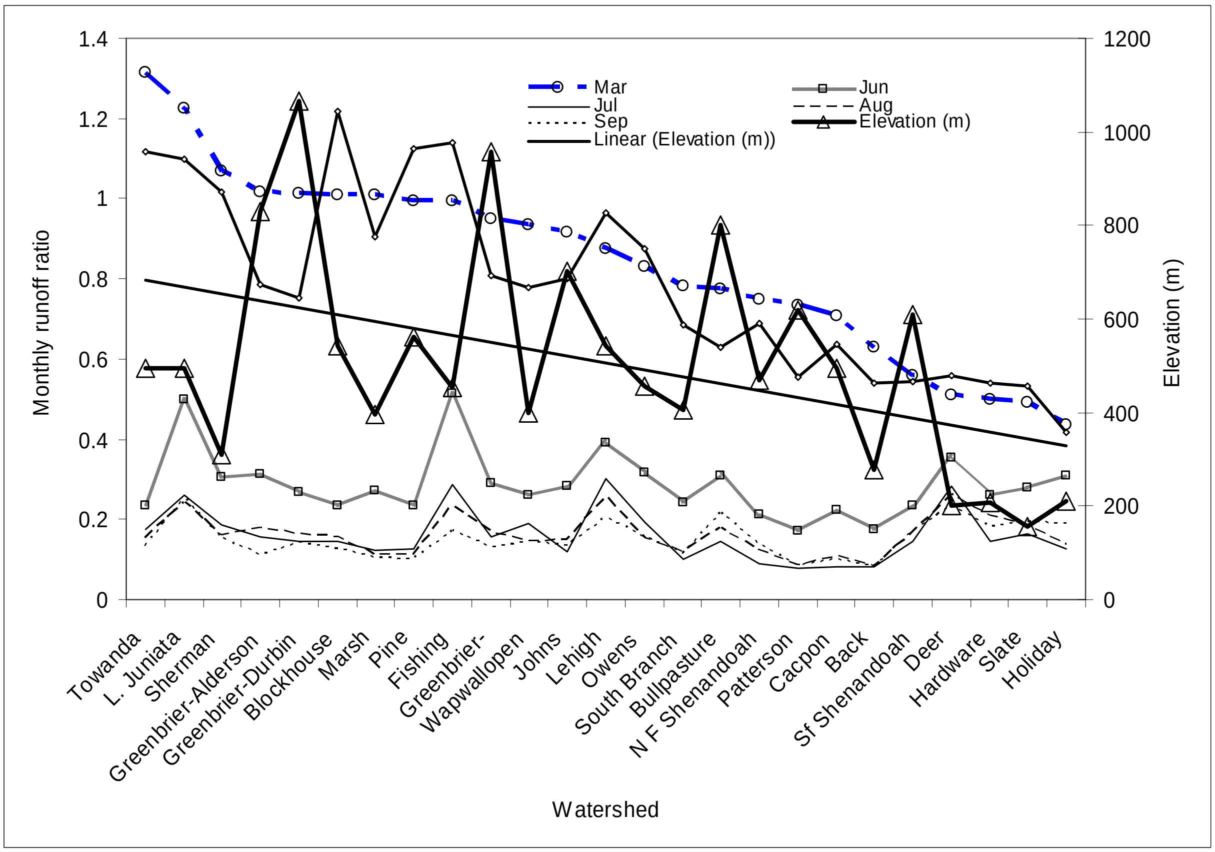


Figure 10. Influence of Elevation on Seasonal Streamflow Patterns.

4.4 Potential Climate Descriptors

To determine useful climate descriptors as predictors of hydrologic response, our approach was to evaluate a number of potential candidate climate descriptors that showed strong correlation with the hydrologic responses of the Mid-Atlantic watersheds. Among the candidate climate descriptors, dryness index seemed to have a strong correlation with hydrologic response descriptors. Indeed, Berger and Entekhabi (2001) had reported that wetness index, the inverse of the dryness index, was highly correlated to long-term hydrologic responses of selected basins. A large dryness index value is indicative of a relatively dry watershed while a small dryness index value reflects a relatively wet watershed. In other words, a watershed with high streamflow has a low dryness index value because the water saved due to reduced evapotranspiration becomes available for streamflow. Using stepwise regression analysis, the climate descriptors listed in Table 7 were tested and the potentially useful climate descriptors selected. Among the climate descriptors listed in Table 7, the dryness index (AET/PREC) and mean monthly rainfall depth showed the highest correlation with the watershed hydrologic response descriptors.

Table 7. Climate Descriptors Examined as Potential Hydrologic Response Descriptors

Variable	Description	Units
MAP	Mean annual precipitation	(mm)
MMP (e.g.,JULYPREC)	Mean monthly precipitation	(mm)
PET	Mean annual potential evapotranspiration	(mm)
AET	Mean annual Actual evapotranspiration	(mm)
PET/PREC	Mean annual dryness index (potential)	(mm/mm)
AET/PREC	Mean annual dryness Index (actual)	(mm/mm)

5 Hydrologic Response Characterization

To compare the hydrologic responses of the Mid-Atlantic watersheds, we employed a conceptual approach that is based on the water balance equation (Thornthwaite and Mather, 1955). This conceptual approach allowed comparison of streamflow, precipitation, and evapotranspiration of the study watersheds. To examine how the terms of the water balance equation vary over different time scales, we conducted comparisons of the watershed hydrologic responses at annual, monthly, and daily time scales. At the annual comparisons, we compared precipitation, streamflow, and actual evapotranspiration for all study watersheds. At the monthly and daily comparisons, however, we only compared the hydrologic responses of representative watersheds. For the hourly time scale comparisons, we did not use the water balance approach, rather we only did hydrograph comparisons for three representative watersheds.

5.1 Conceptual Approach: Water Balance as a Framework for Hydrologic Response Comparisons

The water balance equation is a fundamental hydrology equation that is valid across all spatial and temporal scales (Eagleson, 1978) Theoretically, the water balance equation should serve as the basis of all hydrologic models, but despite its sound theoretical basis, the water balance equation is not widely used in hydrologic models. What limits the widespread application of the water balance equation is the difficulty in measuring or estimating the terms of the water balance equation at different time scales. Figure 11 shows the inflows, outflows, and storage terms of the water balance equation for a small, headwater watershed. The water balance equation can be written in its simplest form as:

$$R = P - AET - \Delta S \qquad (1)$$

where,
R = Streamflow (controlled by climate, soil, geology, topography, and vegetation)
P = precipitation (climate),
AET = Actual evapotranspiration (climate, soil),
ΔS = Change in soil moisture storage (controlled by geology, climate, soil etc.).

The different terms of the water balance equation represent or are dominated by different hydrologic processes. Note that some terms of the water balance equation are more complex and are controlled by many descriptors while other terms are controlled by only one or two descriptors.

Because it is not always possible to estimate some terms of the water balance equation, hydrologists often make assumptions that enable them to ignore some of the terms. Some of the commonly used assumptions are those of no upstream surface and groundwater inflows, and no groundwater outflows. These latter assumptions eliminate all inflows and all outflows except streamflow. In other words, these assumptions are based on the hypothesis that watersheds are hydrologically “isolated”from surrounding watersheds. Another commonly made assumption is that, on a long-term basis, the average net change in soil moisture storage (ΔS) approaches zero.

Based on these assumptions, the change in soil moisture storage can be eliminated and the water balance equation can be written in a reduced form as:

$$R = P - AET \qquad (2)$$

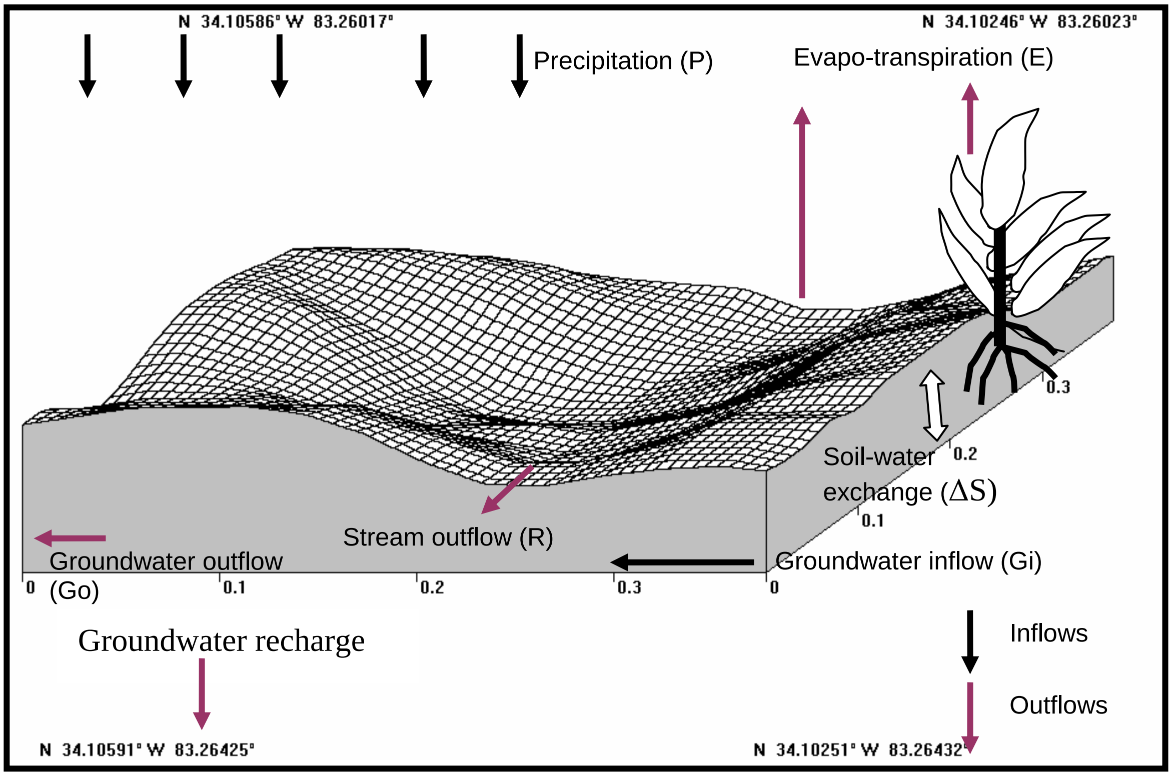


Figure 11. A Schematic Diagram Showing the Components of the Water Balance Equation for a Small Headwater Subwatershed.

5.2 Hydrologic Response Comparisons: Water Balance Approach

5.2.1 Precipitation Data

Daily precipitation was obtained from cooperative weather station databases archived by the National Climate Data Center (NCDC) in Ashville, NC. The station data closest to each watershed was used even if the station was located outside the watershed boundary. A principal term of the water balance equation, precipitation is often measured using a network of rain gages over a watershed. Although precipitation is a measured term, it is not measured at each point in a watershed. Lack of spatially distributed precipitation data over a watershed, therefore, introduces errors in the precipitation input term of the water balance equation.

5.2.2 Streamflow Data

Streamflow is another measured term of the water balance equation. It represents the watershed outflow term and is mainly influenced by the interactions between climate (precipitation and solar radiation) and landscape descriptors. Daily streamflow data was obtained from the USGS website: http://www.waterdata.usgs.gov. All study watersheds were included in the USGS's Hydroclimatic Data Network (HCDN) database (Slack and Landwehr, 1992). The HCDN dataset consists of good-quality hydrologic data compiled by the U.S. Geological Survey. These data had been recommended for climate change studies being compiled from watersheds that had long records of streamflow and from watersheds with limited human-induced disturbances. Most of our study watersheds have a high percent forest cover. To separate the measured total streamflow into its baseflow and stormflow components, computational baseflow separation techniques were used.

5.2.3 Evapotranspiration Data

Unlike precipitation and streamflow, evapotranspiration is not a measured term of the water balance equation. Evapotranspiration was estimated using evapotranspiration equations. Specifically, the daily potential evapotranspiration was estimated using a method developed by Hamon (1961) and later described by Federer and Lash (1978) and Vőrősmarty et al. (1998). The method uses measured daily minimum and maximum air temperatures, daytime length, and saturated vapor pressure. The WDMutil Software, part of USEPA's BASINS Modeling System, was used to calculate the potential evapotranspiration of our study watersheds using Hamon's Method. In addition to the potential evapotranspiration, the actual evapotranspiration (AET) was also estimated as the difference between precipitation and streamflow using Equation 2. Both estimated actual and potential evapotranspiration data were used to derive climate descriptors, such as the dryness index.

5.2.4 Moisture Storage Data

Measured soil moisture storage data are rarely available. The moisture storage term in the water balance equation is normally determined by solving the water balance equation after all the other terms had been either measured or estimated. Moisture storage is an important term of the water balance equation because it determines the fraction of precipitation input that returns to the atmosphere as evapotranspiration and the fraction of the precipitation input that leaves the watershed as both streamflow and groundwater. Landscape descriptors, particularly soil, geology, and vegetation, have strong influence on moisture storage. Lack of measured soil moisture storage data often limits the use of the water balance equation as a basis for hydrologic model development and testing.

5.3 Hydrologic Response Comparisons at Annual Time Scale

For long-term hydrologic response analysis, a three-term water balance equation (Equation 2) was used to estimate actual evapotranspiration as the difference between the measured values for precipitation and streamflow. The measured annual precipitation was apportioned into streamflow and actual evapotranspiration and, for each study watershed, dimensionless ratios (as percent) of streamflow to precipitation (runoff ratio) and precipitation to evapotranspiration (dryness index) were calculated (Table 8). For these calculations, the long-term mean annual precipitation and streamflow data were used. In general, all our study watersheds had comparable long-term mean annual precipitation values with an overall mean of about 1040 mm, with a range about that mean of 318 mm. The overall mean annual streamflow and estimated overall mean annual actual evapotranspiration of the study watersheds were 457 mm and 582 mm, respectively. This means that, on average, little more than half of the mean annual precipitation was evapotranspirated while little less than half of the precipitation became streamflow.

The dryness index is a climate descriptor that is highly correlated to hydrologic responses of a watershed. Comparisons of the dryness indices calculated for our study watersheds show that dryness index varies from province to province. For example, dryness indices of the Appalachian Plateau, Blue Ridge, Ridge and Valley, and Piedmont watersheds were 0.47, 0.49, 0.60, and 0.66, respectively. These comparisons indicate that 47 percent of the precipitation received by the Appalachian Plateau watersheds left as evapotranspiration, while 66 percent left from the Piedmont watersheds.

The average annual runoff ratios of the study watersheds also varied from province to province. The runoff ratios of the Appalachian Plateau, Blue Ridge, Ridge and Valley, and Piedmont watersheds were 0.53, 0.51, 0.40, and 0.34, respectively. These long-term hydrologic response comparisons indicate that 53 percent of the precipitation received by the Appalachian Plateau watersheds left as streamflow, while only 34 percent left from the Piedmont watersheds.

Table 8. Long-term Mean Annual Precipitation, Mean Annual Streamflow, Mean Actual Evapotranspiration Estimates, and Associated Ratios

Watershed	Precipitation (mm)	Streamflow (mm)	AET (mm)	Runoff Ratio %	Dryness Index %
Appalachian Plateau					
Lehigh River, PA	1143	691	452	60	40
Towanda River, PA	970	453	517	47	53
Pine River , PA	1021	483	538	47	53
Blockhouse Creek, PA	1036	517	519	50	50
Greenbrier River at Durban, WV	1067	686	381	66	34
Greenbrier River -Buckeye, WV	1067	574	493	54	46
Greenbrier River- Alderson, WV	1041	499	542	48	52
Ridge and Valley					
Wapwallopen Creek, PA	1057	509	548	48	52
Marsh Creek, PA	970	453	517	47	53
Little Juniata River, PA	1123	588	535	52	48
Sherman Creek, PA	1077	493	575	46	54
Bullpasture Creek, VA	1018	460	558	45	55
Johns Creek, VA	970	424	546	44	56
S. Branch Potomac River, WV	889	325	564	37	63
Cacapon River, WV	914	313	601	36	64
Patterson Creek, WV	914	269	645	29	71
Back River, VA	991	289	702	29	71
S.Fork Shenandoah River , VA	1057	327	730	31	69
N.Fork Shenandoah River, VA	909	330	579	36	64
Blue Ridge					
Owens Creek, MD	1207	632	575	52	48
Fishing Creek, MD	1181	591	590	50	50
Piedmont					
Deer Creek, MD	1130	448	682	40	60
Hardware Creek, VA	1120	395	725	35	65
Slate Creek, VA	1072	350	722	33	67
Holiday Creek, VA	1054	329	725	30	70

5.4 Hydrologic Response Comparisons at Monthly Time Scale

The annual hydrologic response comparisons presented in the preceding section revealed that streamflow varies across physiographic provinces (Table 8). To capture the variability in streamflow, i.e., hydrologic response across different physiographic provinces, we grouped the study watersheds into three categories: high, medium, and low streamflow. The high streamflow category mainly consisted of Appalachian Plateau watersheds whereas medium streamflow watersheds mainly consisted of Ridge and Valley watersheds and low streamflow watersheds mainly consisted of Piedmont watersheds. Note that some valley-dominated Ridge and Valley watersheds had lower annual streamflow than the Piedmont watersheds. To compare the hydrologic responses of the study watersheds at monthly time scales, we selected two representative watersheds from each streamflow category.

The representative watersheds for the high streamflow category were the Greenbrier Watershed in West Virginia and the Towanda Watershed in Pennsylvania. Both watersheds are located in the Appalachian Plateau, but within the high streamflow category, the Greenbrier Watershed represented a very high streamflow subcategory while the Towanda Watershed represented a relatively low streamflow subcategory. The two watersheds selected to represent the medium streamflow category were the Back River Watershed in West Virginia and the Little Juniata Watershed in Pennsylvania. Both these watersheds are located in the Ridge and Valley Physiographic Province, but within the overall medium flow category, these two watersheds represent a very high streamflow subcategory and a very low streamflow subcategory. The two watersheds selected to represent the low streamflow category were the Deer Creek Watershed in Maryland and the Slate Watershed in Virginia. Both these latter watersheds are located in the Piedmont Physiographic Province, but within the overall low streamflow category, these two watersheds represent a high streamflow subcategory and a low streamflow subcategory.

5.4.1 High Streamflow Category Comparisons

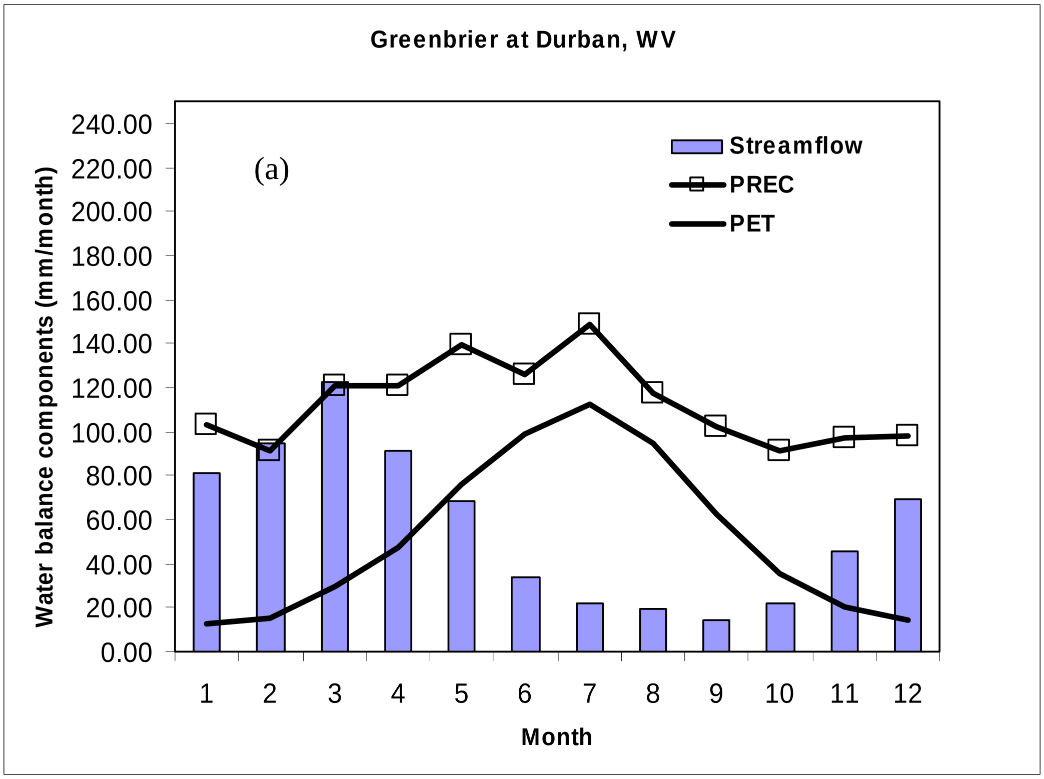
The Greenbrier Watershed represents the low evapotranspiration, high precipitation, and high streamflow watersheds in the Appalachian Plateau. The comparisons of water balance components at the monthly time scale illustrated that monthly precipitation exceeds monthly potential evapotranspiration throughout the year (PREC>>PET) (Figure 12a). Despite very high precipitation and relatively low evapotranspiration, it seems that the months with the highest precipitation did not usually result in the highest streamflow.

For most of the high streamflow watersheds, such as the Greenbrier Watershed, streamflow showed a high degree of variability. The highest streamflow occurred when snow melts in March. The lowest monthly streamflow occurred in September when snow influence no longer exists and when increased evapotranspiration results in depletion of soil moisture storage. Note that precipitation more than satisfies the evaporative demand of the atmosphere throughout the year and moisture storage deficit does not occur because potential evapotranspiration is always less than or equal to actual evapotranspiration.

Comparisons of water balance components of the two representative high flow category watersheds showed some contrasting differences. The two watersheds had almost equal mean monthly potential evapotranspiration of 53 mm, so most of the differences were due to differences in precipitation and streamflow. For instance, the Towanda watershed had 40 percent less mean monthly precipitation and 33 percent less mean monthly streamflow than the Greenbrier Watershed. Precipitation exceeded potential evapotranspiration in the Towanda Watershed for most the year, except in June, July, and August (Figure 12b). During the summer months, soil moisture storage was depleted by evapotranspiration that far exceeded the moisture that precipitation could replenish. As a result, unlike the Greenbrier Watershed where precipitation exceeded potential evapotranspiration throughout the year, the Towanda Watershed experienced a period of moisture storage deficit.

Differences in elevation may explain the differences between the precipitation inputs to the two watersheds. Because of their elevation and latitudinal position, both watersheds receive a large portion of their winter precipitation in the form of snow. The Greenbrier Watershed received 34 percent of its annual precipitation in February, March, and April with about 55 percent of its annual streamflow occurring in February, March, and April. The Towanda Watershed received 22 percent of its annual precipitation in February, March, and April, with about 47 percent of its annual streamflow occurring during these months.

For both watersheds, September was the month with the lowest streamflow. In general, moisture storage builds-up from October to March corresponding to a period of low evaporative demand. As the evaporative demand of the atmosphere increased, streamflow fell until it reached its lowest in September. The rate at which streamflow declined in late spring was somewhat proportional to the rate at which potential evapotranspiration increased during the same period. Streamflow recovered in October when evapotranspiration started to decrease and when moisture storage for the next season started to build-up.



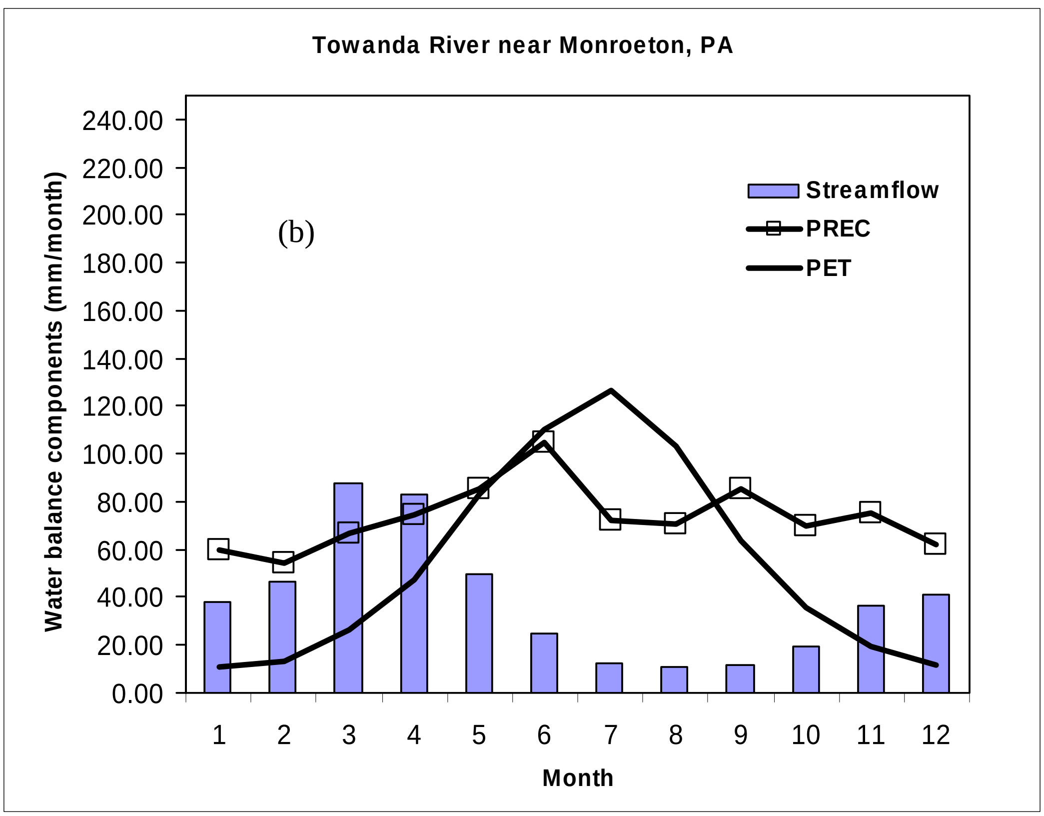
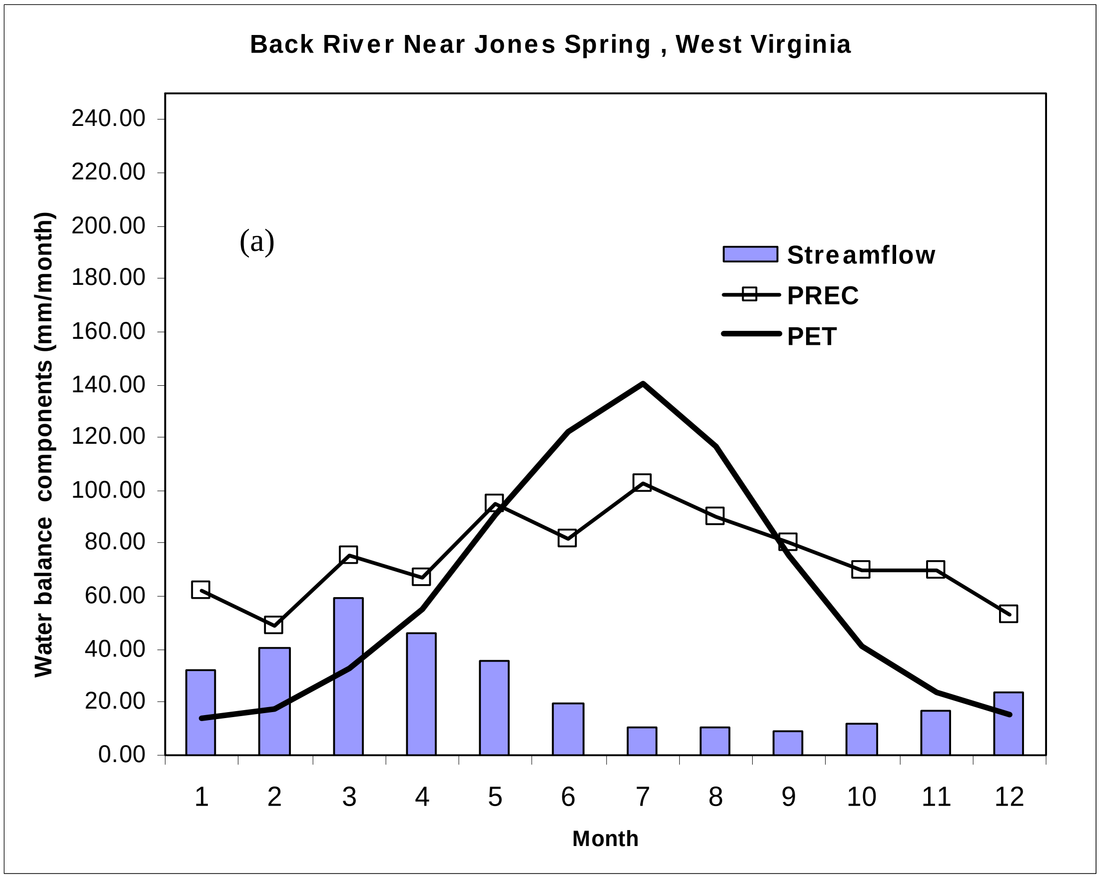


Figure 12. Monthly Water Balance Components of Two Appalachian Plateau Watersheds: (a) reenbrier Watershed and (b) the Towanda Watershed.

5.4.2 Medium Streamflow Category Comparisons

Two Ridge and Valley watersheds, the Back River and the Little Juniata, were selected to represent the medium streamflow hydrologic response category. The Back River and the Little Juniata watersheds represent valley-dominated and ridge-dominated watersheds of the Ridge and Valley Physiographic Province, respectively. Comparisons of the water balance components of these two watersheds are shown in Figures13a and 13b.

These two watersheds received comparable mean monthly precipitation and had nearly similar mean monthly potential evapotranspiration, but the monthly mean streamflows for the ridge-dominated watershed were about twice as high as those of the valley-dominated watershed. One explanation for the differences in mean monthly streamflow may be due to differences in the soil and groundwater storage characteristics of the two watersheds. It appears that the valley-dominated watershed stored less water than the ridge-dominated watershed. The reduced moisture storage capacity of the valley-dominated watershed may indicate that a large percentage of the monthly precipitation may be was lost as deep groundwater. Note that deep groundwater losses are not often measured as streamflow because deep groundwater losses may not resurface as baseflow at the watershed outlet. The valley-dominated watershed also had low elevation and received less precipitation in the form of snow than the ridge-dominated watershed. For both watersheds, the highest streamflow was observed in March, and both showed moisture storage deficit in July, August, and September when potential evapotranspiration exceeded precipitation (PET >> PREC).



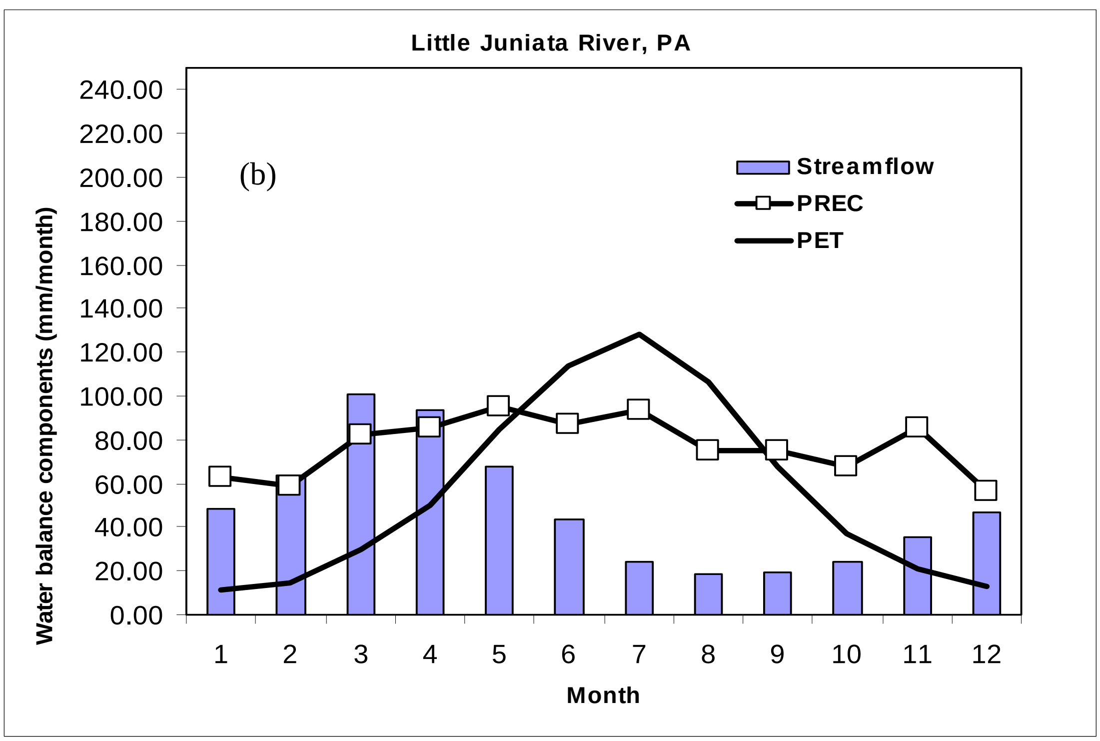


Figure 13. Monthly Water Balance Components of Two Ridge and Valley Watersheds: (a) Back River Watersheds, (b) Little Juniata Watershed.

5.4.3 Low Streamflow Category Comparisons

Figures 14a and 14b show water balance components of two Piedmont watersheds that represent the high evapotranspiration and low streamflow hydrologic response category. Comparisons of the monthly water balance components showed that the hydrologic responses of the Piedmont watersheds were very different from the hydrologic responses of watersheds located in other physiographic provinces. The reasons for these differences were elevation differences, proximity to the Atlantic Coast, and reduced snow accumulation. In comparison to the watersheds in other physiographic provinces, the Piedmont watersheds had less snow-generated streamflow in March and, had therefore, lower seasonal variability of streamflow.

In addition, the Piedmont watersheds also had evenly distributed precipitation and the availability of high soil moisture storage capacity. Among the physiographic provinces, watersheds in the Piedmont Province are characterized by low mean monthly streamflow, high potential evapotranspiration (PET>>PREC), and a long period of moisture deficit (May, June, July, and August). Comparison of the water balance components of the two Piedmont watersheds revealed that the Deer Creek Watershed in Maryland had 25 percent higher streamflow, 13 percent higher precipitation, and 69 percent higher potential evapotranspiration than the Slate Watershed.

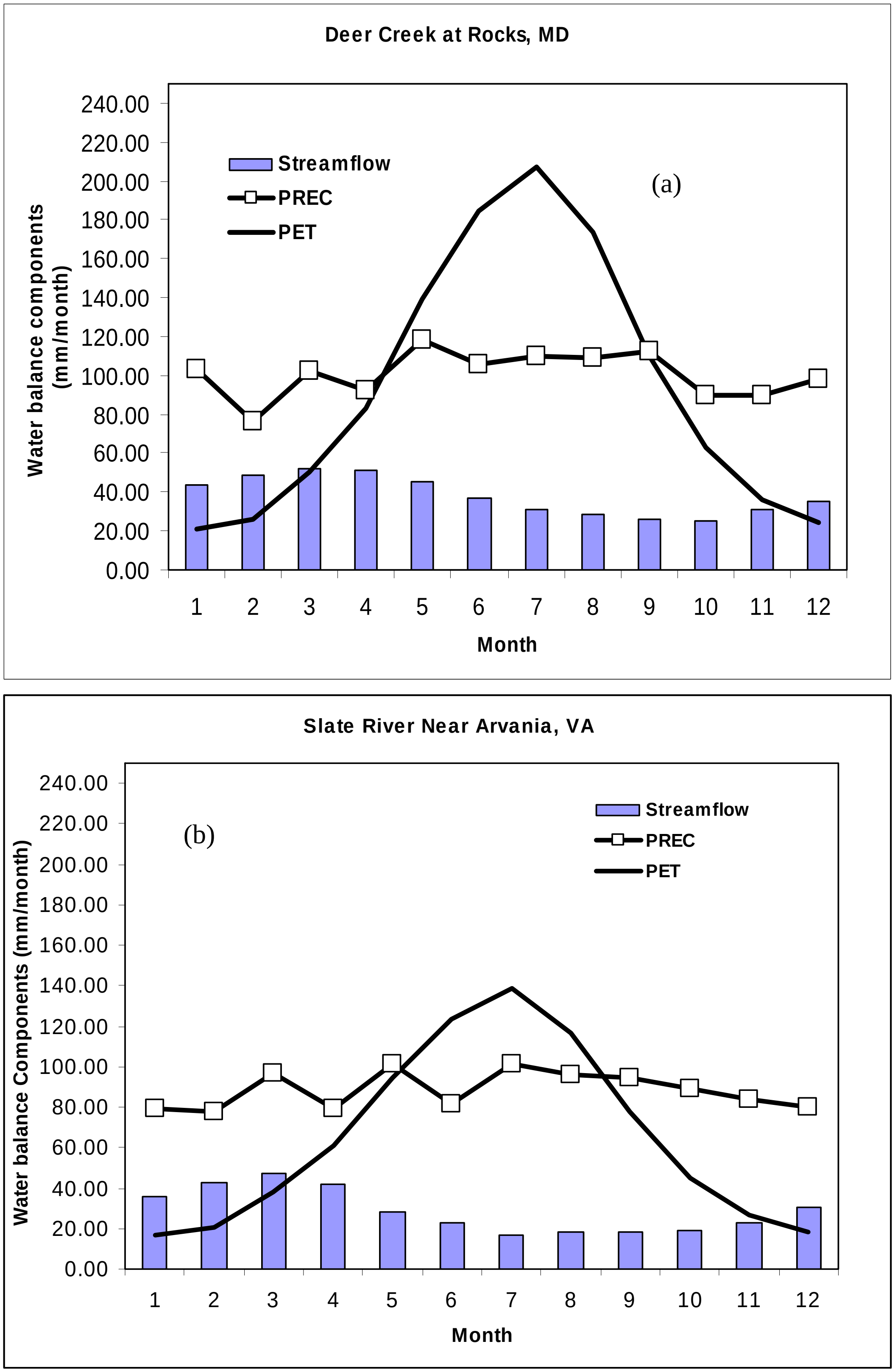


Figure 14. Monthly Water Balance Components of Two Piedmont Watersheds: (a) Deer Creek Watershed and (b) Slate Watershed.

5.5 Hydrologic Response Comparisons at Daily Time Scale

Water balance components at the daily time scale were made using three representative watersheds. The selected representative watersheds were the Blockhouse, the Patterson, and the Hardware Watershed, representing the Appalachian Plateau, Ridge and Valley, and the Piedmont Physiographic Provinces, respectively. Because of elevation influences on hydrologic responses during winter and spring seasons, daily water balance data for the months of July, August, and September was used to compare the hydrologic responses of the three representative watersheds. This period was selected for hydrologic response comparisons at the daily time scale. Note that hydrologic responses at the daily time scale had larger variability than the monthly and annual hydrologic responses. The main source of variability at the daily time scale was the variability associated with the temporal and the spatial distribution of daily rainfall and daily streamflow. Because of the random nature of precipitation occurrence, temporal variability in precipitation dominates the hydrologic response at the daily time scale.

The method used to analyze the components of the water balance equation at the daily time scale is based on the determination of dimensionless indices from daily precipitation, potential evapotranspiration, and streamflow. As shown in the hydrologic response analysis at the monthly scale, this period was almost free of elevation influences on streamflow and coincided the period when most of the watersheds experienced moisture deficit.

To eliminate any differences introduced by differences in drainage area, we converted daily rainfall, potential evapotranspiration, and streamflow into equivalent depth (e.g., mm/day). The Blockhouse, Patterson, and Hardware watersheds had 247, 295, 393 mm of rainfall during the selected three month comparison period. To obtain an average daily rainfall depth ($\overline{P}$) for the three-month period, we divided the sum of the rainfall amount observed over the three-month period by the number of days. The resulting average daily rainfall depth was then assigned to all the days including the rainy days. Using the average daily rainfall depth, the following indices were calculated for each representative watershed:

$$\text{PET} / \overline{PREC} = \text{Potential dryness index} \quad (3)$$

$$1-\overline{Q}/\overline{PREC} = \text{Mean actual dryness index} \quad (4)$$

$$\overline{PREC} - \text{PET} - \overline{Q} = \text{Change in storage} \quad (5)$$

The period selected to compare the water balance components at the daily time scale corresponds to the period when most of the study watersheds experience moisture deficits. The daily time scale comparisons showed more variability in the water balance components and provided more detailed hydrologic response comparisons of the three representative watersheds. The water balance terms of the three representative watersheds compared were potential dryness index, mean actual dryness index, and moisture storage as calculated by Equations 3, 4, and 5, respectively.

Potential dryness index comparisons showed that the Blockhouse and Patterson Creek watersheds had higher potential dryness index values than the Hardware Watershed (Figures 15, 16, and 17). Watersheds with high rainfall and low evapotranspiration are usually wetter and exhibit a low dryness index. For all three watersheds, the potential dryness index decreased as the season comparison progressed, the highest potential dryness index was observed in early July while the lowest was observed in September. This decrease in potential dryness index was mainly due to a decrease in temperature, resulting in a decrease in the potential evapotranspiration.

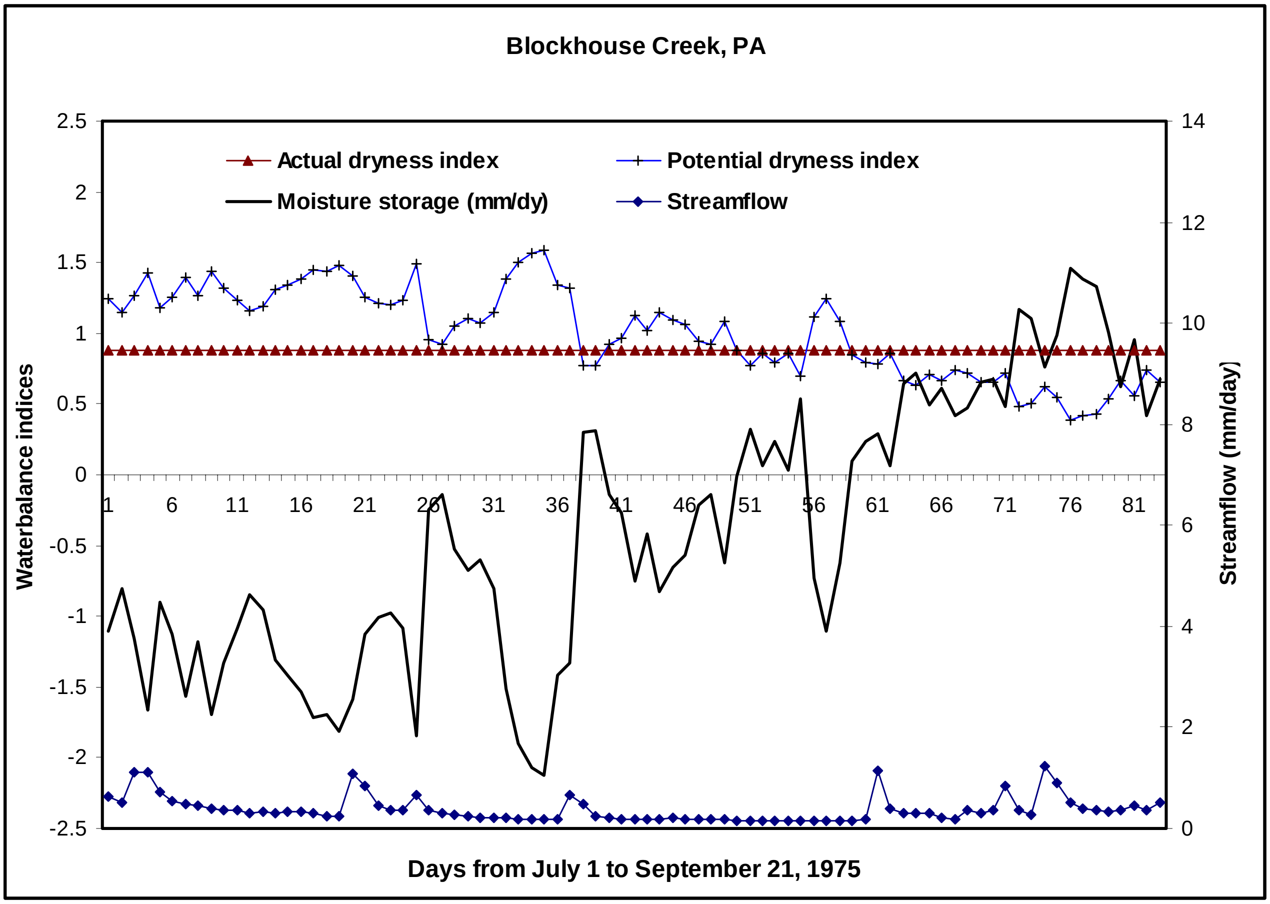


Figure 15. Comparisons of Water Balance Components of an Appalachian Watershed at Daily Time Scale.

As noted previously, the mean actual dryness index was calculated using Equation 4 that assumes zero net soil moisture storage. As a function of actual soil moisture storage, the mean actual dryness index was lower than the potential dryness index whenever a soil moisture storage deficit existed, was equal to the potential dryness index when soil moisture storage was equal to zero, and became higher than the potential dryness index as the soil moisture storage surplus increased.

In summary, a soil storage surplus occurred whenever the potential dryness index was less than the mean actual dryness index. The difference between potential dryness index and mean actual dryness index reflects the amount of moisture deficit or moisture surplus in a watershed. Among the three representative watersheds, the potential dryness index of the Hardware Watershed was nearly equal to the mean actual dryness index throughout the comparison period. When the potential dryness index is nearly equal to the mean actual dryness index line, soil moisture storage is nearly zero and potential evapotranspiration is nearly equal to the actual evapotranspiration. For the Blockhouse and Patterson watersheds, the potential dryness index was greater than the mean actual dryness index during the early part of the comparison season, and was lower than the mean actual dryness index at the end of the three-month season.

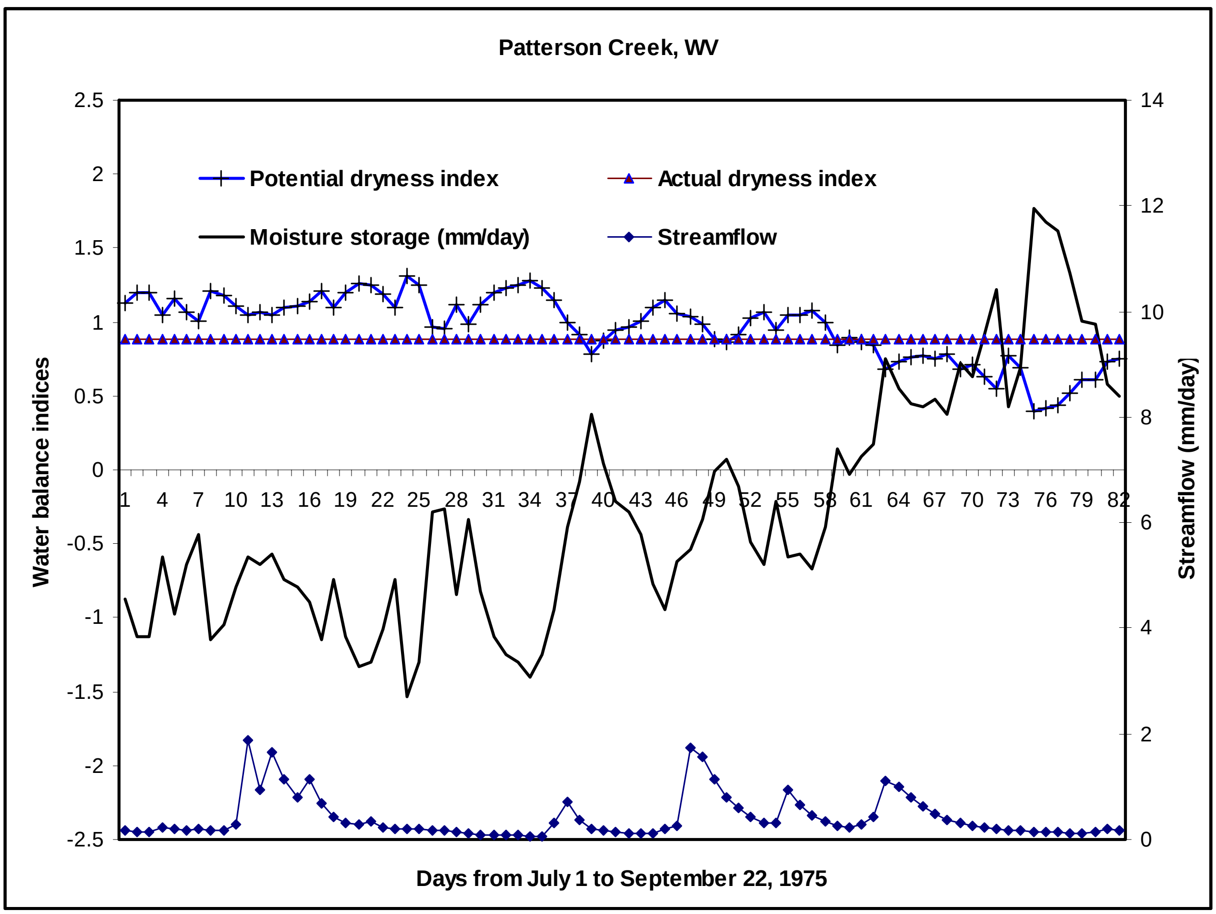


Figure 16. Comparisons of Hydrologic Response of a Ridge and Valley Watershed at the Daily Time Scale

Comparisons of the estimated soil moisture storages of the three representative watersheds showed that the Hardware watershed of the Piedmont Physiographic Province generally exhibited high moisture storage. Moisture storage comparisons also revealed some useful insights about the storage characteristics of the three watersheds. For example, the Hardware Watershed not only had high storage capacity but also a controlled storage release mechanism. As a result, the streamflow of this Piedmont watershed rarely declined to low levels because streamflow was sustained by release of moisture stored in the soil regolith. By comparison, the Blockhouse Watershed of the Appalachian Plateau Province and the Patterson Creek of the valley-dominated Ridge and Valley Province watersheds, had low soil moisture storage. In general, those watersheds with high soil moisture storage capacity maintained sustained low flows during the summer when potential evapotranspiration exceeded precipitation (PREC< PET).

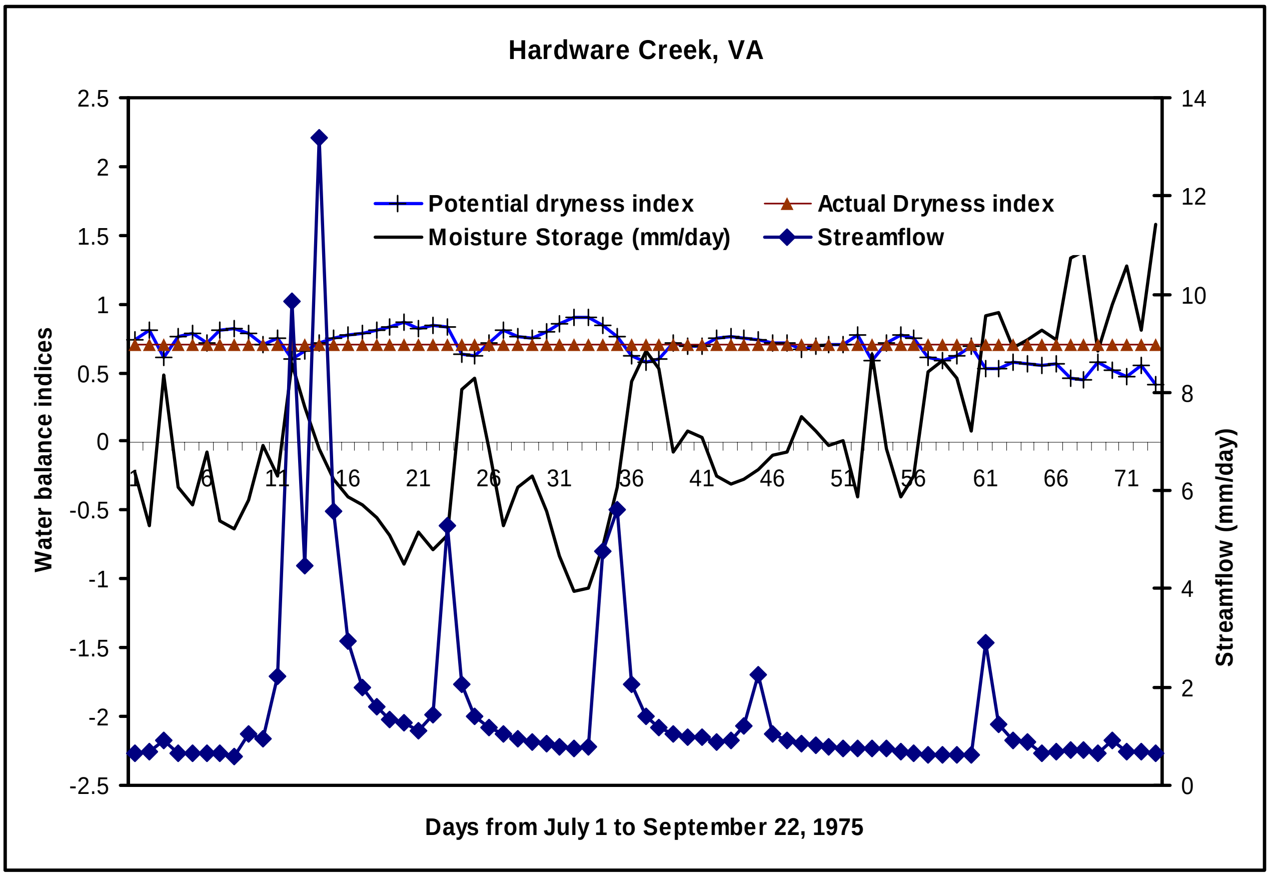


Figure 17. Comparisons of Water Balance Components of a Piedmont Watershed at the Daily Time Scale

5.6 Hydrologic Response Comparisons at the Hourly Time Scale

At the hourly time scale, the water balance components were highly variable and comparisons made at the hourly scale may not be meaningful. As a result, hourly water balance comparisons were not made, but hydrograph comparisons were made. The volume of the runoff hydrograph is influenced by the drainage area of the watershed, initial moisture storage condition, and the characteristics of the storm event. Watersheds with large drainage areas tend to have large runoff volumes - assuming similar precipitation inputs and antecedent soil moisture conditions. To compare hydrographs of watersheds with different drainage areas at the hourly time scale, the hourly streamflow data was converted to equivalent depth (mm/day).

Because the three watersheds received rainfall with different characteristics, the watersheds showed runoff hydrographs that had different hourly peak flows. To adjust for differences in hydrograph peak flows, we divided all hourly streamflow data by the highest hourly peak flow depth. Figure 18 plots the logarithm of standardized streamflows of the three hydrographs adjusted to a unit peak flow depth versus time for the last 13 days of the comparison period.

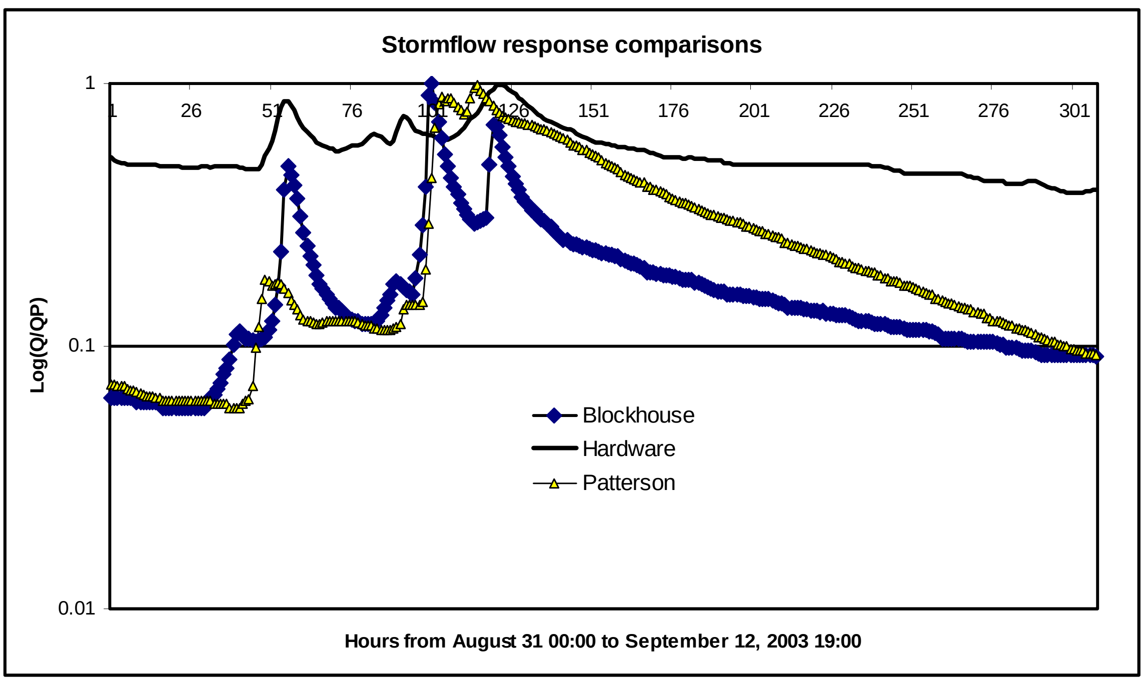


Figure 18. Comparisons of Standardized Hourly Runoff Hydrographs

Comparisons of the adjusted hydrographs (Figure 18) showed that the Hardware Watershed generally had higher and relatively consistent adjusted streamflow than the other two watersheds. When adjusted, the Blockhouse and the Patterson Creek Watersheds seemed to have similar streamflows, both more variable than that of the Hardware Watershed. Figure 18 also shows the recession curves of the three representative watersheds. For the Piedmont Watershed, the recession curve remained steady with almost zero slope; for the Appalachian Plateau watershed, however, the recession curve decreased sharply soon after the rainfall ended and then decreased slowly with relatively flat slope. Unlike the other watersheds, the Ridge and Valley watershed had a recession curve that declined steadily during the recession period.

The shape of the three recession curves may provide some valuable information about the storage and release properties of the soil and geology of the representative watersheds. As the recession curve indicated, the Piedmont watershed had adequate soil moisture storage that could be released to maintain streamflow during non-rainy days. By contrast, the recession curve of the Patterson Creek Watershed indicated that available soil moisture storage could not sustain streamflow during non-rainy days. That is to say the recession curve showed that storage releases were constantly decreasing with time and could not, therefore, maintain sustained low flows. The Blockhouse Watershed behaved as if it had two distinct storage compartments. The first compartment may constitute a fast release of water stored in the area near the stream channels at the end of a rainfall event. After releases from this first compartment have ended, releases from the second soil moisture storage compartment are low and can only maintain a very low streamflow.

Part III

6 Hydrologic Response Prediction

To develop relationships between landscape-climate descriptors and hydrologic response descriptors, one must first identify and quantify the key descriptors that can represent landscape, climate, and hydrologic response. A major challenge in hydrologic response comparison studies at different watershed scales is how to identify hydrologic response variables that can represent a wide range of hydrologic conditions. In an effort to identify hydrologic response descriptors that can represent high, medium, and low flows, we evaluated several potential hydrologic response variables, such as mean, minimum and maximum flow. We ultimately selected the flow duration curves as the most suitable hydrologic response descriptor because the flow duration curve (FDC) synthesizes a lot of information on hydrologic response of a watershed (Bonta and Cleland, 2003).

Flow duration curves cover a wide range of flow conditions and provide valuable information about streamflow variability over time (Smakhtin, 2001). The FDC synthesizes complex and long-term records of time series streamflow data as a graphical display that illustrates the relationship between flow magnitude and the frequency that is associated with each magnitude. Flow duration curves are continuous, but to represent them herein we selected only 10 discrete points on the curve. These 10 points are the normalized streamflow values (cfs/mi^2) that correspond to the 1, 5, 10, 20, 30, 40, 50, 70, 90, and 95 percent exceedance probabilities. We denoted these 10 points on the flow duration curve as flow duration indices (FDIs). These points define the shape of the flow duration curve and characterize a wide range of flow conditions that include both high frequency low flows (Q95) and low frequency very high flows (Q1) (Figure 19). Throughout this report, we denote these 10 points as flow duration indices (FDIs) that represent the hydrologic responses of a watershed.

Unlike other hydrologic response descriptors such as mean, minimum and maximum flows, the flow duration indices (FDIs) represent a wide range of hydrologic responses. For example, Q1 corresponds to a very high flow (flood condition), whereas Q5 and Q10 indices correspond to high flows that are equaled or exceeded only 5 percent and 10 percent of the time, respectively. Flows that correspond to Q20, Q30, Q40, and Q50 FDIs are considered as medium flows, equaled or exceeded 20, 30, 40 and 50 percent of the time, respectively. Likewise, flows that correspond to Q70, Q90 and Q95 indices are low flows, equaled or exceeded 70, 90 and 95 percent of the time, respectively.

FDCs graphically illustrate the percent of time during which a streamflow value is equaled or exceeded over a given period of observation. A number of other investigators have reviewed the application of FDCs for water resources management and planning (Searcy, 1959; Vogel and Fennessey, 1994, and Smakhtin, 2001). Searcy (1959) provided a summary of FDC applications that includes an analysis of the relationship between flow duration curve shape and watershed geology, hydropower, and water quality issues. Recently, Vogel and Fennessey (1994) reviewed FDC use and presented a number of applications that included water resources management and wasteload allocations. Smakhtin (2001) also reviewed low flow hydrology and stated that flow duration curves are one of the most informative methods of displaying the complete range of streamflow conditions - from low flows to high flows. FDCs have also been used for the determination of wastewater treatment plant capacity (Male and Ogawa, 1984), hydropower feasibility studies (Warwick, 1984), estimation of optimal reservoir release schedules (Alouze 1991), design of flow diversions (Pitman, 1993), assessment of in-stream flow requirements for river habitats, and calibration of rainfall-runoff models (Gustard and Wesselink, 1993).

When observed streamflow data is available, the FDC can be determined therefrom. The problem is that observed streamflow is not always available because many small watersheds are ungaged. Managing ungaged watersheds is a problem for environmental planners and resource managers who often need these data to make sound resource management decisions. FDCs have been used to predict streamflow for ungaged watersheds. Because FDCs have important water resources management applications, in recent years, there has been a renewed interest in predicting FDCs for ungaged watersheds (Croker et al. 2003). Yu et al. (2002) presented a new method to predict FDCs from annual rainfall, altitude, and drainage area. Dingman and Lawlor (1995) predicted annual minimum seven-day average flow (7Q) for ungaged and unregulated drainage basins in New Hampshire and Vermont from drainage area, elevation, and percent of watershed covered by sand and gravel deposits.

One of the key objectives of this study is to identify suitable hydrologic response descriptors and then develop relationships between the landscape-climate descriptors and the selected hydrologic response descriptors (flow duration indices). Once the relationships between the landscape-climate descriptors and the flow duration indices are developed in the form of regression equations, these regression equations can be used to predict flow duration curves and streamflow for ungaged watersheds.

6.1 Approach

Spatial scale has strong influence on watershed hydrology because streamflow rate increases with an increase in drainage area. When comparing watersheds with different drainage areas, it is necessary to eliminate the effect of spatial scale (drainage area) on streamflow by dividing the daily streamflow values by the drainage area of each watershed (cfs/sq.mile). After normalization, the normalized daily streamflow data (cfs/sq. mile) was used to generate the flow duration curves.

Using the normalized streamflow, we conducted a multivariate analysis to discover relationships between landscape-climate descriptors and the hydrologic response descriptors (flow duration indices). Note that the normalized streamflow data that correspond to the 10 flow duration indices represent the dependent variables in the multiple regression equation while the landscape and climate descriptors represent the independent variables. A large number of quantitative landscape and climate descriptors were examined. The landscape-climate descriptors represented climate (e.g., precipitation and climate-related dimensionless indices), soil (e.g., saturated hydraulic conductivity, soil depth, and texture, etc.), geology (e.g., baseflow index), land use and land cover (percent of deciduous forest cover), and topography (e.g., elevation and slope parameters). Factor analysis and correlation analysis were used to reduce the number of landscape and climate descriptors. These analyses identified landscape and climate descriptors that were further evaluated to develop relationships between the landscape-climate descriptors and hydrologic response descriptors using a stepwise regression analysis.

Two periods of record were selected to generate flow duration curves for all our study watersheds. The two periods represented two time scales: a long period of record, based on 21 years (1980 to 2000) of daily streamflow data, and a short period of record, based on a single year (October 1974 to September 1975) of streamflow data. Throughout this report, we refer to the 21-year period as the long period of record or the composite flow duration curve period and the one-year period as the single year period. The 21-year indices are also based on regional scale data aggregation while the one-year indices are based on physiographic province spatial scale data aggregation.

Flow duration curves based on a long period of record are suitable for the determination of low flow indices that can be used for establishing ecological flow requirements as well as for establishing high flow indices that can be used for assessing the risk of flooding. In summary, FDCs that are based on a long period of record may be suitable for water resources management while FDCs based on a single year record are more suitable for hydrologic modeling applications.

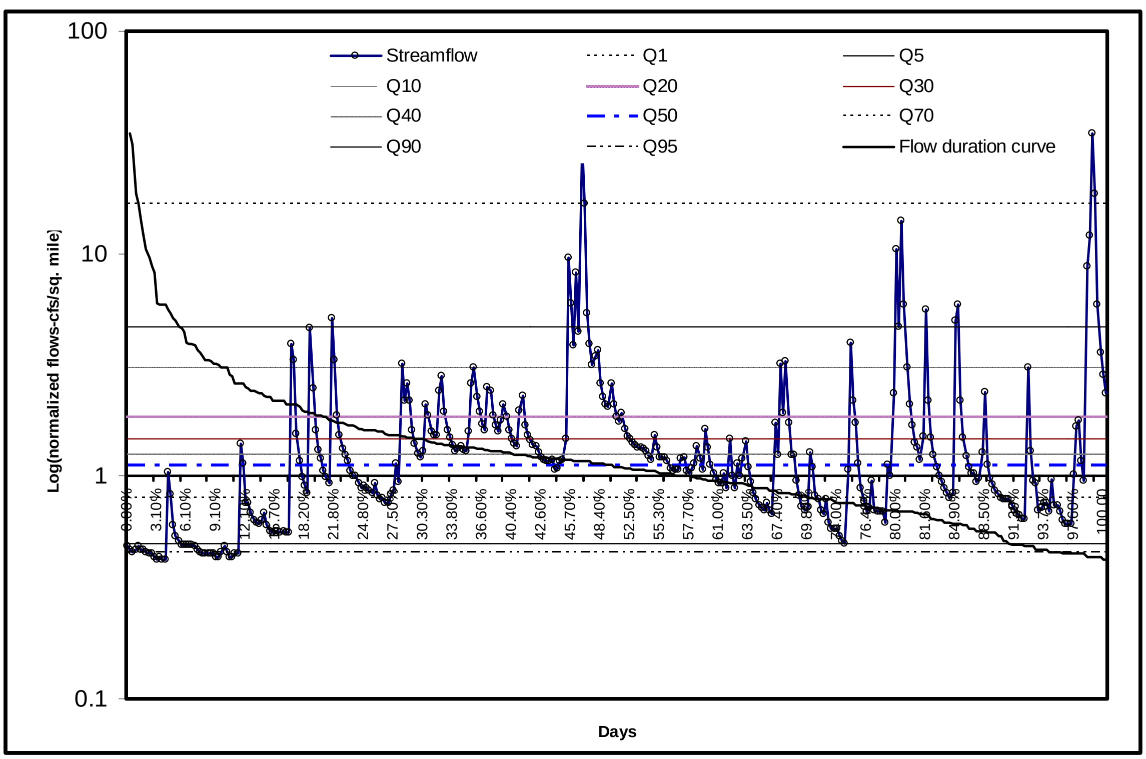


Figure 19. A One-year Flow Duration Curve Showing Lines that Represent the 10 Flow Duration Indices (FDIs) and Normalized Daily Streamflow Data.

Figure 19 illustrates the relationship among the daily streamflow, the flow duration curve and the 10 flow duration indices. Note that each flow duration index line intersects both the streamflow time series and the flow duration curve. The intersection points represent the magnitude of each flow duration index. These intersection points are useful when reconstructing a flow duration curve from the 10 flow duration indices. The intersection points between the flow duration indices and the streamflow time series curve link the flow duration indices to the actual streamflow data. For example, the Q1 index line crosses only the peaks of the two highest daily streamflow hydrographs while the Q5 index line crosses a number of smaller peak flow hydrographs and both the rising and recession limbs of some high flow hydrographs.

This approach determines 10 flow duration indices (Q1 to Q95) as a function of the landscape-climate descriptors. These predicted flow duration indices (Q1 to Q95) can then be used to reconstruct the entire flow duration curve. After the flow duration curve is reconstructed, then the normalized flow duration curve is converted to streamflow rates by multiplying the values by the drainage area of the watershed. This approach is proposed for the prediction of streamflow for ungaged watersheds where lack of data currently restricts the use of physically-based hydrologic models.

6.2 Comparisons of Hydrologic Responses at the Regional Scale

The hydrologic response of a watershed may not be adequately defined by a single response descriptor such as mean flow, but can be defined by the10 flow duration indices because these indices cover a wide range of flow conditions that include very high, high, medium, low, and very low flows (Figure 19). To compare the hydrologic responses across the Mid-Atlantic Region, we grouped the 10 flow duration indices into three categories that represented high flow (Q1, Q5, Q10, Q20), medium flow (Q30, Q40, Q50), and low flow conditions (Q70, Q70, Q95). The hydrologic responses of the study watersheds were then compared by ranking the study watersheds in the order of increasing high flow represented by the Q5 index, medium flow represented by the Q50 index, and low flow represented by the Q95 index.

Some FDIs, such as the Q5 and Q10, were highly correlated to each other, and watersheds that had high Q5 index also had high Q10 and Q20 indices. Figure 20 displays the study watersheds ranked in the order of increasing Q5 index. Note that the Q5 index corresponds to the normalized streamflow value that is equaled or exceeded only 5 percent of the time. The Q5 rankings showed that the study watersheds seem to follow the physiographic province arrangement. Among the study watersheds, the Appalachian Plateau and Blue Ridge watersheds had relatively high Q5 indices followed by the ridge-dominated Ridge and Valley watersheds. Figure 20 also shows that the Piedmont and valley-dominated watersheds had the lowest Q5 indices. Because Q5 index does not represent rare flood events that are highly dependent on rainfall characteristics, watersheds with high Q5 indices may have soils with low infiltration capacity while, on the other hand, watersheds that have low Q5 index have soils with high infiltration capacity (Cole et al. 2003). We hypothesized that the Q5 index was a good indicator of the dominant runoff mechanisms of a watershed and that watersheds, with high Q5 indices had higher surface runoff components than watersheds with low Q5 indices.

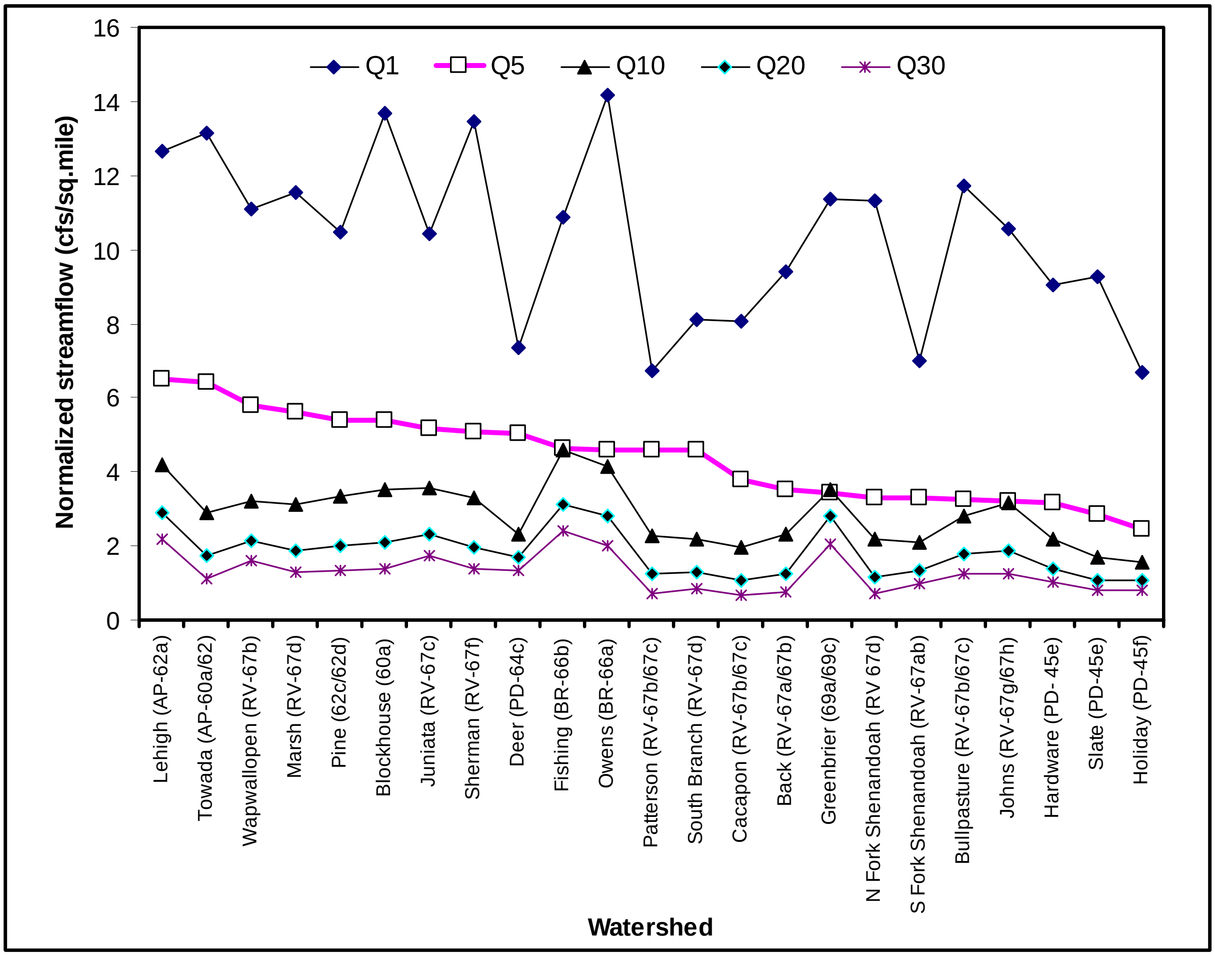


Figure 20. Comparisons of Hydrologic Responses Across Study Watersheds Using the Q5 Index.

Comparisons of the hydrologic responses of the study watersheds at medium flow conditions are given in Figure 21. To see how different watersheds compare at medium flow conditions, we ranked the study watersheds in the order of increasing median flow, i.e., Q50 index. The Q50 index rankings do not follow the physiographic province arrangement. When compared to the Q5 index rankings, the Q50 index rankings show a slight shift in the order of arrangement of the watersheds. It appears that, as a group, the two Blue Ridge watersheds had the highest medium flows, followed by the Appalachian Plateau, and the ridge-dominated Ridge and Valley watersheds. The valley-dominated Ridge and Valley watersheds had the lowest Q50 indices. It is interesting to note that most of the Piedmont watersheds also have low Q50 indices. This implies that, most of the time, the Piedmont watersheds are more likely to have low flows than to have high flows or even high medium flows.

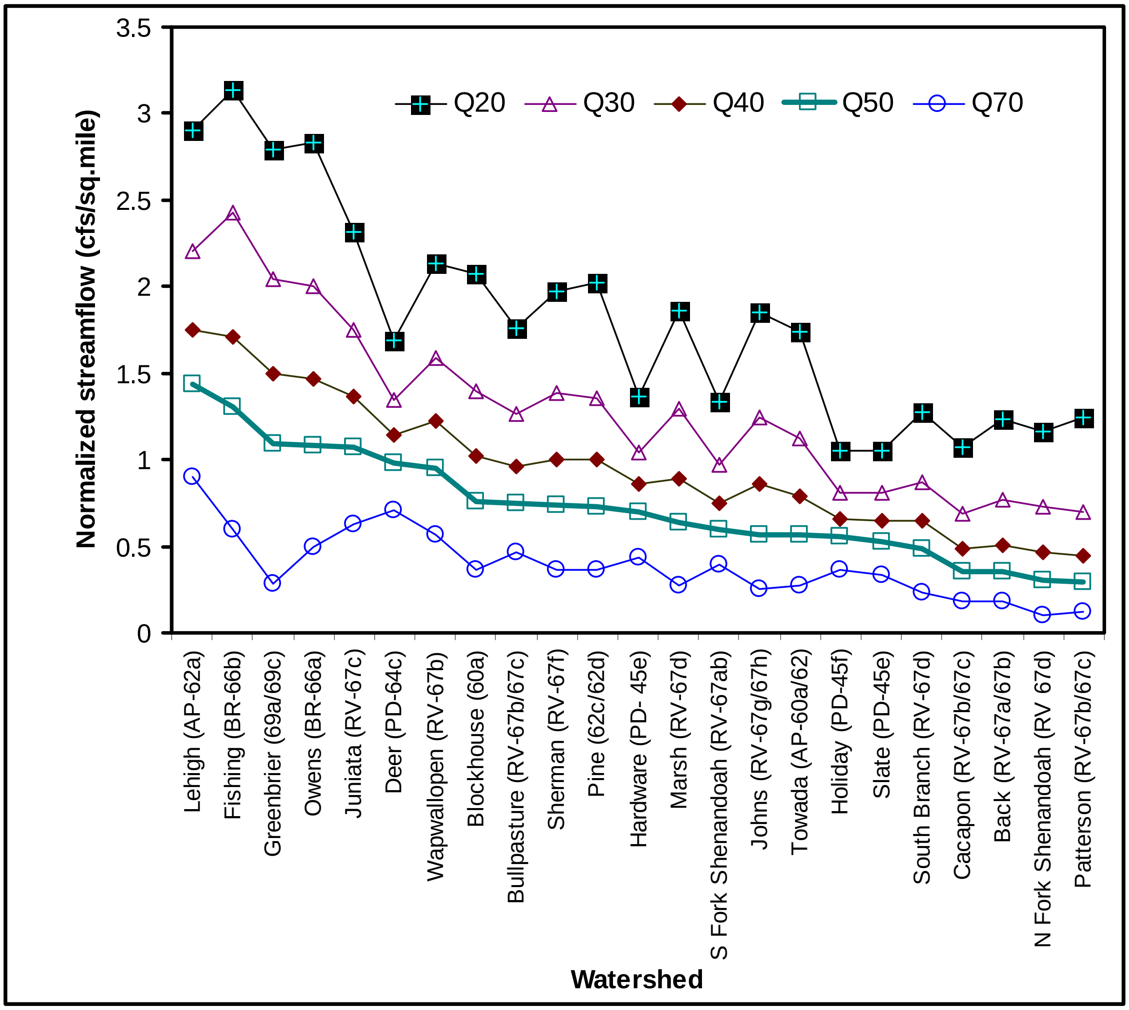


Figure 21. Comparisons of Hydrologic Responses Across Study Watersheds Using the Q50 Index.

The Q95 index was used to compare the hydrologic responses of the study watersheds at low flow conditions. When the study watersheds were arranged in the order of increasing Q95 index, watersheds that had low risk for droughts were placed on the left side and watersheds that had high risk for droughts were placed on the right side of Figure 22. The Q95 rankings did not group the study watersheds according to physiographic province or within a physiographic province; some watersheds had high Q95 indices while others had low Q95 index. In general, however, Q95 index was highly correlated to baseflow index; watersheds that had high baseflow indices had also high Q95 indices.

The Q95 rankings revealed that, as a group, the Piedmont watersheds had sustained low flows and were less vulnerable to drought. The Piedmont watersheds have desirable hydrologic response characteristics that are influenced by both the soil moisture storage and release characteristics of the thick soil regolith. The Q95 index rankings also showed that the Appalachian Plateau and Ridge and Valley watersheds were generally vulnerable to droughts because these watersheds had low Q95 indices.

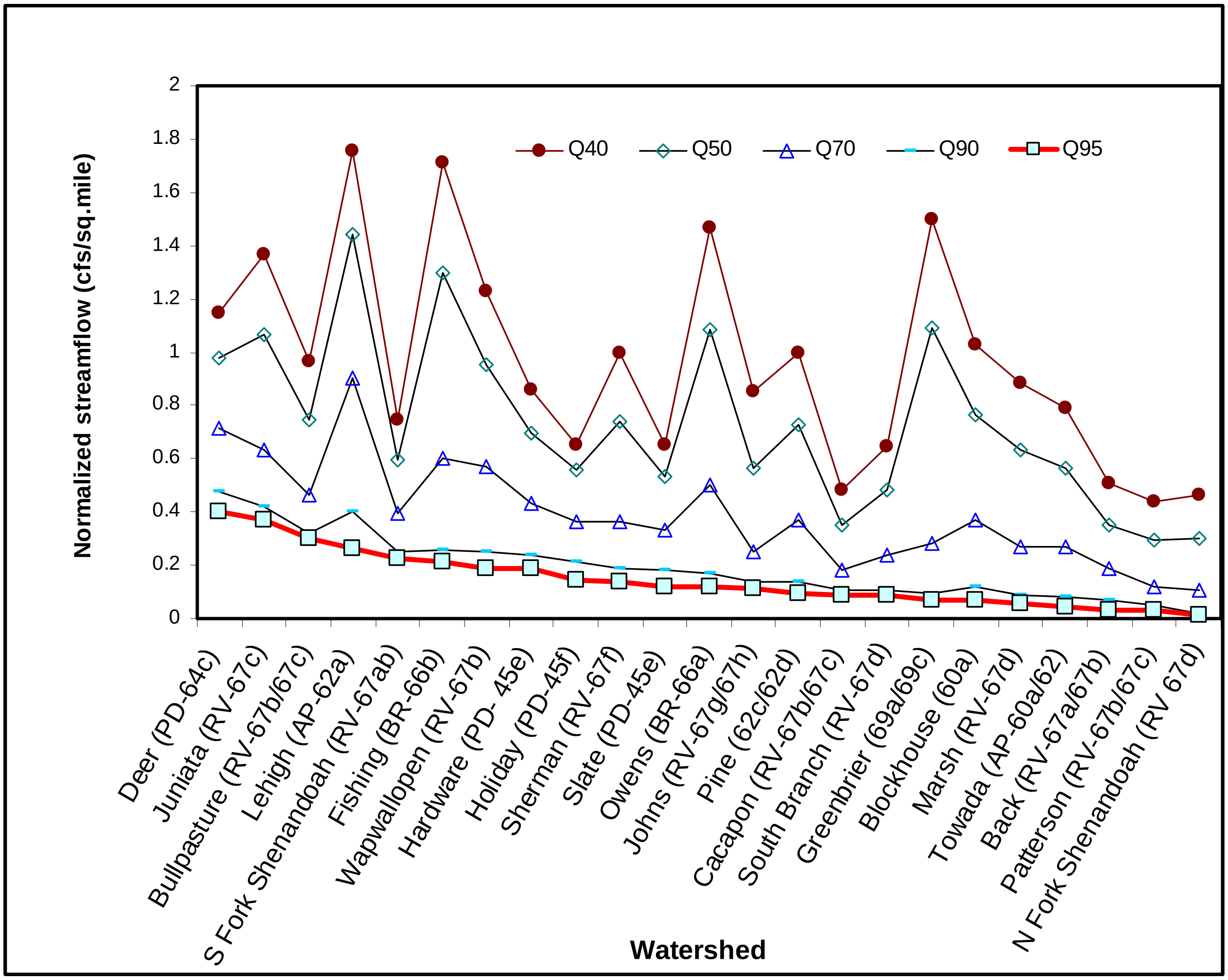


Figure 22. Comparisons of Hydrologic Responses Across Study Watersheds Using the Q95 Index.

6.3 Prediction of Flow Duration Indices (FDIs) for Ungaged Watersheds at Regional Spatial Scale and Multi-year Time Scale

Table 9 presents a correlation matrix between landscape-climate descriptors and the hydrologic response descriptors, i.e., the FDIs (Q1…Q95). The correlation matrix shown in Table 9 was based on a long period of record (1980-2000). It shows that flood conditions characterized by the Q1 indices were negatively correlated to the dryness index (AET/PREC) and the saturated hydraulic conductivity of the upper soil layer, and were positively correlated to the bulk density of the top soil layer, percent of deciduous forest cover, and the normalized hypsometric elevation that corresponds to 1 percent of the normalized area. Table 9 also shows that medium flows, characterized by the Q50 index, are negatively correlated to dryness index (AET/PREC) and saturated hydraulic conductivity of the upper soil layer. However, the Q50 index was positively correlated to soil depth of the upper soil layer and the normalized elevation that corresponds to 1 percent of the normalized area of the hypsometric curve. Unlike the high and medium flows that were highly correlated to dryness index, low flows characterized by the Q95 index, were poorly correlated to the dryness index, but were highly correlated to the baseflow index (BFI).

Table 9. Correlation Coefficients Between Landscape, Climate, and Selected Hydrologic Response Descriptors

	Q1	Q20	Q50	Q95	BFI	Rr	MdSL	AET/P	KSA1	BD2	AWC2	KSA2	CLAY2	SILT2	FRSD	SOLD	HPC10
Q1	1.00																
Q20	0.64	1.00															
Q50	0.44	0.90	1.00														
Q95	-0.13	0.28	0.59	1.00													
BFI	-0.23	0.30	0.62	0.86	1.00												
Rr	0.35	0.55	0.40	0.04	0.27	1.00											
MdSL	-0.04	-0.17	-0.37	-0.28	-0.47	-0.09	1.00										
AET/P	-0.79	-0.88	-0.81	-0.29	-0.19	-0.34	0.21	1.00									
KSA1	-0.44	-0.50	-0.53	-0.19	-0.24	-0.18	0.51	0.48	1.00								
BD2	0.70	0.60	0.38	-0.03	-0.07	0.50	0.06	-0.63	-0.42	1.00							
AWC2	-0.04	0.19	0.39	0.21	0.57	0.35	-0.66	-0.01	-0.52	-0.08	1.00						
KSA2	-0.19	-0.25	-0.32	-0.15	-0.34	-0.33	0.32	0.12	0.65	-0.32	-0.68	1.00					
CLAY2	0.10	0.35	0.41	0.10	0.48	0.63	-0.39	-0.06	-0.36	0.09	0.85	-0.63	1.00				
SILT2	0.08	0.20	0.32	0.21	0.45	0.43	-0.42	-0.07	-0.49	0.11	0.78	-0.85	0.65	1.00			
FRSD	0.69	0.56	0.37	0.04	0.01	0.51	0.11	-0.70	-0.21	0.69	-0.18	-0.17	0.05	0.06	1.00		
SOLD	0.08	0.22	0.42	0.34	0.57	0.09	-0.73	-0.24	-0.69	0.04	0.74	-0.47	0.53	0.46	0.06	1.00	
HPC10	0.56	0.62	0.45	0.09	0.07	0.43	0.01	-0.69	-0.27	0.54	-0.04	-0.01	0.01	0.14	0.62	0.14	1.00

6.3.1 Q1 Model

The 10 flow duration indices (FDIs) correspond to flows with different magnitudes and frequencies. For instance, the Q1 index represents a very high flow condition that can be predicted from climate, geology, and soil descriptors (Table 10). The stepwise multiple regression analysis identified the best predictors of Q1 index as dryness index (AET/PREC), a climate descriptor, baseflow index, a geology descriptor, and a soil descriptor - percent clay in the second soil layer. Soil descriptors control the infiltration and moisture storage processes; climate controls the precipitation inputs (rainfall and snow), and geology controls groundwater discharge (i.e., BFI = baseflow index). The results of the regression analysis also revealed a negative relationship between BFI and the hydrologic response index Q1 that may indicate that watersheds with very high baseflow index do not usually generate very high flows. The high flows represented by the Q1 index are mainly influenced by climate particularly precipitation characteristics. The percent of clay in the second soil layer (CLAY2) was also a good predictor of the Q1 index and may indicate the presence of flow impeding layers and possibly the occurrence of very high subsurface lateral flows from hillslopes.

Table 10. Flow Duration Indices Equations for Regional Spatial Scale and Multi-year Time Scale

FDIs		Regression equations	Coefficient of Determination
Q1	=	27.38-22.95 (AET/PREC)-12.95(BFI)+0.075 (CLAY2)	R^2 = 0.85
Q5	=	11.83-10.82 (AET/PREC)-0.025(Rrat)-2.389 (BFI)-3.976(AWC2)	R^2 = 0.95
Q10	=	7.61-6.63 (AET/PREC)+0.019(Rrat)-0.029 (SILT2)-0.187(KSAT1)	R^2 = 0.92
Q20	=	6.38-7.67 (AET/PREC)+0.028(CLAY2)-0.011 (SOLD)-0.485 (FRSD)	R^2 = 0.92
Q30	=	4.59-6.44 (AET/PREC)+0.02(CLAY2)-0.673 (FRSD)+0.016(MDSL)	R^2 = 0.92
Q40	=	3.06-4.787 (AET/PREC)+0.851(BFI)+0.01 (CLAY2)-0.399 (FRSD)	R^2 = 0.93
Q50	=	2.263-3.66 (AET/PREC)+1.027(BFI)-0.379 (FRSD)-0.007(CLAY2)	R^2 = 0.93
Q70	=	0.736+ 1.419(BFI)-1.42(AET/PREC)-0.437(HPC10)+0.015(SOLD)	R^2 = 0.95
Q90	=	-0.206+ 1.19 (BFI)-0.005(CLAY2)-0.031(Rrat)	R^2 = 0.88
Q95	=	-0.15+ 1.02(BFI)-0.004(CLAY2)-0.602(AWC2)	R^2 = 0.88

Symbol descriptions are given in Tables 2 and 7.

6.3.2 Q5 and Q10 Models

Q5 and Q10 indices represent high flow conditions that correspond to peak daily flows generated by medium to low intensity rainfall events or flows observed at the rising or receding limbs of high flow hydrographs (Figure 19). Both Q5 and Q10 indices are highly correlated to dryness index and relief ratio. Moreover, Q5 is also correlated to baseflow index and available soil water content in the second soil layer (AWC2). The landscape descriptors that are correlated to the

Q10 index include the percent of silt in the second soil profile layer (SILT2) and the saturated hydraulic conductivity of the upper soil profile layer (KSAT1). Q10 was also highly correlated to Q5 and similar watershed characteristics may influence both Q5 and Q10 flow conditions (Figure 20). We hypothesized that the Q5 and Q10 indices represent a period of high soil moisture availability, when the hydrologic responses of a watershed are controlled by topographic descriptors that control the flow conveyance system, i.e., relief ratio, stream channel length, and drainage density.

6.3.3 Q20 and Q30 Models

Streamflow magnitudes that correspond to Q20 and Q30 flow duration indices were classified as high to medium flows. As shown in Figure 19, Q20 and Q30 indices corresponded to the rising or the recession limbs of the streamflow hydrographs. As shown in Table 10, the dryness index (AET/PREC) was the best predictor of Q20 and Q30 indices, followed by the percent of clay in the second soil profile layer (CLAY2). Other landscape descriptors that were highly correlated to the Q20 and Q30 indices included percent of deciduous forest cover (FRSD), depth of the top two soil profile layers (SOLD), and median watershed slope (MDSL). We hypothesize that the Q1, Q5, and Q10 indices reflect conditions so wet that the watersheds are energy limited for maximum evapotranspiration to occur, while the Q40, Q50, Q70, Q90, and Q95 indices reflect conditions too dry for maximum evapotranspiration to occur. Based on this hypothesis, Q20 and Q30 indices correspond to relatively wet hydrologic conditions that are characterized by the availability of sufficient water and energy to support maximum evapotranspiration.

6.3.4 Q40 and Q50 Models

Q40 and Q50 indices correspond to the low end of the medium flow conditions and to the high end of the low flow conditions. Note that the Q50 index corresponds to the flow that is equaled or exceeded 50 percent of the time. Among the hydrologic response descriptors, climate had a strong influence on the Q40 and Q50 indices and dryness index was the best predictor of the Q40 and Q50 indices (Table 10). In addition to dryness index, baseflow index (BFI), which was used as a surrogate descriptor for geologic properties, emerged as the second best predictor for the Q40 and Q50 indices. The inclusion of baseflow index as a predictor for the Q40 and Q50 indices indicated the beginning of a shift in hydrologic response. This shift implies that as watersheds become dry soil and geology have more influence on hydrologic response than climate. Other landscape descriptors that are correlated to medium flow conditions (i.e., the Q40 and Q50 indices) include the percent of clay in the second soil profile layer (CLAY2) and the percent of deciduous forest cover (FRSD).

6.3.5 Q70, Q90 and Q95 Models

The climate descriptors that correlated best to the high flow conditions had no strong correlation to the low flow conditions. For example, dryness index, the best predictor for medium and high flow FDIs, was the second best predictor for the Q70 index and had no significant correlation with Q90 and Q95. Unlike the high flow conditions where climate was the dominant hydrologic response predictor, it appeared that low flow conditions were mainly influenced by soil and geologic descriptors. The regression equations shown in Table 10 indicated that base flow index was the best predictor of the Q70, Q90, and Q95 indices. Among the landscape and climate descriptors, baseflow index explained a high percentage of the variance associated with low to very low FDIs (Q70, Q90, and Q95). The percent of clay in the second soil profile layer (CLAY2) was the second best predictor for the Q90 and Q95 indices. Other descriptors that influenced low flow conditions included soil depth of the top two soil profile layers (SOLD), relief ratio (RRAT), and soil water content in the second soil profile layer (AWC2).

6.4 Predicting FDIs for Ungaged Watersheds at the Physiographic Province Spatial Scale and Single-year Time Scale

FDCs vary with the period of record. For example, a 30-year based FDC would differ from a 10-year based FDC or a one-year based FDC. Table 11 presents regression equations that relate landscape-climate descriptors to hydrologic response descriptors for a single year. Unlike the equations developed for the long-term regional flow duration indices (Table 10), the single-year based FDI regression equations are not applicable to the entire region, but are only applicable to specific physiographic provinces within the Mid-Atlantic Region (Table 11). The regression equations presented in Table 11 indicate that different landscape-climate descriptors dominated the hydrologic responses among the different physiographic provinces.

The landscape-climate descriptors, particularly the dryness index, were the best FDI predictors for both the single-year and multi-year flow duration indices for the Ridge and Valley watersheds. The similarities between the regional regression equations (Table 10) and physiographic-based, single-year equations (Table 11) for Ridge and Valley watersheds might be explained by the fact that almost half of the study watersheds are located in the Ridge and Valley Province and, therefore, these watersheds may mask the influence of watersheds from other provinces. Another explanation is that, the Ridge and Valley watersheds show the highest climate variability and therefore the dryness index, a climate descriptor, is a logical FDI predictor.

A climate predictor that corresponds to the mean monthly precipitation for December (DECPREC) was the best FDI or hydrologic response predictor for the Appalachian Plateau watersheds (Table 11). Other important hydrologic response predictors included soil, topography, and geology descriptors. Among the soil descriptors, saturated hydraulic conductivity (KSAT1 and KSAT2), percent clay (CLAY1 and CLAY2), silt (SILT1 and SILT2), and rock fragments (percent ROCK2) were correlated to the hydrologic responses of the Appalachian plateau watersheds. For the Piedmont province watersheds, however, monthly rainfall was the best hydrologic response predictor for the highest three indices (Q1, Q5, Q10). At medium flow conditions, soil moisture storage of the upper soil profile layer (STOR1) was highly correlated to medium flow conditions (Q20, Q30, Q40, and Q50). For low to very low flows (Q70, Q90, Q95), monthly precipitation had the highest influence on the hydrologic response for both the Appalachian and Piedmont watersheds. For these latter watersheds, soil descriptors were also important hydrologic response predictors, followed by topography, vegetation, and geology.

Table 11. Flow Duration Indices Equations for Physiographic Province Spatial Scale and One-year Time Scale

Regression equation			Coefficient of Determination		
Appalachian Plateau					
Q1	=	22.169-1.968(DECPREC)+0.376(KSAT2)	R^2	=	1.0
Q5	=	-2.97+2.076(JUNPREC)+0.055(CLAY2)	R^2	=	1.0
Q10	=	7.121+0.321(DECPREC)-0.13(SILT2)	R^2	=	1.0
Q20	=	-0.078+0.447(DECPREC)+.010(MCHS)	R^2	=	1.0
Q30	=	-1.39+0.562(DECPREC)+0.057(SMED)	R^2	=	1.0
Q40	=	1.1392+1.117(DECPREC)-11.894 (BFI)	R^2	=	1.0
Q50	=	-0.313+0.338(DECPREC)-0.046(KRATIO)	R^2	=	1.0
Q70	=	-0.903 +0.279(DECPREC)+0.014(CLAY2)	R^2	=	1.0
Q90	=	0.288+0.161(DECPREC)-0.038(SAND2)	R^2	=	1.0
Q95	=	-0.265+0.145(DECPREC)-0.005(ROCK2)	R^2	=	1.0
Piedmont					
Q1	=	-19.856-10.146 (APRPREC)+1.723(SILT1)-20.537(AET/P)	R^2	=	1.0
Q5	=	5.94-1.154(JULPREC)+0.155(STOR TOTAL)	R^2	=	1.0
Q10	=	8.414-2.041(JUNPREC)+0.126(DRATIO)	R^2	=	1.0
Q20	=	-3.694+5.12(STOR1)-0.0010(SOLD2)	R^2	=	1.0
Q30	=	-0.372+3.44(STOR1)-0.125(CLAY1)	R^2	=	1.0
Q40	=	-2.621+3.318(STOR1)+0.003 (MCHS)	R^2	=	1.0
Q50	=	-1.754+3.193(STOR1)-0.047(CLAY1)	R^2	=	1.0
Q70	=	3.789 -0.326 (AUGPREC)-0.192(STOR2)	R^2	=	1.0
Q90	=	0.997-0.077(AUGPREC)+0.002(CLAY2)	R^2	=	1.0
Q95	=	0.986-0.079(AUGPREC)+0.002(FRSD)	R^2	=	1.0
Ridge and Valley					
Q1	=	-0.310+8.495 (JULPREC)+0.056(KSAT1)-0.003(SOLD)	R^2	=	0.89
Q5	=	5.126-7.847(AET/P)-0.010 (SLENG)+4.313(DRI)+0.058(CLAY2)	R^2	=	0.96
Q10	=	5.482-6.038(AET/P)+0.872(DRI)-0.031(RRAT)	R^2	=	0.95
Q20	=	4.507-4.308(AET/P)+0.858(DRI)-5.427(AWC1)	R^2	=	0.98
Q30	=	5.905-6.971(AET/P)-0.013(FRSD)+0.226(SEPPREC)	R^2	=	0.96
Q40	=	5.818-5.744(AET/P)-0.009 (FRSD)-0.072(OCTPREC)	R^2	=	0.93
Q50	=	1.821-2.028(AET/P)-0.189(SOLD1)+2.424(BFI)	R^2	=	0.94
Q70	=	-1.312+2.727(BFI)-0.005(SOLD1) -0.002(STLEN)	R^2	=	0.90
Q90	=	-0.561+2.024(BFI)-0.001(TCHL)+0.033(FEBPREC)	R^2	=	0.99
Q95	=	-.514+1.659(BFI)-0.001(TCHL)+0.021(FEBPREC)	R^2	=	0.94

Symbol descriptions are given in Tables 2 and 7

Table 12 presents a summary of the factors that control the hydrologic responses of the Mid-Atlantic watersheds. The results of this study showed that climate controlled the long-term high and medium flow conditions of the Mid-Atlantic watersheds, while geology and soil descriptors controlled the low flow hydrologic responses. For most of the flow conditions, in addition to climate and geology, soil descriptors were also good predictors of the hydrologic responses, followed by topography and vegetation.

The single-year based regression equations showed that different landscape and climate descriptors were important in the various physiographic provinces. Specifically, the one-year based relationships showed that climate was the best predictor of hydrologic response for the Ridge and Valley Province, whereas monthly rainfall was the best hydrologic response predictor for the Appalachian Plateau and Piedmont watersheds, followed by various soil descriptors. The difference between the regional scale and physiographic province scale regression equations were due to the spatial scale and temporal scale influences on both inputs and hydrologic response. Note that spatial scale is a major source of variability in watershed hydrologic response. As the spatial scale was reduced from region to physiographic province, the variability in watershed hydrologic response also reduced - thus improving the predictive capability of the regression equations.

Table 12. Summary of Dominant Hydrologic Response Predictors at Different Spatial and Temporal Scales

Flow condition	Hydrologic Response Variables	Controlling Variable(s)
Multi-year time scale and regional spatial scale		
Very High flow	Q1	climate and soil
High flow	Q5	climate, topography, and soil
High flow	Q10	climate and topography
High to medium flow	Q20	climate, soil, and vegetation
Medium flow	Q30	climate, soil, and vegetation
Medium flow	Q40	climate, soil, vegetation
Medium to low flow	Q50	climate and soil
Low flow	Q70	geology and climate
Very low flow	Q90	geology and soil
Very low flow	Q95	geology and soil
Single year time scale and physiographic province spatial scale		
	Appalachian Plateau	
Very High Flow	Q1	climate and soil
High flow	Q5	climate and soil
High flow	Q10	climate and soil
High to medium flow	Q20	climate and soil
Medium flow	Q30	climate and topography
Medium flow	Q40	climate and topography
Medium to low flow	Q50	climate and geology
Low flow	Q70	climate and soil
Very low flow	Q90	climate and soil
Very low flow	Q95	climate and soil
	Ridge and Valley	
Very high flow	Q1	climate and soil
High flow	Q5	climate and topography
High flow	Q10	climate and topography
High to medium flow	Q20	climate and topography
Medium flow	Q30	climate and vegetation
Medium flow	Q40	climate and vegetation
Medium to low flow	Q50	climate and soil
Low flow	Q70	geology and soil
Very low flow	Q90	geology and topography
Very low flow	Q95	geology and topography
	Piedmont	
Very high flow	Q1	climate and soil
High flow	Q5	climate and soil
High flow	Q10	climate and soil
High to medium flow	Q20	soil and soil
Medium flow	Q30	soil and soil
Medium flow	Q40	soil and topography
Medium to low flow	Q50	soil and soil
Low flow	Q70	climate geology and climate
Very low flow	Q90	climate and soil
Very low flow	Q95	climate and vegetation

Part IV

7 Implications For Watershed Management

Streamflow measured at a watershed outlet is the result of complex watershed processes that operate at the watershed scale. These watershed processes are normally influenced by landscape and climate descriptors. Some of the dominant hydrologic processes are recharge, controlled mainly by precipitation, moisture storage controlled mainly by soil, groundwater storage characteristics, and deep groundwater and evapotranspiration losses.

Many investigators have reviewed the current state of the art in hydrologic modeling and made recommendations for future research (Hornberger and Boyer, 1993; Beven, 1996). Hornberger and Boyer (1993), in a review paper, stressed the need to develop procedures to measure model input parameter values independently of the model output values. They pointed-out that a major limitation in hydrololgic modeling is lack of methods to easily and reliably specify model input parameters. In their review, they concluded that progress in hydrologic modeling is linked to acquisition of new data and to new experimental work. Troch et al. (2003) acknowledged that key input parameter identification and specification is a major constraint to the use of distributed hydrologic modeling. They recognized the current mismatch between model complexity and the level of data available to parameterize, initialize, and calibrate models.

In addition to parameter specification limitations, general lack of high quality data has also been recognized as one of the constraints to the development of hydrologic models. Beven (1996) stated that, “Essentially hydrological science suffers from very severe data constraints. What happens at the point scale is reasonably well understood (at least well enough to understand that our ‘physically-based’ descriptions are inadequate due to the effects of both surface and subsurface preferential flows), but data and ideas are lacking to know how to extend that knowledge to larger scales”. NAS (1993) and Hornberger (1993) concluded that hydrologic science is in greater need of more and better experimentation than of more and better models (NAS, 1991; Hornberger, 1993).

Many of the currently used hydrologic models are based on relationships developed from data and observations obtained from field plot or small watershed studies where soils, geology, and vegetation are nearly homogeneous and where the complex interactions of watershed characteristics and climate inputs are absent. The small field plots provide a more controlled environment where researchers can understand processes and their interactions, identify parameters, and develop models based on data and observations at the point scale. Hornberger and Boyer (1993) also recognized data limitations and associated scaling problems that occur when incorporating a relatively small scale heterogeneity into models applied to relatively larger scales. As a result, models developed from data and observations obtained from small areas are often applied to large watersheds without undergoing any upward scaling procedures. Because reliable methods to identify the key parameters and estimate parameter values for large watersheds are not currently available, the inaccuracies associated with upward scaling will also remain unknown until such methods are developed.

In traditional hydrology, streamflow measured at the watershed outlet is often used to parameterize hydrologic models using various calibration procedures. Use of model calibration procedures as a model parameter estimation tool assumes that hydrologic models have the correct model structure, that processes are represented correctly in the model, and that all parameters that influence the hydrologic processes are included in the model. Such assumptions falsely assume that the current state of hydrologic modeling is satisfactory and, therefore, reduce the incentive to look for new methods to identify model parameters. Nevertheless, the approach presented in Part III of this report can be used to identify the key parameters for large watershed response. Hornberger and Boyer (1993) also underscore the need for “empirical studies” to develop relationships among measurable catchment characteristics and the estimated parameters of watershed models.

The use of empirical relationships between landscape-climate descriptors and hydrologic response descriptors also provides insight into the dominant hydrologic processes, and the key parameters representing those processes, in hydrologic models. An understanding of the dominant hydrologic processes would enhance our ability to select the most appropriate models, or build new hydrologic models when necessary.

7.1 Applications to Hydrologic Modeling

This work has presented an alternative approach to the identification of key watershed hydrologic model parameters. The approach is based on the development of empirical relationships between landscape-climate descriptors and hydrologic response descriptors using multi-variate regression analysis. In Tables 10 and 11, we presented two sets of regression equations that can be used to predict the 10 flow duration indices (e.g., Q1…Q95) that represent a wide range of hydrologic responses. The regional flow duration indices equations presented in Table 10 are suitable for development of long-term watershed hydrologic responses and are useful for water resources management applications. The single-year based regression equations presented in Table 11 may be suitable for general watershed hydrologic modeling applications.

The regression equations in Table 10 and 11 are also suitable for predicting flow duration indices for ungaged watersheds. The procedure to follow for this is to develop the regression equations using landscape-climate descriptors and hydrologic response descriptors (Q1… Q95) for gaged watersheds located near the ungaged watersheds of interest. Once the regression equations are developed, users can then determine the specific landscape and climate descriptors for the ungaged watersheds to be modeled, and then substitute these parameters into the regression equations to predict the flow duration indices for the ungaged watersheds. After the flow duration indices have been determined for the ungaged watersheds, the entire flow duration curve can be constructed. The constructed flow duration curves can then be converted to streamflows by multiplying the normalized FDCs by the drainage area of each watershed.

7.2 Applications to Watershed Vulnerability Assessment

Watersheds are widely recognized as important resource management units. Today, in the United States, many watersheds are continuously undergoing land use change, and watershed management is becoming an essential tool for sustainable development and protection of natural resources. Such land use change usually results in altered hydrologic response of the watershed. An analysis of the hydrologic response of a watershed, therefore, can provide useful information about the dominant watershed hydrologic controls. This study attempts to link landscape descriptors that represent watershed characteristics and watershed climate descriptors to those hydrologic response descriptors that represent the dominant watershed hydrologic regimes. Specific knowledge of the likely hydrologic responses of a watershed would enable environmental planners and resource managers to assess the risks that are associated with different management decisions. Environmental planners and water resources managers clearly need tools to better manage natural resources under changing conditions. A reliable method that predicts FDIs from watershed characteristics under natural and changing conditions has, therefore, important implications to water resource management.

7.2.1 Climate Change Applications

Fisher et al. (2001) presented a detailed analysis of the potential consequences of climate variability and change in the Mid-Atlantic Region. They reported climate model projections indicating drier conditions in the summer and winter months. These drier conditions might have serious impacts on the water resources of the Mid-Atlantic Region. For example, reduced streamflow and increased drought frequency and severity would affect both water quantity and water quality. In addition, agricultural water use, particularly the need for irrigation may increase along with the need for water supply management during prolonged droughts.

As the frequency and intensity of droughts increase, rivers and streams may become more polluted due to reduced assimilative capacity for point source wastewater treatment plant discharges. During extremely wet years, serious floods may occur and rivers and streams become polluted by non-point source pollution, particularly - high levels of sediments, nutrients, and pathogens from agricultural lands. In the Mid-Atlantic Region, climate change might also influence snow accumulation and the timing of snowmelt runoff. Among the study watersheds, high-elevation watersheds in the Appalachian, ridge-dominated Ridge and Valley, and Blue Ridge provinces are more vulnerable to climate change because these watersheds have high snow accumulations. On the other hand, the Piedmont watersheds are the least vulnerable to climate change because streamflow there is less dependent on snow accumulation and more dependent on soil and groundwater storage reservoirs. Environmental planners can use flow duration indicates such as Q1 and Q5 for flood risk assessment and Q90 and Q95 for drought management.

7.2.2 Land Use Change Applications

Non-point source pollution (NPS) is mainly produced from land surfaces and is transported by overland flow, interflow, and baseflow from groundwater. The hydrologic response of a watershed has a strong influence on the production of sediments and the ultimate transport of sediments and nutrients from land surfaces to streams, rivers, and lakes. Production of non-point source pollution is land use related and the specific pollutants generated by a watershed often depend upon the type of land use in the watershed (Mueller et. al. 1995). The characteristics of the soil, geology, land use and land cover, and topography of a watershed can all be used to assess vulnerability to land use change. To evaluate the landscape characteristics of a watershed and their interaction with land use change, one can use the results of this study. For example, land use change, by urbanization, would result in changes in the landscape descriptors such as percent of forest cover that would, in turn, result in changes in predicted hydrologic response of the watershed using the FDIs developed using the methods presented herein. Environmental planners and water resources managers can therefore link changes in land use to changes in hydrologic response by monitoring the changes in predicted flow duration indices, particularly the high flow indices (Q1 and Q5) and low flow indices (Q90 and Q95).

7.2.3 Water Quality Applications

In general, there is a relationship between the quantity and quality of the water in a stream. During drought periods, when streamflow falls below a certain threshold value such as the Q95 index, the ability of a stream to assimilate pollutants decreases with decrease in streamflow. Low flow indices are often used for the determination of instream flows to meet ecological flow requirement and to allocate water withdrawal levels among multiple water users within a watershed. Low flow indices can be easily determined from observed streamflow data. However, for ungaged watersheds, these low flow indices have to be estimated. In this study, we presented a set of regression equations that can be used to estimate the Q70, Q90, and Q95 low flow indices from landscape and climate descriptors.

7.2.4 Water Resources Applications

Some of the scale dependent issues that water resources managers often encounter include water withdrawal allocations between the upstream and downstream segments of large watersheds, assessment of the risk of downstream floods and its dependence on upstream land use change, and the assessment of the sustainability and reliability of water supply systems during prolonged droughts. Watershed scale influences the availability of water resources in a number of ways. For example, large watersheds have higher streamflow rates than small watersheds. In addition, unlike small watersheds, large watersheds have longer and deeper channels that intersect the water table. As a result, large watersheds have higher sustained low flows and are, therefore, more suitable for water supply development.

Small headwater watersheds located in the Appalachian Plateau, Ridge and Valley, and Blue Ridge Provinces have steep slopes and shallow soils. These watersheds also have limited soil moisture storage capacity and may not have sustained low flows. Because small headwater watersheds are often located in mountainous areas with erosion resistant geologic formations, small watersheds usually have low yield and may not be suitable for water supply development unless supplemented by groundwater or water supply reservoirs.

In general, watersheds that have high Q5 indices have high surface flow runoff components and low subsurface runoff components. On the other hand, watersheds with high Q90 and Q95 indices have sustained low flows and are, therefore, suitable sources for water supply. Among the study watersheds, the Appalachian Plateau and Ridge and Valley watersheds had the lowest sustained low flows and thus the highest vulnerability to drought whereas the Piedmont watersheds had the highest sustained low flows and therefore the lowest vulnerability to drought. To determine a given watershed's vulnerability, resource managers can use combinations of landscape descriptors such as slope, soil depth, baseflow index, and hydrologic response descriptors, such as flow duration indices Q5 and Q95.

Environmental planners and water resource managers need methods to estimate low flow indices, i.e., Q70, Q90, and Q95 so that they can assess the likelihood of exceeding a particular index, say Q95, as well as the risks associated with exceeding that particular index. One of the attractive features of flow duration indices application is that managers can use sequences of indices, say Q70 to Q95, as trigger points for different management decisions, such as water use restrictions.

8 Summary and Conclusions

The physiographic provinces and ecoregions of the Mid-Atlantic Region were used as a selection framework for the study watersheds. We selected 25 watersheds from the different physiographic provinces. This study links landscape descriptors of watershed characteristics and descriptors of watershed climate to hydrologic response descriptors of the dominant hydrologic regimes of Mid-Atlantic watersheds. We presented two approaches to hydrologic response comparisons: a conceptual water balance based approach and an empirical flow duration curve or statistical based approach.

The water balance approach was used to compare hydrologic responses at different time scales, i.e., annual, monthly, daily, and hourly. Based on long-term water balance comparisons, watersheds with high elevation and latitudinal influences had high streamflow and low evapotranspiration, while watersheds with low elevation and latitudinal influence had low streamflow and high evapotranspiration. At the monthly time scale comparisons, watersheds with high elevation and latitudinal influences (i.e., the Appalachian Plateau and ridge-dominated Ridge and Valley watersheds) had greater seasonal variability in hydrologic response than watersheds with low elevation and latitudinal influences (i.e., the Piedmont and valley-dominated Ridge and Valley watersheds). At daily time scale comparisons, all the water balance components had high temporal variability driven mainly by the daily precipitation inputs. The water balance comparisons revealed that mountainous watersheds located in the Appalachian Plateau, Ridge and Valley, and Blue Ridge watersheds had higher streamflow, lower evapotranspiration, and lower soil moisture storage capacity than the Piedmont watersheds.

The empirical approach represented the hydrologic responses of the study watersheds as flow duration indices (Q1…Q95). Using flow duration indices, we ranked the study watersheds according to increasing Q5, Q50, and Q95, and identified those watersheds that have a high risk of flooding or risk of drought. We developed two sets of regression equations that had different temporal and spatial scales. Among the potential hydrologic response predictors, dryness index, a climate descriptor, was the best predictor of long-term hydrologic response or flow duration indices. Soil descriptors that were good predictors of hydrologic response included soil texture, bulk density, soil depth, and saturated hydraulic conductivity of the top two soil profile layers. The characteristics of the lower of the top soil layers seemed to have more influence on hydrologic response than the characteristics of the upper soil layer. Percent of deciduous forest, a land cover descriptor, was not highly correlated to all hydrologic response descriptors, but had some influence on medium hydrologic responses (Q30 and Q40). Among the geomorphologic descriptors, drainage density and relief ratio had some influence on hydrologic responses. Another important hydrologic response predictor was the baseflow index, a surrogate geologic descriptor.

Among the study watersheds, the Appalachian Plateau and the Ridge and Valley watersheds had the lowest sustained low flows and, thus, the highest vulnerability to drought. The Piedmont watersheds had the highest sustained low flows and, therefore, the lowest vulnerability to droughts. The Piedmont watersheds had desirable hydrologic response characteristics characterized by relatively high Q95 indices and relatively low Q5 indices. Based on our general hydrologic response comparisons of the Mid-Atlantic watersheds, the Piedmont watersheds were the least vulnerable to drought, flooding, land use change, and climate change. To determine a watershed's vulnerability, resource managers can use combinations of landscape descriptors, such as slope, soil depth, and baseflow index, and hydrologic response descriptors such as flow duration indices, .i.e., Q5 and Q95.

We conclude that the methods presented in this report have important implications to hydrologic modeling particularly the prediction of streamflow for ungaged watersheds. More research is needed to further develop both the water balance approach and the empirical approach towards the development of a hydrologic model. There is a need for hydrologic models that have a strong physical basis and yet have less parameters than those currently available. The resultant model should be tested with observed data and compared with existing hydrologic models such as the Stanford Watershed Model – HSPF.

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