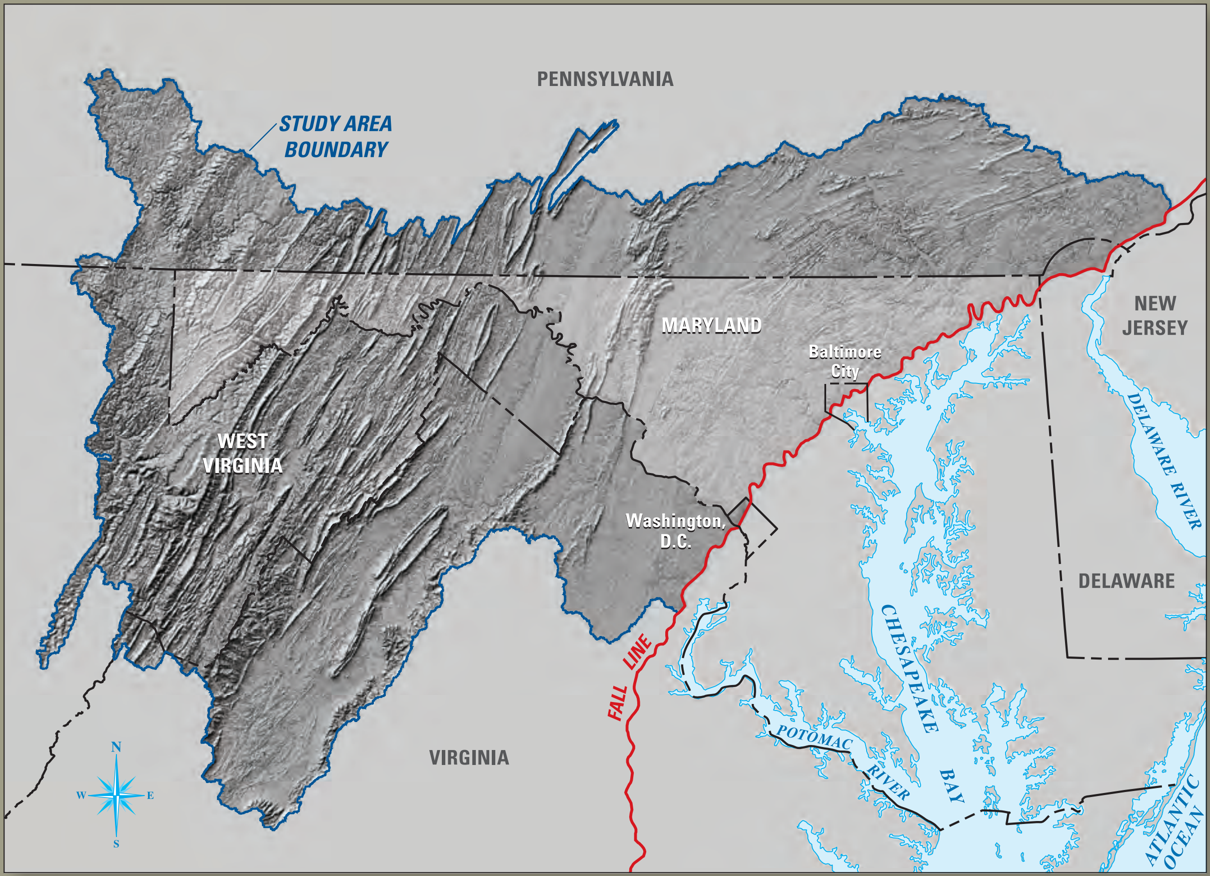
Prepared in cooperation with the
Maryland Department of the Environment

Statistical Classification of Hydrogeologic Regions in the Fractured Rock Area of Maryland and Parts of the District of Columbia, Virginia, West Virginia, Pennsylvania, and Delaware



Scientific Investigations Report 2013–5043

U.S. Department of the Interior
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Cover. Location of study area for the statistical classification of hydrogeologic regions.

Statistical Classification of Hydrogeologic Regions in the Fractured Rock Area of Maryland and Parts of the District of Columbia, Virginia, West Virginia, Pennsylvania, and Delaware

By Brandon J. Fleming, Andrew E. LaMotte, and Andrew J. Sekellick

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U.S. Department of the Interior
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U.S. Department of the Interior
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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Water year in USGS reports is the 12-month period October 1 through September 30. The water year is designated by the calendar year in which it ends and includes 9 of the 12 months. Thus, the year ending September 30, 2002, is the “2002 water year.”

Statistical Classification of Hydrogeologic Regions in the Fractured Rock Area of Maryland and Parts of the District of Columbia, Virginia, West Virginia, Pennsylvania, and Delaware

By Brandon J. Fleming, Andrew E. LaMotte, and Andrew J. Sekellick

Abstract

Hydrogeologic regions in the fractured rock area of Maryland were classified using geographic information system tools with principal components and cluster analyses. A study area consisting of the 8-digit Hydrologic Unit Code (HUC) watersheds with rivers that flow through the fractured rock area of Maryland and bounded by the Fall Line was further subdivided into 21,431 catchments from the National Hydrography Dataset Plus. The catchments were then used as a common hydrologic unit to compile relevant climatic, topographic, and geologic variables. A principal components analysis was performed on 10 input variables, and 4 principal components that accounted for 83 percent of the variability in the original data were identified. A subsequent cluster analysis grouped the catchments based on four principal component scores into six hydrogeologic regions. Two crystalline rock hydrogeologic regions, including large parts of the Washington, D.C. and Baltimore metropolitan regions that represent over 50 percent of the fractured rock area of Maryland, are distinguished by differences in recharge, Precipitation minus Potential Evapotranspiration, sand content in soils, and groundwater contributions to streams. This classification system will provide a georeferenced digital hydrogeologic framework for future investigations of groundwater availability in the fractured rock area of Maryland.

Introduction

The U.S. Geological Survey (USGS), in cooperation with the Maryland Department of the Environment Water Supply Program (MDE WSP), began the Maryland Fractured Rock Water Supply Study in 2009. As the first phase of this study, an initial framework describing regions with similar hydrogeologic characteristics was developed. The methods and results used to develop the framework are described in this report.

In Maryland, the hydrogeologic systems can be most generally divided into physiographic provinces defined by Fenneman and Johnson (1946), with the Fall Line separating the unconsolidated layered system of aquifers and confining units in the Coastal Plain from the spatially varying igneous and metamorphic bedrock of the Piedmont, essentially dividing the State in half. West of the Piedmont lie the Blue Ridge, Valley and Ridge, and Appalachian Plateau Physiographic Provinces that consist of fractured siliciclastic, igneous and metamorphic, and carbonate formations. Groundwater in these rocks moves chiefly through networks of fractures. The water-bearing materials in this area are generally anisotropic and heterogeneous, which has made assessing groundwater availability difficult. The area inclusive of these provinces west of the Fall Line will hereafter be referred to as the "fractured rock area of Maryland" (fig. 1). A report by the Advisory Committee on the Management and Protection of the State's Water Resources (Wolman, 2008) raised awareness of potential water supply issues in the fractured rock area of Maryland. Issues of particular concern to the MDE WSP are increased groundwater demand from expected population growth near Baltimore, Maryland and Washington, D.C.; the impacts of climate variability on groundwater supplies; and adverse impacts on the aquatic health of streams from water withdrawals.

The fractured rock area of Maryland has significant variations in factors affecting groundwater availability including climate, topography, and geology. As such, groundwater and surface-water availability west of the Fall Line is difficult to determine at a regional scale. To better manage the groundwater resources in the fractured rock area of Maryland, a common hydrogeologic framework for resource managers and researchers is needed to integrate information on factors relating to groundwater availability, hydrologic processes, aquatic health, and response to climate variability. In addition, the framework needs to be in digital format and georeferenced for use in the Maryland Fractured Rock Aquifer Information System (FRAIS), a geographic information system (GIS) designed to support the water supply study in the region underlain by fractured rock in Maryland (Fleming and others, 2012). The hydrogeologic framework can then be used as a starting point for subsequent research efforts to quantify water availability in the fractured rock area of Maryland.

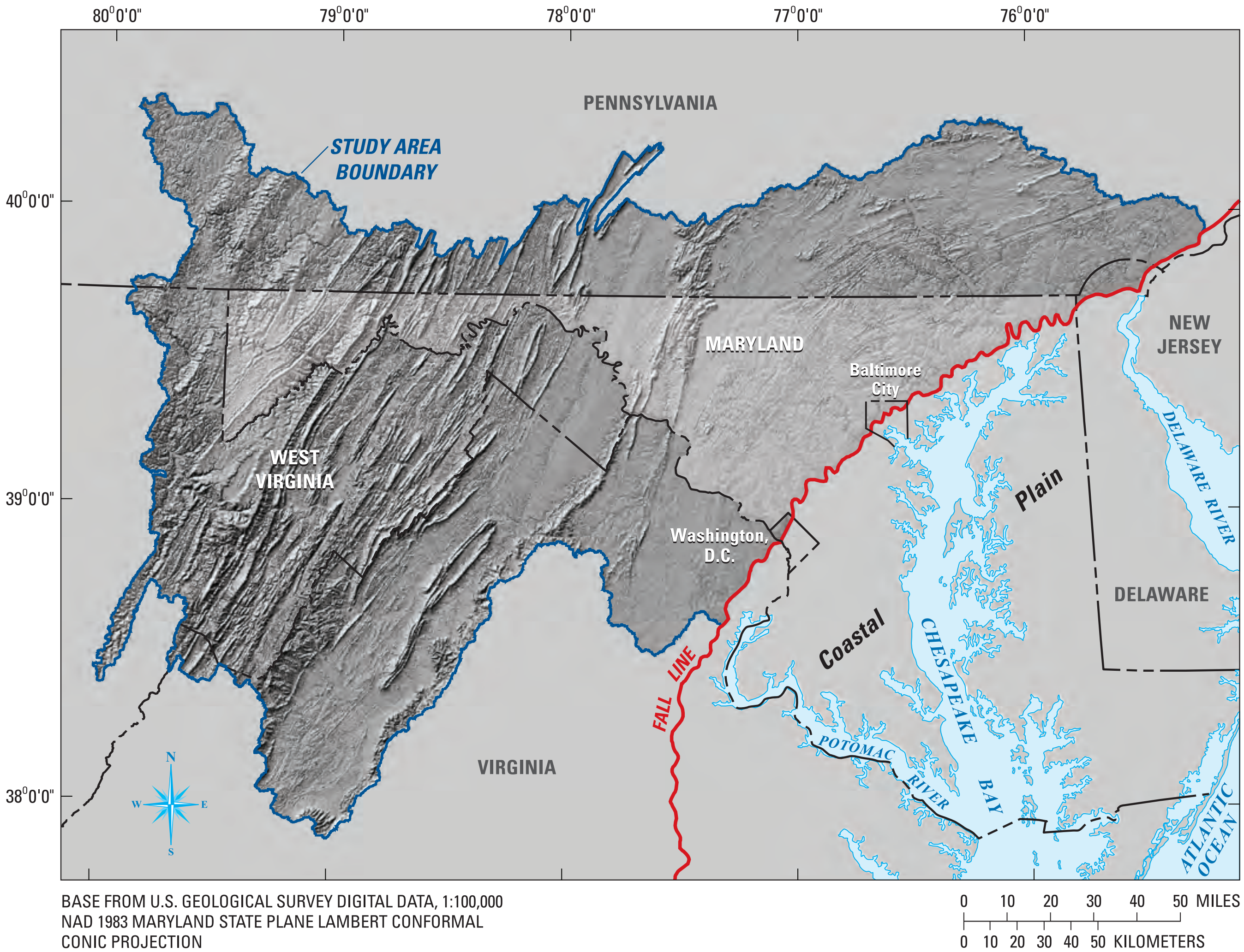

Figure 1. Location of study area for the statistical classification of hydrogeologic regions.

Purpose and Scope

This report describes the results of a statistical analysis designed to identify regions with similar hydrogeologic characteristics in the fractured rock areas of Maryland and adjacent states. The study area is bounded by the Fall Line to the east and the outer boundaries of the 8-digit Hydrologic Unit Code (HUC) watersheds, which contribute streamflow through the fractured rock area of Maryland (fig.1). The study area was selected based on naturally occurring hydrologic and physiographic boundaries rather than political boundaries and includes parts of the District of Columbia, Virginia, West Virginia, Pennsylvania, and Delaware with similar physical environments to areas in Maryland. This classification will provide a hydrogeologic framework in support of the Maryland Fractured Rock Water Supply Study.

Previous Investigations

Studies combining areas of similar geologic, hydrologic, or hydrogeochemical characteristics have been conducted at multiple spatial scales. Non-statistical methods for grouping physiographic provinces in the United States are well known (Fenneman and Johnson, 1946). For the Chesapeake Bay watershed, hydrogeomorphic regions were developed on the basis of rock type and physiography to look at base-flow nitrate loads of nontidal streams (Bachman and others, 1998; Brakebill and Kelley, 2000). Hydrogeologic units were categorized for Allegany and Washington Counties (Slaughter and Darling, 1962), and a recent physiographic map of Maryland based on detailed local knowledge of the geology shows both the Coastal Plain and fractured rock areas (Reger and Cleaves, 2008).

Statistical methods for grouping terrains that have been implemented more recently have taken advantage of modern computing capabilities. GIS and multivariate statistical analysis methods were used to develop hydrologic landscape regions for the United States (Wolock and others, 2004). The authors performed a principal components analysis (PCA) and cluster analysis to delineate 20 distinct regions based on land-surface form, geologic texture, and climate. The hydrologic landscape regions were compared to other regional frameworks and found to be as good (if not better) in delineating regions of distinct land-surface form and geologic texture. PCA and cluster analysis were used by Armstrong and others (2008) to identify basins with similar hydrologic characteristics based on ecologically relevant streamflow indices for least altered sites in southern New England. In central Idaho, Lipscomb (1999) used basin characteristics as input variables for a PCA as the basis for a data-collection network for quantifying in-stream flows. In Maryland, Preston (2000) applied cluster analysis to identify hydrochemical response units. These units were later used by the State to design a water-quality management plan.

Study Methods

GIS methods were used to compile relevant data for catchments derived from the National Hydrography Dataset Plus (NHDPlus) (Horizon Systems, 2010) in order to perform a PCA on hydrogeologic variables (fig. 2). Catchment study units, nested within the 8-digit HUCs and derived from the NHDPlus dataset are hydrologically defined units that provide enough resolution to describe known hydrogeologic variability for areas within Maryland and adjacent states. The catchment study units ranged in area from less than 1 to 76 square kilometers (km^2) with a mean of 2.4 km^2 and a median of 1.5 km^2. A clustering algorithm was then applied to the principal components scores for each of 21,431 catchment study units in the study area.

Geographic Data

The extent of the fractured rock study area was delineated by 8-digit HUC watersheds that contribute streamflow into the non-Coastal Plain part of Maryland (fig. 1). Catchment study units were defined by NHDPlus catchments (fig. 2). Characteristics such as topography, hydrology, and geology, among others, were assigned to each NHDPlus catchment by use of a GIS. Data layers included Precipitation minus Potential Evapotranspiration (PET), base-flow index (BFI), recharge, mean elevation, mean slope, relief, percent sand in soils, and geology (carbonate rock, siliciclastic rock, and crystalline rock, for a total of 10 input variables. Each input variable was converted to a 30-meter (m) grid to match the resolution of the elevation base-data layer and used as input for area statistics. Input variable values for each NHDPlus catchment were calculated in the GIS and exported to tables to be used as input for the PCA and cluster analysis.

An 800-m, long-term (30-year annual average) precipitation grid produced by the PRISM Climate Group (Daly and others, 2008) was converted to a 30-m grid. A 1-kilometer (km) estimated PET grid developed from long-term (30-year) climate data by the USGS (Wolock and others, 2004) was converted to a 30-m grid and subtracted from the precipitation grid to produce Precipitation minus PET, which was treated as a single variable and summarized by catchment study unit.

The hydrologic characteristics BFI and recharge were converted from 1-km grids to 30-m grids. Base flow is the component of streamflow that can be attributed to groundwater discharge into streams. The BFI is the ratio of base flow to total streamflow, expressed as a percentage. The source dataset was the base-flow index for the conterminous United States (Wolock, 2003a). Recharge represents the mean annual natural groundwater recharge, in millimeters. Recharge is derived from BFI (representing long-term natural groundwater discharge to streams) and long-term mean annual runoff values. The source dataset for recharge was estimated mean annual natural ground-water recharge in the conterminous United States (Wolock, 2003b). All hydrologic characteristics were summarized for each catchment study unit.

The topographic features—mean elevation, mean slope, and relief—for each catchment study unit were derived from the USGS 30-m National Elevation Dataset (Gesch and others, 2009). Mean elevation values, in meters, were calculated from raster cells within each catchment study unit. Slope was defined as percent rise over run, for each raster cell, and the mean value calculated for each catchment study unit. Relief is the maximum elevation of a catchment study unit minus its minimum elevation, in meters.

Percent sand was derived from the U.S. Department of Agriculture's STATSGO soils database (Wolock, 1997). Percent sand was used as a proxy of the soil's permeability (the higher the percentage of sand, the more permeable the soil). Percent sand was calculated as a mean percentage by catchment study unit.

The geologic layer is a compilation of igneous and metamorphic crystalline rock, carbonate rock, and siliciclastic rock. This grid was made by overlaying a map layer of carbonate rocks compiled from State geologic maps (Dicken and others, 2005; Nicholson and others, 2005) onto a map layer made up of igneous and metamorphic crystalline rocks and siliciclastic rocks modified from the USGS database of principal aquifers (U.S. Geological Survey, 2003). This resulted in three geology input variables: carbonate rock, siliciclastic rock, and crystalline rock. The dataset was selected because of its consistency across political boundaries. Each rock type was treated as a separate variable and calculated as a percentage by catchment study unit.

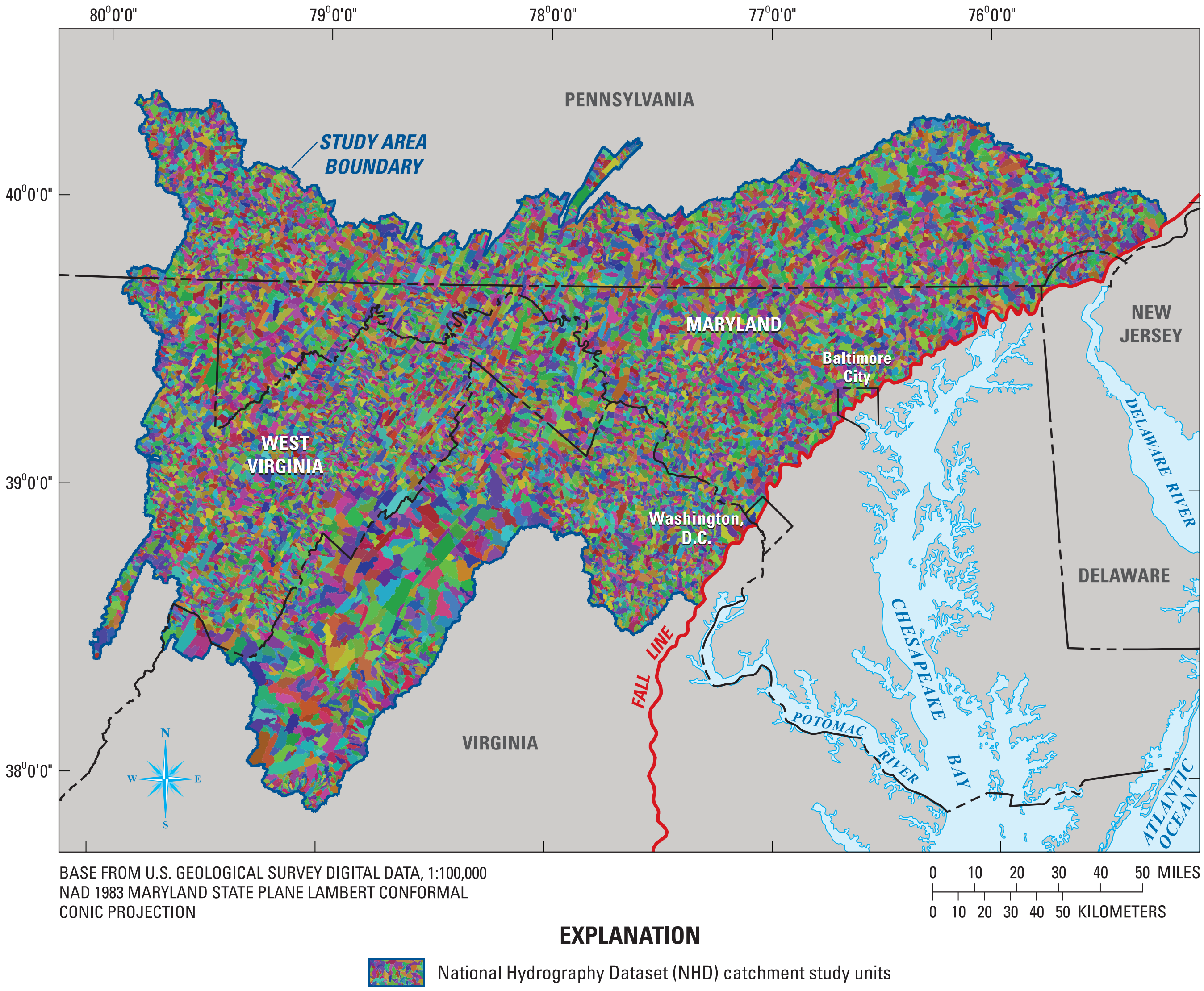

Figure 2. Location of catchment study units derived from NHDPlus.

Statistical Analysis Methods

A PCA was performed to examine the relations among the 10 variables described above and reduce them to a statistically significant number of components (Hamilton, 1992; SAS Institute, 2002). The central idea of a PCA is to reduce the dimensionality of a dataset consisting of a large number of interrelated variables, while retaining as much as possible of the variation present in the dataset (Jolliffe, 2010). The variables with high loadings in a principal component are correlated among themselves and less correlated with other variables. For this study, two criteria were used to determine the number of principal components to use in the subsequent cluster analysis: first, the proportion of variance explained by a component's Eigenvalue (variance of the original components) had to be above 10 percent (table 1), and second, a scree plot showing the break in slope of the Eigenvalues between components 1–4 and components 5–10 for the 10 principal components (fig. 3). Each input variable has a value for each principal component, called a principal component loading. Specific loadings of variables for the four principal components are listed in (table 2).

The results of the PCA are used in a cluster analysis to aggregate the NHDPlus catchments into groups with similar component scores. The cluster analysis was performed using Ward's minimum variance method, an agglomerative hierarchical clustering technique (McGarigal and others, 2000; Ward, 1963). Individual observations are considered unique clusters and are further grouped into larger clusters on the basis of the Euclidean distance between data values of the catchment at its centroid. A similar approach was used by Preston (2000) and Lipscomb (1999). The selection of the final number of clusters is dependent on the study goals, in this case, attempting to account for the most information in the data while maintaining a minimum number of groupings for easy interpretation.

Table 1. Variance explained by principal components.

Principal component	Eigenvalue	Proportion of variance explained	Cumulative variance explained
1	3.40	0.34	0.34
2	2.05	0.21	0.55
3	1.58	0.16	0.70
4	1.28	0.13	0.83

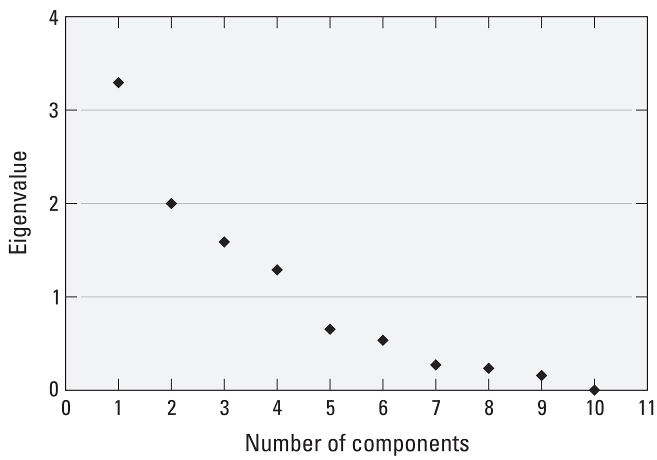

Figure 3. Scree plot showing the Eigenvalues of the principal components.

Statistical Classification of Hydrogeologic Regions

The results of the PCA and subsequent cluster analysis are presented below. Six hydrogeologic regions are presented for the fractured rock area of Maryland. The characteristics of the hydrogeologic regions derived from the principal components and cluster analysis are described. Distinction is made between two hydrogeologic regions both underlain by crystalline rock, and their differences are explained.

Principal Components Analysis

The results of the PCA are four principal component scores for each NHDPlus catchment. The four principal components are ranked by the variance they account for (table 1), and the loadings of the input variables on each principal component are shown in table 2. Loadings in table 2 are rotated using the varimax rotation, which aids in interpreting the principal components (Jolliffe, 2010). The first four principal components account for 83 percent of the variability in the original data. Subsequent principal components contribute decreasing amounts of information (fig. 3), while adding complexity to the PCA results. Therefore, four components were selected for use in the cluster analysis.

Table 2. Principal component loadings.

[--, loadings are less than 0.5; Precipitation-PET, Precipitation minus Potential Evapotranspiration]

Variable	Principal component			
	1	**2**	**3**	**4**
Base-flow index	-0.50	--	--	--
Crystalline rock	-0.48	--	--	--
Siliciclastic rock	0.62	--	--	--
Precipitation-PET	--	0.63	--	--
Recharge	--	0.64	--	--
Sand	--	--	0.58	--
Carbonate rock	--	--	-0.69	--
Elevation	--	--	--	0.36
Relief	--	--	--	0.63
Slope	--	--	--	0.59

Cluster Analysis

The cluster analysis resulted in six clusters that represent hydrogeologic regions. The hierarchical grouping of the first 100 clusters is shown in figure 4, with the hydrogeologic regions color coded, accounting for 65 percent of the information within the principal component data. Six hydrogeologic regions account for much of the variability in the principal component dataset while producing a set of hydrogeologic regions that is relatively easy to describe. The distribution of input variable values for the catchments in each hydrogeologic region is shown in figure 5.

The Piedmont Crystalline Uplands (PCU) hydrogeologic region covers 26 percent of the fractured rock area of Maryland (table 3). It is underlain by igneous and metamorphic crystalline rock and includes areas near the divide between the Monocacy and Patapsco watersheds, much of northern Baltimore, Harford, and Cecil Counties in Maryland and parts of southeastern Pennsylvania. Compared to the other regions, it has high recharge, and a high base-flow index, meaning much of the streamflow in these areas is derived from groundwater.

The Blue Ridge and Piedmont Crystalline Lowlands (BRPCL) hydrogeologic region covers 28 percent of the fractured rock area of Maryland. It is also underlain by igneous and metamorphic crystalline rock, and includes much of the Blue Ridge Physiographic Province (fig. 6) (Fenneman and Johnson, 1946) including parts of western Frederick County, Maryland. Central Carroll and eastern Frederick Counties are in this region, as well as most of Montgomery County. Parts of Howard and Baltimore Counties nearest the Fall Line within the Coastal Plain are also in this hydrogeologic region. Although the underlying rock type is similar to the PCU, there are several differences, including base-flow index, and they will be discussed later in the report.

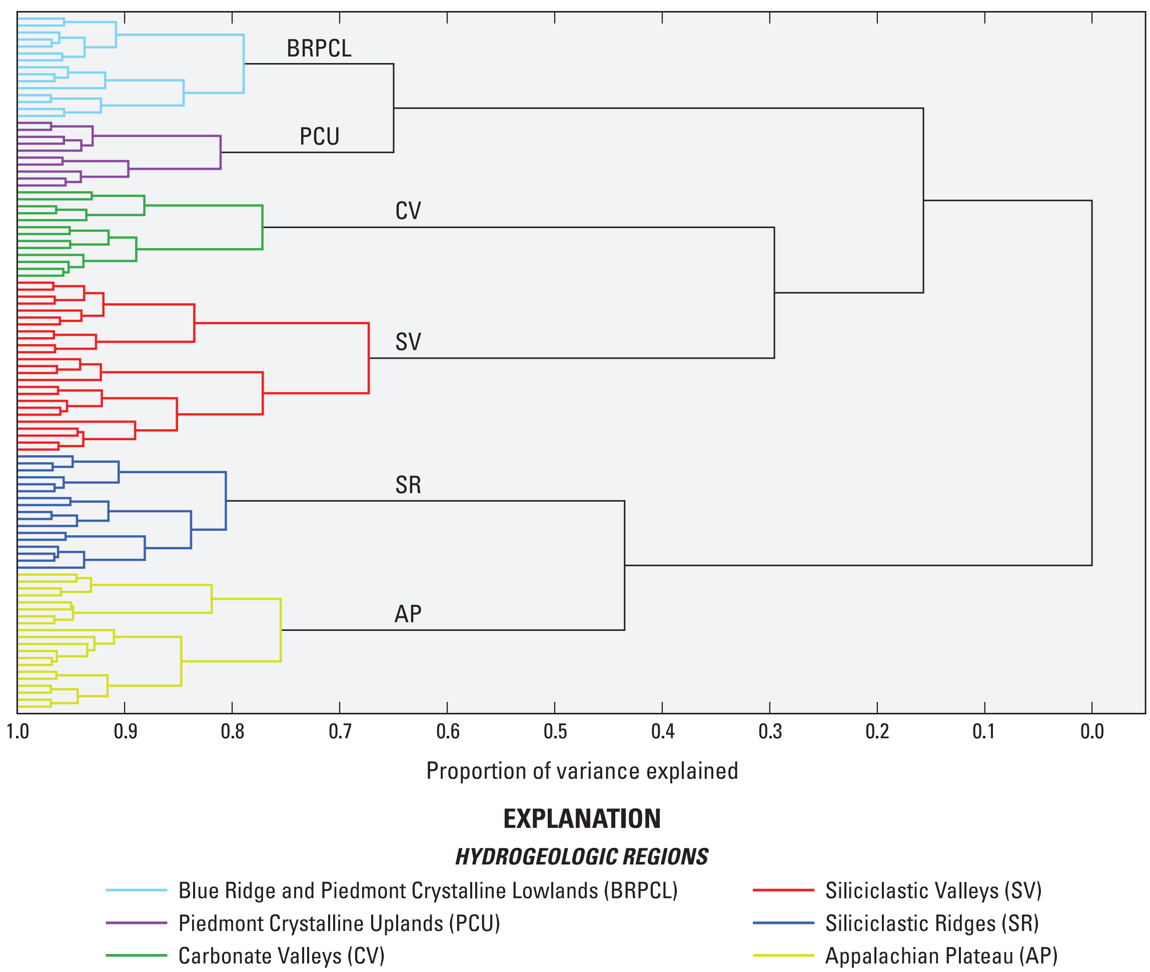

Figure 4. Dendrogram showing the hierarchical grouping of NHDPlus catchments by hydrogeologic region.

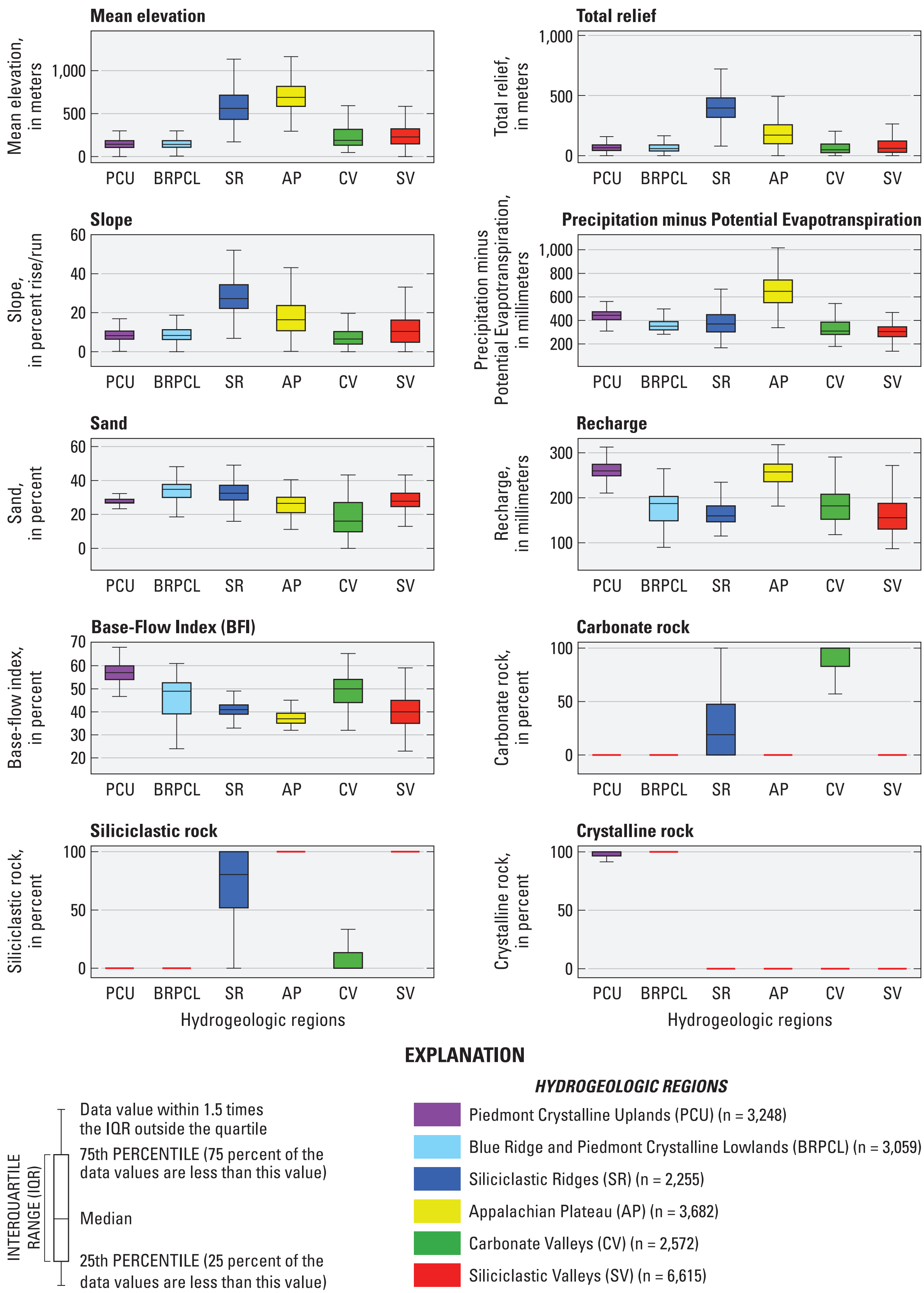

Figure 5. Boxplots showing the distribution of input variables for each hydrogeologic region (n = number of catchment units in each hydrogeologic region).

Table 3. Description of hydrogeologic regions.

[Precipitation-PET, Precipitation minus Potential Evapotranspiration]

Hydrogeologic region	Abbreviation	Percent of Maryland fractured rock terrain	Description
Piedmont Crystalline Uplands	PCU	26	Regions of crystalline rock with low elevation, low relief and low slope, and high base-flow index and high recharge.
Blue Ridge and Piedmont Crystalline Lowlands	BRPCL	28	Regions of crystalline rock with low relief, low elevation, and low slope and sandy soils.
Siliciclastic Ridges	SR	4	Regions of siliclastic rock with high relief and slope, relatively high elevations, and sandy soils.
Appalachian Plateau	AP	17	Regions of siliclastic rock with the highest elevation and Precipitation-PET along with relatively high recharge and low base-flow index.
Carbonate Valleys	CV	10	Regions of carbonate rock with the lowest percent sand, low slope, low relief, and low elevation and relatively high base-flow index.
Siliciclastic Valleys	SV	16	Regions of siliclastic rock with low relief, low elevation, moderately sandy soils, and low Precipitation-PET.

The Siliciclastic Ridges (SR) hydrogeologic region covers only 4 percent of the fractured rock area of Maryland, and is by far the smallest in areal extent in the State. It is underlain by mostly siliciclastic rock with some carbonate rocks. In Maryland, catchments falling into this hydrogeologic region are in Washington, Allegany, and Garrett Counties. This region has high total elevation, steep slopes, and the greatest within-catchment relief.

The Appalachian Plateau (AP) hydrogeologic region covers 17 percent of the fractured rock area of Maryland and includes western Allegany and most of Garrett Counties (fig. 7). This region is almost exclusively underlain by siliciclastic rock. It has the highest mean elevation, the highest Precipitation minus PET values, and high recharge.

The Carbonate Valleys (CV) hydrogeologic region covers 10 percent of the fractured rock area of Maryland. Although only 10 percent of the land area, this is an important region in central and western Maryland because the valleys underlie the cities of Hagerstown and Frederick. Sand content is lowest in this region and base-flow index is high, relative to the other hydrogeologic regions (fig. 5).

The Siliciclastic Valleys (SV) hydrogeologic regions account for 16 percent of the fractured rock area of Maryland. Catchments in this hydrogeologic region are underlain by siliciclastic rocks and sand content in soil is moderately sandy. Precipitation minus PET, recharge, and base-flow index are relatively low, likely because of topographic shadow effect. These regions include the Gettysburg Basin, and part of northern Frederick and Carroll Counties, as well as the Culpepper Basin, with parts of southern Frederick and western Montgomery Counties. Parts of Washington and most of Allegany County are included in this hydrogeologic region.

Details of the New Classification of the Crystalline Rock Area

Population growth and accompanying water demands are anticipated near the Baltimore and Washington, D.C. metropolitan areas, much of which are areas underlain by fractured crystalline rock. As described by Fleming and others (2012), it is important to understand the factors affecting reliable yields of individual groundwater supplies and to understand the potential impacts from newly developed groundwater supplies to existing water users. This report describes a hydrogeologic classification for all of Maryland and parts of adjacent states underlain by fractured rock, but also shows a new classification for the crystalline rock area which makes up over 50 percent of the fractured rock area in Maryland (table 3). The differences between the two crystalline rock hydrogeologic

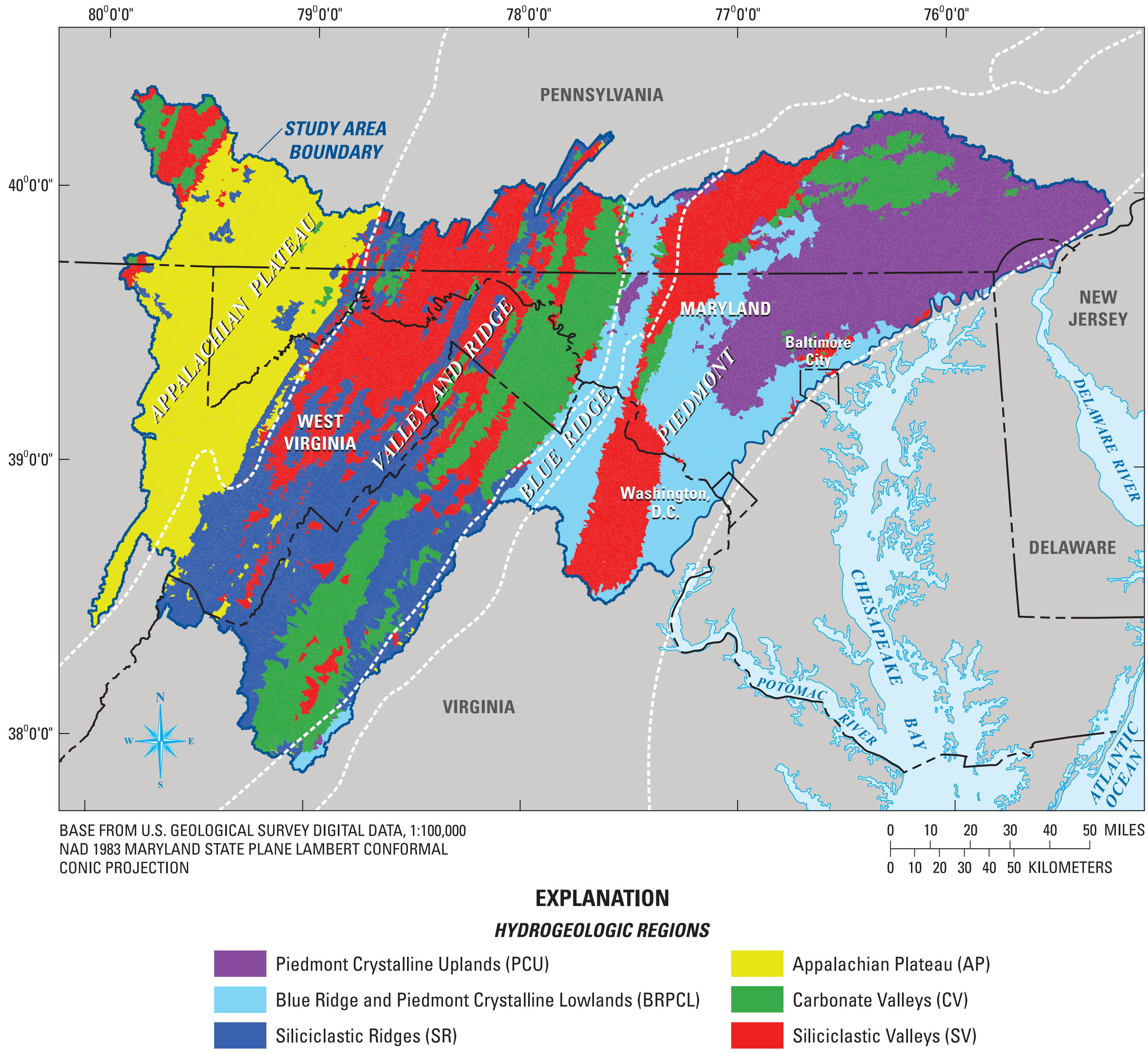

Figure 6. Hydrogeologic regions derived from hierarchical clustering of NHDPlus catchments by principal components for entire study area. (Dashed lines are from Fenneman and Johnson, 1946).

regions PCU and BRPCL are shown in figure 8. PCU has a higher base-flow index, recharge, and Precipitation minus PET than BRPCL (table 4). PCU includes headwater catchments along the divide of the Monocacy River and Patapsco River watersheds in Maryland (fig. 7). Headwater areas can be more dependent on groundwater discharge to generate streamflow and maintain base flow (Winter, 2007). This new classification in the crystalline rock areas of Maryland identifies those areas where groundwater discharge to streams is a larger component of total streamflow and supports results from hydrograph separation analysis performed by the MDE WSP (Patrick Hammond, Maryland Department of the Environment, Water Supply Program, oral commun., 2011). The differences between PCU and BRPCL described in this report indicate that streamflow in PCU may be more sensitive to changes in groundwater levels because groundwater is a larger component of the water budget.

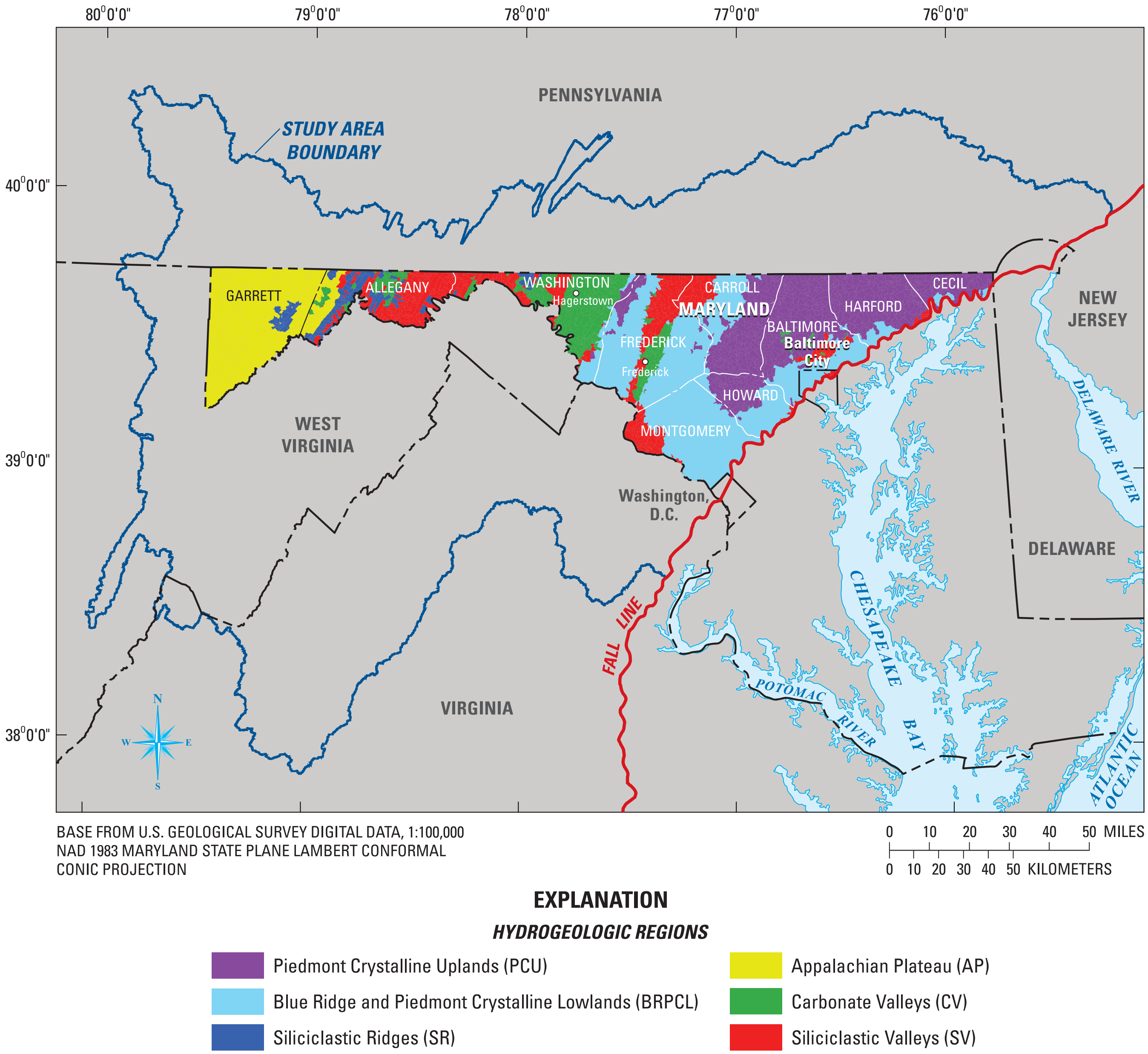

Figure 7. Hydrogeologic regions derived from hierarchical clustering of NHDPlus catchments by principal components for Maryland.

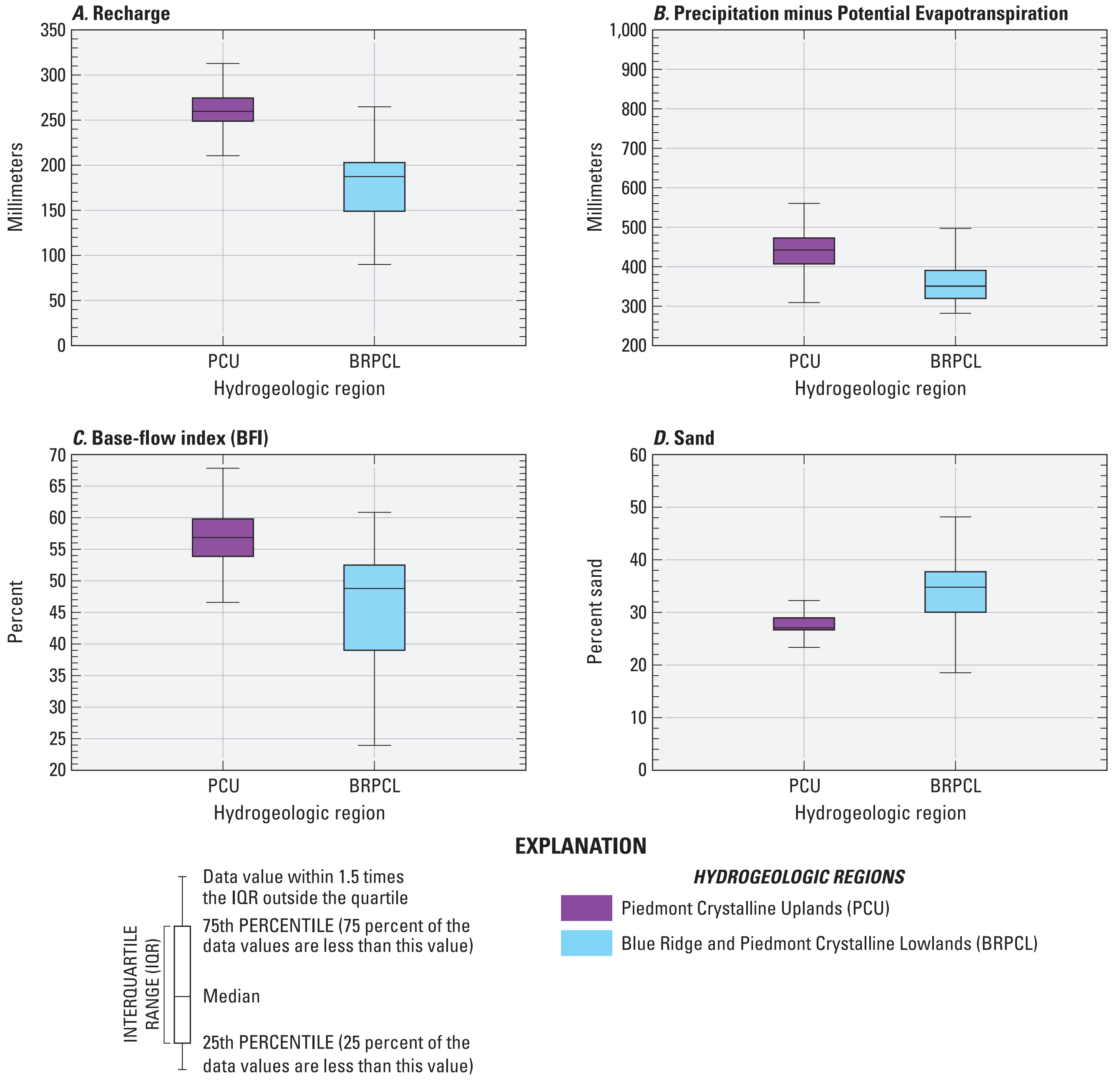

Figure 8. Boxplots showing *(A)* recharge, *(B)* Precipitation minus Potential Evapotranspiration, *(C)* base-flow index (BFI), and *(D)* sand for Piedmont Crystalline Uplands and Blue Ridge and Piedmont Crystalline Lowlands hydrogeologic regions.

Table 4. Statistically significant differences of descriptive variables between the two crystalline-rock hydrogeologic regions.

[<, less than]

Variable	Unit	Median Piedmont Crystalline Uplands	Median Blue Ridge and Piedmont Crystalline Lowlands	p-values	Statistically significant differences (alpha = 0.0001)
Mean elevation	Meters	143.485	141.900	0.1306	No
Total relief	Meters	72.980	65.850	0.0072	No
Slope	Percent rise/run	8.195	8.270	0.1059	No
Climate	Millimeters	442.455	350.410	< 0.0001	Yes
Sand	Percent	27.050	34.760	< 0.0001	Yes
Recharge	Millimeters	259.845	187.370	< 0.0001	Yes
Base-flow index	Percent	57.000	48.920	< 0.0001	Yes

Summary

A hydrogeologic framework for the fractured rock area of Maryland was derived using geographic information system applications and multivariate statistical methods. The goal of this new classification is to provide future investigations of groundwater resources with a hydrogeologic framework. Further investigation is needed within these hydrogeologic regions to determine how other factors, such as overburden thickness, topographic position, and well yields relate to one another. The study area is bounded by the Fall Line to the east and expanded beyond the Maryland state boundary to include parts of the 8-digit Hydrologic Units with rivers that flow through the fractured rock area of Maryland. The study area was further subdivided into 21,431 catchments from the National Hydrography Dataset Plus. Geologic, topographic, climatic, and soils data were compiled for each catchment to perform a principal components analysis and subsequent cluster analysis. These analyses resulted in six hydrogeologic regions that correspond well with previous regional frameworks and provide new information in crystalline rock areas. Delineation of hydrogeologic regions in the crystalline rock area of Maryland differed from previous frameworks that were based solely on physiography. Differences in recharge, base-flow index, and Precipitation minus Potential Evapotranspiration are the significant factors for this new classification. The results of this study provide a georeferenced hydrogeologic framework to support the Maryland Fractured Rock Water Supply Study being conducted by the U.S. Geological Survey, the Maryland Department of the Environment Water Supply Program, and the Maryland Geological Survey.

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Appendix

Hydrogeologic regions (HRs) for the fractured rock area of Maryland and parts of adjacent states are available online in a comma-delimited ASCII file at *http://pubs.usgs.gov/sir/2013/5043/frac_rx_HRs.csv*. Variables in the file are described in the header (denoted by lines starting with "#") and also include principal component scores that were derived from principal components analysis on the 10 original input metrics and were used in cluster analysis to create the HRs. The file includes the hydrogeologic regions predictions for local catchments contributing to 21,431 stream reaches in the fractured rock area of Maryland and adjacent states as defined by the National Hydrography Dataset Plus (NHDPlus) medium resolution (1:100,000-scale) geospatial dataset (Horizon Systems, 2010).

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