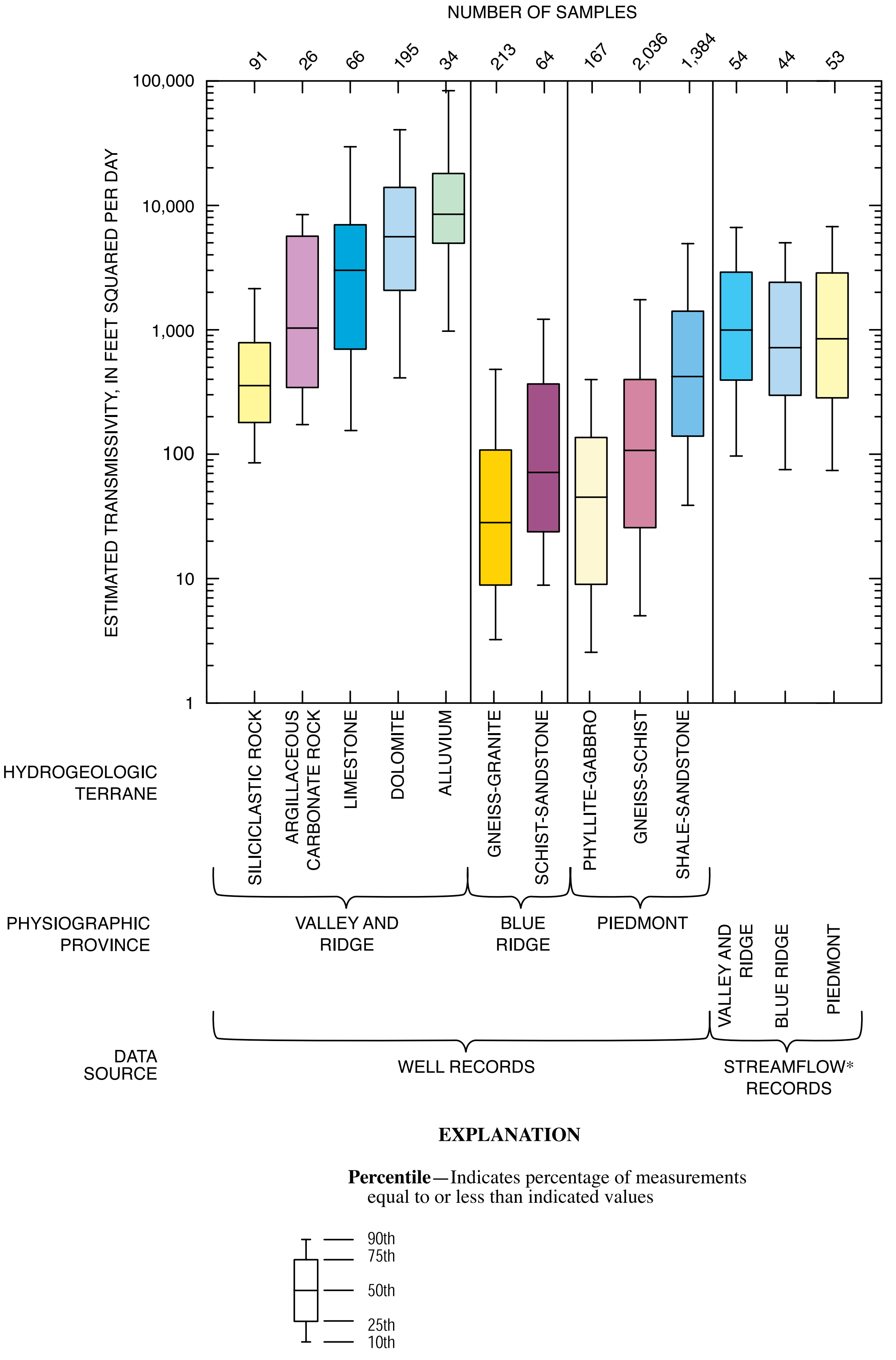


*Note: Transmissivity values estimated from streamflow records are based upon an assumed log-normal distribution.

Figure 4. Variation of transmissivity values estimated from well records and streamflow records in the three physiographic provinces.

The equation given by Theis and others (1963, eq. 6, p. 337) computes a value of T′, which must be used in a diagram (Theis and others, 1963, fig. 99, p. 334) to estimate transmissivity from specific capacity. Because it is difficult to select values of transmissivity from this diagram for specific capacity values less than 1.0, the original equation given by Theis and others (1963, eq. 1, p. 332) was modified for contemporary units and programmed into a spreadsheet to iteratively calculate transmissivity. The modified equation is:

$$T = 15.32\frac{Q}{s}\left(-0.577 - \ln\left(\frac{r^2 S'}{4Tt}\right)\right) , \qquad (1)$$

where

T is transmissivity, in feet squared per day;
Q is discharge of the well, in gallons per minute;
s is drawdown in the pumping well, in feet;
Q/s is specific capacity, in gallons per minute per foot;
ln is the natural logarithm;
r is the radius of the pumped well, in feet;
S is the storage coefficient, in feet per foot; and
t is the time since pumping started, in days.

The following average values for well radius and duration of pumping were determined from data for municipal and industrial wells in the GWSI database; radius of 0.33 ft (8-inch diameter well) and time of 0.33 day (8 hours of pumping). A storage coefficient of 0.0005 was estimated from values in the literature as described heretofore. These three fixed values were used in all calculations of transmissivity from specific capacity. Using the spreadsheet, a final value of transmissivity was calculated by iteration from an initial estimate until final and initial transmissivity values differed by less than 0.01 percent. This convergence typically occurred within three to five manual iterations.

Considering all 10 of the hydrogeologic terranes, 80 percent (10th to 90th percentile) of the values for estimated transmissivity range from 2.6 to 84,000 ft^2/d (fig. 4). For any 1 of the 10 hydrogeologic terranes, the interquartile range (25th to 75th percentile) is typically slightly greater than one order of magnitude; the siliciclastic-rock and alluvium hydrogeologic terranes have the smallest ranges—slightly greater than one-half order of magnitude. Well records were analyzed separately for each of the three physiographic provinces. Consequently, pairs of terranes where each is selected from a different province may have estimated transmissivity distributions with considerable overlap. As examples, siliciclastic rock (Valley and Ridge) and shale-sandstone (Piedmont), gneiss-granite (Blue Ridge) and phyllite-gabbro (Piedmont), and schist-sandstone (Blue Ridge) and gneiss-schist (Piedmont) are three pairs of hydrogeologic terranes from different physiographic provinces that are not likely to have significant differences in their estimated transmissivities. In contrast, the rock types in the three hydrogeologic terranes of the Piedmont could be regrouped into five new terranes and still have significant differences among their median values of estimated transmissivity because of the large sample of wells in the Piedmont. However, the large overlap among the five distributions of estimated transmissivity for these five new terranes probably would not indicate a usable difference among the five terranes for water-supply purposes; fewer terranes (three) would be more useful.

The transmissivity varies greatly among the hydrogeologic terranes in part because of differences in the character of the water-yielding openings within each terrane. These openings include (1) intergranular openings in sand and gravel of glacial origin; (2) conduits and caverns dissolved in carbonate rocks; (3) networks of many small dissolution openings along joints, bedding planes, or fractures, that when acting together, provide a uniform distribution of permeability of large to moderate magnitude; and (4) networks of many openings along joints, bedding planes, or fractures that are partly plugged with clay residuum and, that when acting together, provide a uniform distribution of permeability of moderate to low magnitude. In those terranes that are characterized by openings of type 1, 3, and 4, laminar flow predominates; however, in terranes with conduits and caverns, turbulent flow may occur.

For the hydrogeologic terranes in which laminar flow predominates, the methods developed for aquifer-test analysis for porous media are applicable. For the hydrogeologic terranes in which turbulent flow may occur, these aquifer-test methods only generally indicate how an equivalent porous media might respond to stress. The response curves of aquifer tests outside of cavernous areas generally match the classic non-leaky type curves, especially for short tests, and the leaky or delayed-yield type curves for longer tests. Water-level response in cavernous areas can be unusually small, almost instantaneous, and approximately the same at the pumped well and at a considerable distance from the pumped well. In areas in which ground-water flow is predominantly in conduits, caverns, joints, bedding planes, and fractures, cones of depression are typically asymmetric.

When all 10 hydrogeologic terranes are considered together, the range in estimated transmissivity is more than 4 orders of magnitude (fig. 4) as a result of the wide variation in hydrogeologic conditions. The conditions that most affect transmissivity are the type of water-yielding openings (intergranular, conduit, or fracture), the rock composition, and the degree of dissolution. In unconsolidated deposits, high transmissivities usually are associated with clean, coarse-grained materials such as glacial outwash within the alluvium hydrogeologic terrane. In consolidated rocks, high transmissivities usually are associated with soluble rocks in areas in which vigorous ground-water flow has enhanced development and widening of dissolution openings. The variations in transmissivities for the geographic areas underlain by the terranes are produced by a combination of hydrologic and geologic conditions (table 1). The ranges in estimated transmissivities given in table 1 are a generalization of the interquartile ranges shown for each hydrogeologic terrane in figure 4. An exception is the western-toe, whose range was taken from a source document (see table 1, footnote b).

In general, the largest values of transmissivity (greater than 7,000 ft^2/d for the 75th percentile in table 1) occur in the alluvium hydrogeologic terrane near the northeastern end of the

Table 1. Hydrogeologic conditions that control the transmissivity of the hydrogeologic terranes in various provinces and locations in the Appalachian Valley and Piedmont Regional Aquifer-System Analysis study area.

[Range in estimated transmissivity is approximately between the 25th percentile and the 75th percentile of a distribution of estimated transmissivities (fig. 4, with the exception of western-toe); ft^2/d, foot squared per day]

Terrane[a]	Locality	Water-yielding opening	Rock composition	Degree of dissolution	Generalized, interquartile range in estimated transmissivity, in ft^2/d
Alluvium	Glacial margin in Pennsylvania and New Jersey	Intergranular	Siliciclastic, some carbonate	Not a factor	5,000 - 17,000
Western-toe subdivision of the dolomite terrane (Elkton aquifer)	Southeastern margin of the Valley and Ridge	Conduits and caverns	Dolomite	Well developed	900 - 17,000[b]
Dolomite	Valley and Ridge; carbonate-rock valleys in the Blue Ridge and the Piedmont	Conduits and dissolution networks	Dolomite, limestone, marble	Moderate to well developed	2,000 - 13,000
Limestone	Valley and Ridge; carbonate-rock valleys in the Blue Ridge and Piedmont	Dissolution networks and conduits	Limestone, marble	Moderate to well developed	700 - 7,000
Argillaceous carbonate rock	Valley and Ridge	Minor dissolution networks	Argillaceous limestone and dolomite; carbonate-rich shale	Poor to moderately developed	300 - 6,000
Siliciclastic rock; shale-sandstone	Valley and Ridge; Piedmont	Fracture networks; minor intergranular	Sandstone, siltstone, noncalcareous shale	Not a factor	130 - 1,300
Schist-sandstone; gneiss-schist	Blue Ridge; Piedmont	Fracture networks	Sandstone, schist, gneiss, etc.	Not a factor	20 - 400
Gneiss-granite; phyllite-gabbro	Blue Ridge; Piedmont	Fracture networks	Granite, gneiss, phyllite, gabbro, etc.	Not a factor	9 - 130

[a] With the exception of the western-toe, see figs. 3 and 4 for mapped distribution of hydrogeologic terrane, description, and estimated transmissivity. For western-toe subdivision of the dolomite terrane (Elkton aquifer) see Hollyday and Hileman, 1996, figs. 7 and 8, and p. C13-C16 for distribution and description.

[b] Based on an interquartile range in specific capacity of 3.3 to 55 (gal/min)/ft (Hollyday and Hileman, 1996, fig. 13, p. C23).

Valley and Ridge (fig. 3), in the western-toe subdivision of the dolomite terrane (Hollyday and Hileman, 1996, p. C13-C16) along the southeastern margin of the Valley and Ridge, in the dolomite hydrogeologic terrane throughout the Valley and Ridge, and within carbonate-rock valleys in the Blue Ridge and Piedmont Physiographic Provinces (Mesko and others, 1999, fig. 1). The alluvium hydrogeologic terrane is adjacent to the glacial margin. It is derived from outwash sand and gravel, and has large, well-connected intergranular pore spaces. The western-toe subdivision of the dolomite hydrogeologic terrane (renamed the Elkton aquifer in Hollyday and others, 1997) is in an area of high relief at the toe of the slope of the northwestern edge of the Blue Ridge Mountains. The western-toe subdivision (Elkton Aquifer) is dolomite overlain by saturated thick residuum, colluvium, and alluvium, and contains numerous caverns and conduits. The dolomite terrane throughout much of the Valley and Ridge has moderate relief resulting from a resistant, protective cap of residual chert. The terrane is predominantly dolomite and limestone, and contains conduits and dissolution networks. The carbonate-rock valleys are in four areas of low to moderate relief in the Piedmont and in two areas of high relief in the Blue Ridge. In the Blue Ridge, these valleys are typically adjacent to highlands underlain by quartzite. The erosion of the quartzite results in a colluvial and alluvial apron covering the limestone, dolomite, and marble in the valley, a hydrologic setting very similar to the Elkton aquifer.

The smallest values of transmissivity (less than 1,300 ft^2/d) occur in the hydrogeologic terranes of dense, consolidated rock that lack significant amounts of soluble, carbonate minerals throughout the three physiographic provinces. These terranes (siliciclastic rock, shale-sandstone, schist-sandstone, gneiss-schist, gneiss-granite, and phyllite-gabbro) occupy almost all of the Blue Ridge and Piedmont Physiographic Provinces and much of the northern half of the Valley and Ridge Province (fig. 3). The terranes include siliciclastic sedimentary, metamorphic, and igneous rocks with fracture networks that may be plugged, more or less, with fine-grained, insoluble residue.

Transmissivity from Streamflow Recession

Streamflow recession index values (Rutledge and Mesko, 1996) were transformed to estimates of transmissivity (fig. 4) using the method described by Rorabaugh and Simons (1966, p. 12). Percentile values of recession index for basins in each of the three physiographic provinces were picked from boxplots of the distribution of recession-index values (Rutledge and Mesko, 1996, fig. 7, p. B11).

The equation given by Rorabaugh and Simons (1966, p. 12) may be rearranged to the following form to estimate transmissivity from recession index (Rutledge and Mesko, 1996, p. B15):

$$T = \frac{0.933 S_y a^2}{K}, \qquad (2)$$

where

T is transmissivity, in feet squared per day;

S_y is the apparent specific yield of the zone of water-table fluctuation, in feet per foot;

a is the average distance from the stream to the hydrologic divide, in feet; and

K is the recession index, in days per log cycle of decline in discharge.

Although estimates of transmissivity could be made for specific basins, the intent was to give estimates of the range in transmissivities in each of the physiographic provinces in the APRASA study area. For this estimate, the 25th and 75th percentile values of recession indexes for each province as provided by Rutledge and Mesko (1996, fig. 7, p. B11) were used. A range in a of 1,000 to 2,000 ft and a range in S_y of 0.01 to 0.08 were obtained by reviewing the literature (Rutledge and Mesko, 1996, p. B15). These ranges were used in equation 2 in order to estimate log-normal distributions of transmissivity for the three physiographic provinces (fig. 4).

The distributions of transmissivities estimated from streamflow records generally lie within the midrange of distributions estimated from well records when all distributions are considered together (fig. 4). This similarity suggests that the two sets of distributions may be related to the same physical controls. The variation in the distributions estimated from streamflow records, however, is much less than the variation in distributions estimated from the well records. This difference may be due to the fact that streamflow is the integrated discharge from several rock types or terranes and is derived primarily from regolith and rock at shallow depths. Integrated discharge and release from shallow depths would tend to reduce the variation in estimated transmissivities. Creating subsets of the recession-index data by basins underlain by rocks with predominantly small well yields and basins underlain by rocks with large well yields resulted in greatly increased variation in the distributions of recession index (and, presumably, estimated transmissivity) for the Valley and Ridge and the Piedmont Physiographic Provinces (Rutledge and Mesko, 1996, figs. 13 and 14, p. B16 and B17).

Ground-Water Recharge and Discharge, and Hydrologic Budgets

Mean rates of ground-water recharge and discharge were estimated by an analysis of the base flow of streams (Rutledge and Mesko, 1996, p. B19-B28) (fig. 5). Ground-water recharge and discharge are important components of the hydrologic budget of any basin. The analytical methods were applied over 10- or 30-year periods of continuous record, so that the effects of changes in ground-water storage could be considered negligible. The mean ground-water discharge (base flow), therefore, may be considered to be equal to effective recharge. The mean ground-water recharge should exceed the mean effective

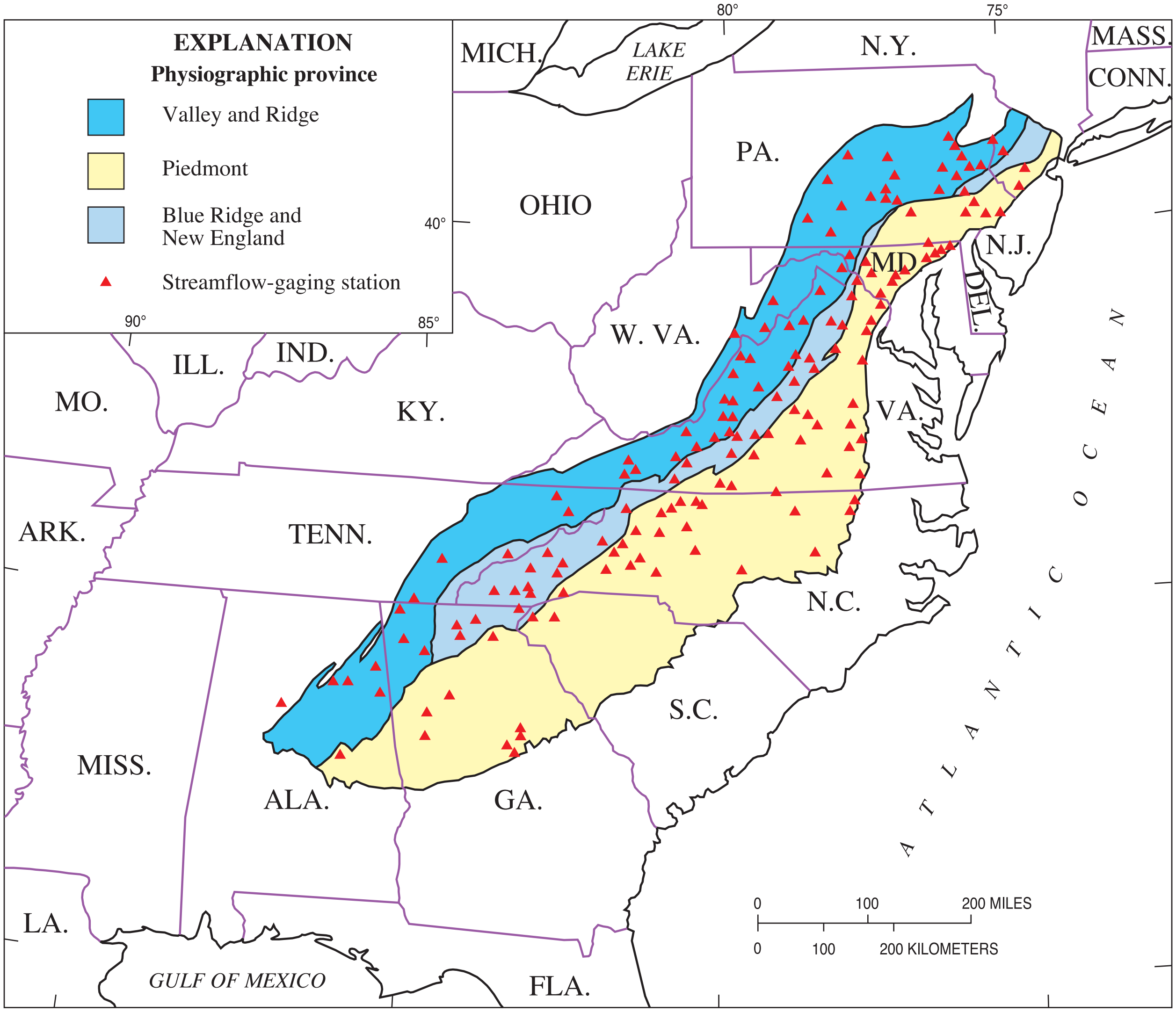


Figure 5. Distribution of streamflow-gaging stations in the study area that were used in recession and base-flow analysis.

recharge by an amount equal to the riparian evapotranspiration—losses to the atmosphere from the stream channel and adjacent, shallow ground water.

Two computerized methods were used in base-flow analysis—recession-curve displacement, which estimates ground-water recharge; and base-flow record estimation (adapted from methods called streamflow partitioning), which estimates ground-water discharge. The documentation of the computerized methods, including detailed discussion of the mathematical development of the methods, instructions for execution of the programs, and comparisons between results of the programs and those of the corresponding manual methods were reported by Rutledge (1998).

Ground-water recharge and discharge (effective recharge) were determined by independent methods. Yet the sense and magnitude of the difference between recharge and discharge (table 2) is to be expected if a small amount of evapotranspiration were occuring from the ground-water reservoir. Riparian-zone evapotranspiration ranges between 0.4 and 3.8 in/yr (Rutledge and Mesko, 1996, p. B21), and mean riparian-zone evapotranspiration (the difference between mean recharge and mean discharge) is usually between 1 and 2 in/yr (table 2).

The median of the mean ground-water discharge (table 2) may be used to calculate a rough estimate of total ground-water discharge in the study area. If the 157 basins are assumed to be representative of the entire study area, then a median ground-water discharge of 12 in/yr (table 2) indicates that as much as 90 Bgal/d of ground water may be available for use in the 142,000 mi^2 study area.

A comparison of precipitation and recharge for the study area shows a considerable amount of scatter (Rutledge and Mesko, 1996, fig. 19); however, the best-fit linear equation has an approximate unit gradient of 0.86 and an X-intercept of about 28 in/yr. The intercept may depend on total evapotranspiration and may represent a threshold that must be exceeded by precipitation before recharge is significant. The relation between precipitation and recharge for each physiographic province is positive (Rutledge and Mesko, 1996, fig. 20). The

Table 2. Statistical distribution of ground-water recharge and discharge, in inches per year, for basins in the Appalachian Valley and Piedmont Regional Aquifer-System Analysis study area.

Distribution	1981 to 1990 (number of samples, 157)		1961 to 1990 (number of samples, 89)	
	Mean recharge	Mean discharge	Mean recharge	Mean discharge
Maximum	46	42	50	46
75th percentile	18	16	19	17
Median	13	12	13	12
25th percentile	10	9	10	9
Minimum	5	4	6	5

relation between basin relief and recharge tends to be negative for the Valley and Ridge Physiographic Province; however, the relation is positive for the Blue Ridge and Piedmont Physiographic Provinces (Rutledge and Mesko, 1996, fig. 21). For these two physiographic provinces, a reasonably good estimator of recharge can be derived from precipitation and basin relief (fig. 6).

The base-flow index is calculated as the ratio of mean ground-water discharge (base flow) to mean streamflow. This index is ideal for basin comparisons when the various basins have differing periods of streamflow record or when the available period of record is short. The base-flow index of 157 basins in the APRASA study area ranges from 32 to 94 percent, and the 25th, 50th, and 75th percentiles are 59, 67, and 75 percent, respectively. The base-flow index is exceptionally large in the Blue Ridge Physiographic Province for the 28 basins south of Roanoke, Va., as compared with the index for 16 basins in the northern part of the province. This anomaly is accompanied by a significant increase in precipitation and a very slight decrease in evapotranspiration south of Roanoke.

Simple water-budget equations were combined with the results of the base-flow analysis to obtain hydrologic budgets of basins in the study area. Except for the Blue Ridge Physiographic Province south of Roanoke, Va., the median values for components of the budgets of the study area (sample size, 72) are precipitation, 43 in/yr; evapotranspiration, 26 in/yr; streamflow, 16 in/yr; ground-water recharge, 12 in/yr; ground-water discharge, 11 in/yr; and storm runoff, 6 in/yr. For the southern part of the Blue Ridge Physiographic Province (sample size, 17), the median values are precipitation, 58 in/yr; evapotranspiration, 25 in/yr; streamflow, 38 in/yr; ground-water recharge, 33 in/yr; ground-water discharge, 29 in/yr; and storm runoff, 8 in/yr. The map location, physical characteristics, streamflow recession characteristics, components of hydrologic budgets, and base-flow index for each basin are listed in Rutledge and Mesko (1996, tables 1, 2, 3, and 4).

Ground-Water Flow in Selected Basins

The fundamental approach to quantifying ground-water flow in the APRASA was similar to that of other RASA studies (Sun, 1986) in that available geologic and hydrologic data were compiled and used to describe the regional aquifer systems. In the APRASA study, however, the lack of regional continuity of the ground-water reservoirs and the diverse nature of the aquifers devalued the development of a regional ground-water flow model for the entire study area. A more logical approach was to select "type areas" that were considered representative of conditions in those settings and hydrogeologic terranes that are most important to water supply. For this approach, a flow system was conceptualized for each hydrogeologic terrane or combination of terranes, and ground-water flow in selected type areas was analyzed and simulated by using ground-water flow models. These models were used primarily to improve the understanding of ground-water flow related to various hydrogeologic components and streams. At the time of the study, pumping stresses were so small or localized in the type areas that it would have been very difficult to calibrate a transient-flow model with any regional significance. Techniques used to quantify recharge, discharge, storage, and flow

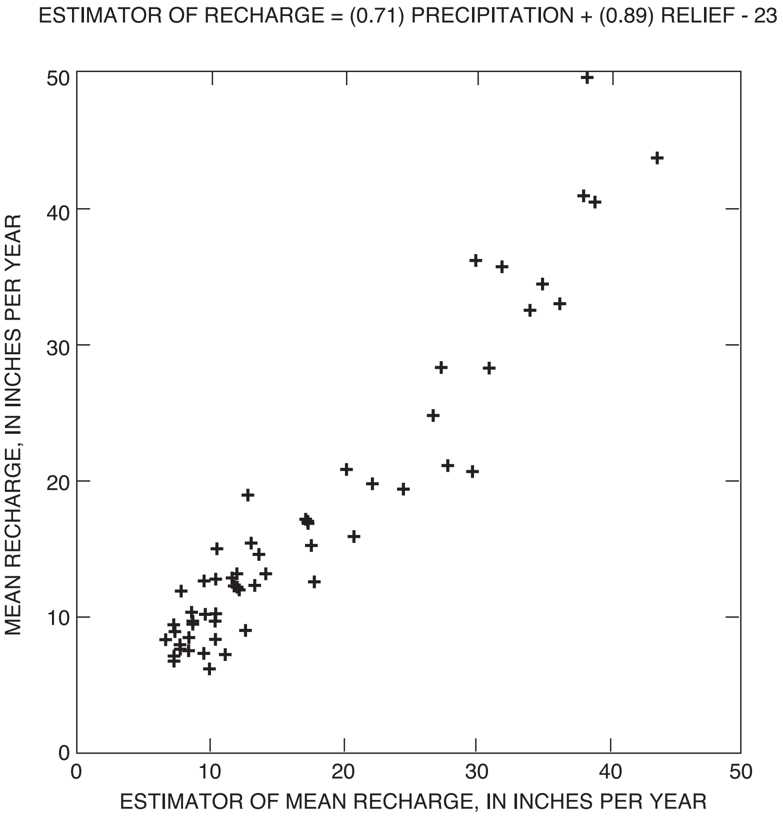


Figure 6. Relation between mean recharge and an estimator of mean recharge that is a linear function of precipitation and relief for the Blue Ridge and Piedmont Physiographic Provinces.

within the type areas may be transferable to other areas with similar hydrologic settings and hydrogeologic terranes.

The three published type-area studies (fig. 7) and the hydrogeologic settings (conceptual flow systems) that they represent are Cumberland Valley, Pa., (Chichester, 1996) with folded crystalline carbonate rocks mantled by thick and thin regolith; Indian Creek, N.C., (Daniel and others, 1997) with massive and foliated crystalline silicic rocks mantled by thick regolith; and Stony Brook, N.J., (Lewis-Brown and Jacobsen, 1995) with Mesozoic sedimentary and igneous rocks mantled by very thin regolith. The Cumberland Valley type area is mostly within the Valley and Ridge Physiographic Province. The Indian Creek and Stony Brook type areas are within the Piedmont Physiographic Province. No type area was selected in the Blue Ridge Physiographic Province because of the lack of available data to construct or calibrate a model. However, the hydrogeologic setting in most of the Blue Ridge Physiographic Province is similar to the Indian Creek type area, provided that the greater relief—typical of the Blue Ridge—is taken into account. Small areas of the Blue Ridge that are underlain by carbonate rocks have a hydrogeologic setting similar to the Cumberland Valley type area.

The type areas and each associated model are similar in several ways. The average annual precipitation for all three sites is between 40 and 48 inches. The ground-water flow model selected for simulation in each type area was a modular, three-dimensional, finite-difference, ground-water flow model (MODFLOW) documented by McDonald and Harbaugh (1988). In both the conceptual and digital models, flow through fractured and dissolved rock was simulated as flow through an equivalent porous medium. All three models were designed to simulate steady-state conditions. All model grids had equal spacing and were set parallel to bedding or foliation. Permeability was not considered isotropic and typically was least in the direction perpendicular to bedding or foliation. The water table was considered as the top of the model and impermeable rock

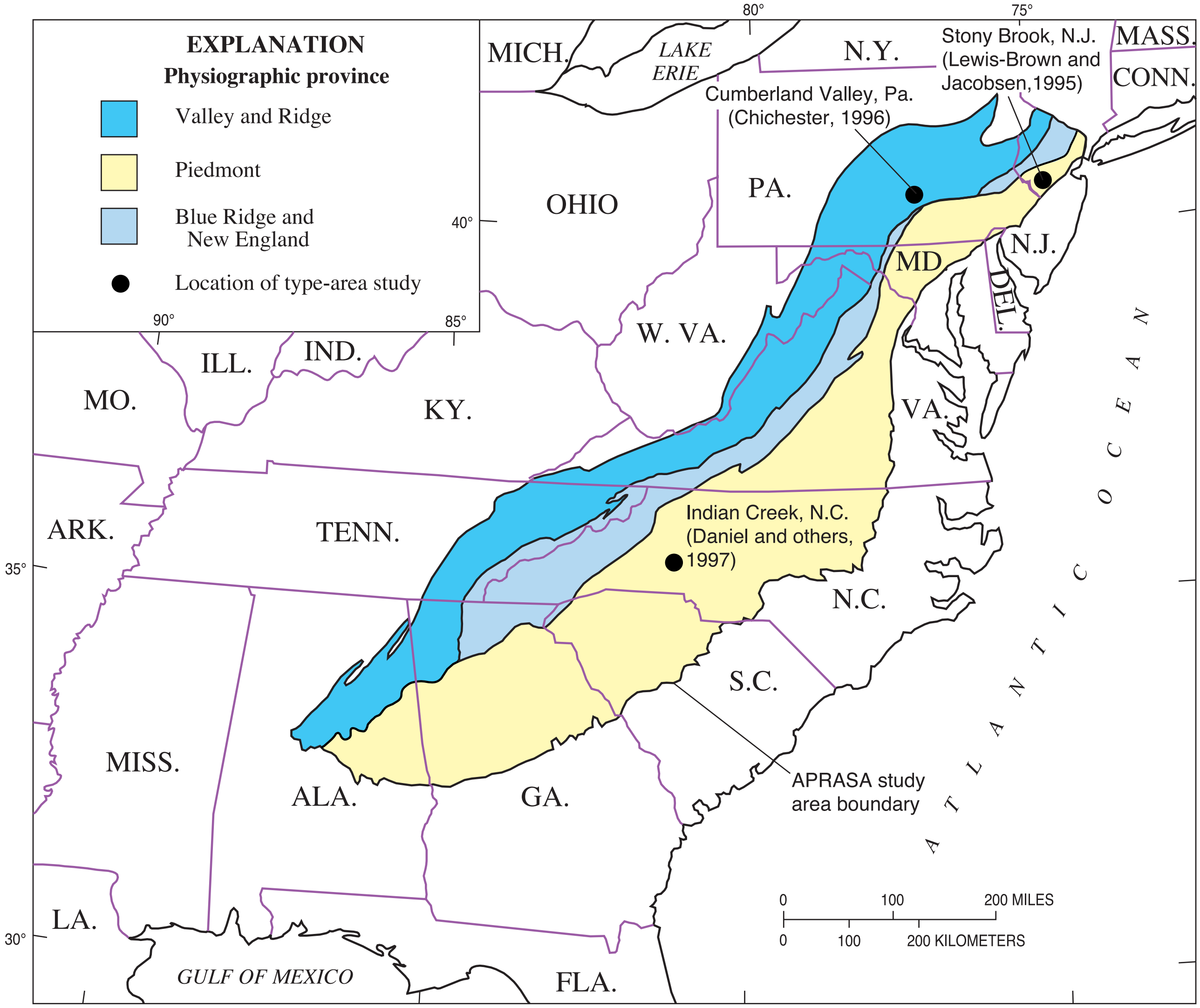


Figure 7. The Appalachian Valley and Piedmont Regional Aquifer-System Analysis (APRASA) study area and location of three type-area studies where ground-water flow was modeled.

as the bottom of the model. Vertical changes in transmissivity were incorporated into the models, with the simulated transmissivity decreasing rapidly with depth below the water table and decreasing rapidly downdip in the case of gently dipping beds (Stony Brook type area). Results indicate that the volume of lateral ground-water flow decreases significantly in layers deeper than the first one to three layers below the water table. For all three type-area models, more than 54 percent of the ground-water flow occurs in the top one to three layers.

The three type areas and the models have several differences (table 3). The Cumberland Valley, Pa., type area contains four of the five hydrogeologic terranes of the Valley and Ridge Physiographic Province and has the largest stream basin area. The Stony Brook and Indian Creek type areas contain the most transmissive hydrogeologic terranes in the Piedmont, but within much smaller stream basins. The Cumberland Valley, Pa., type area has much thicker regolith in some areas, greater depth to water, greater recharge, greater bedrock transmissivity, and larger ground-water withdrawals than the other two type areas. The Cumberland Valley, Pa., type-area model had an intermediate number of layers and the least anisotropy. Results indicate that the Cumberland Valley, Pa., type area had significantly more interbasin flow compared to the Stony Brook, N.J., type area—the only other type area with more than a single stream drainage basin. The larger interbasin flow appears to be related to the karst carbonate rocks that underlie the two basins within the Cumberland Valley, Pa., type area. Although specific values of model parameters are unlikely to be transferable to other areas, the methods and results of ground-water flow simulation used for the type area could guide further investigations to quantify ground-water conditions and flow in similar hydrogeologic settings and terranes.

Water Geochemistry

The chemistry of the water in rocks (including alluvium), springs, and streams in the three physiographic provinces was determined by assembling and interpreting 196,852 analyses of water from 15,263 sites stored primarily in the water-quality database in NWIS. The geographic distribution of water-quality sites in the study area is highly uneven (Briel, 1997, figs. 1, 2, and 3). For ground-water and surface-water sites, the majority of data are for the Piedmont Physiographic Province with emphasis on sites in Maryland, New Jersey, and Pennsylvania. For springs, most of the data are for the Valley and Ridge Physiographic Province with emphasis on sites in Maryland and Pennsylvania. For all three types of sites, the least amount of data is for the Blue Ridge Physiographic Province.

In the study area as a whole, typical ground water is not highly mineralized: the median dissolved-solids concentration is 164 mg/L. Typical ground water also is nearly neutral (median pH is 6.9) and is classified as moderately hard (median hardness is 82 mg/L as $CaCO_3$). The chemical quality of ground water in each physiographic province, however, differs substantially.

Ground water in the Valley and Ridge Physiographic Province has the largest median dissolved-solids concentration (226 mg/L, fig. 8), is slightly basic (median pH is 7.3), and is classified as hard (median hardness is 149 mg/L as $CaCO_3$). Ground water in this province also has high alkalinity and large concentrations of calcium, magnesium, sulfate, bicarbonate,

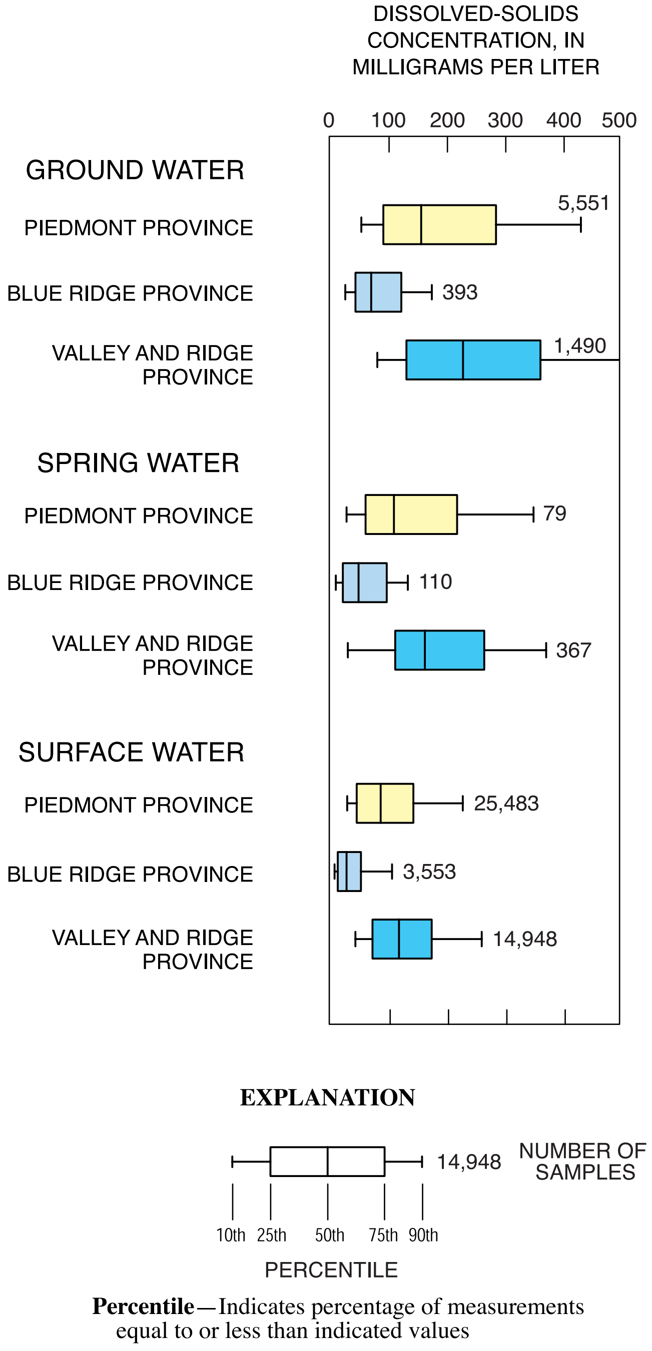


Figure 8. Distribution of dissolved-solids concentrations in ground water, spring water, and surface water in the three physiographic provinces.

Table 3. Comparison of selected characteristics of the three type areas and ground-water flow models in the Appalachian Valley and Piedmont Regional Aquifer-System Analysis study area.

[---, not available or not determined]

Characteristics	Type areas Cumberland Valley, Pa.	 Indian Creek, N.C.	 Stony Brook, N.J.
Setting			
Physiographic province	Mostly Valley and Ridge	Piedmont	Piedmont
Physiographic region	Mostly Great Valley	Inner Piedmont	Newark Basin
Hydrogeologic setting (Conceptual flow system)	Folded crystalline carbonate rocks mantled by thick and thin regolith	Massive and foliated crystalline silicic rocks mantled by thick regolith	Mesozoic sedimentary and igneous rocks mantled by very thin regolith
Hydrogeologic terranes	Dolomite, limestone, argillaceous carbonate, and siliciclastic rocks	Gneiss-schist	Shale-sandstone, gneiss-schist
Rock types	Limestone, dolomite, shale, diabase	Hornblende gneiss, granite	Siltstone, shale, sandstone, diabase
Stream basins	Conodoguinet and Yellow Breeches Creeks	Indian Creek	Stony and Beden Brooks and Jacobs Creek
Basin area, in square miles	686	69	89
Regolith thickness, in feet	0 to 450	63	less than 10
Average or range in depth to water table, in feet	41	26	10 to 35
Recharge, in inches	12 to 15	10.4	8.6
Estimated storativity, regolith	0.05	0.01 to 0.20	0.01 to 0.10
Estimated storativity, bedrock	Less than 0.02	0.0002	0.0001 to 0.001
Estimated transmissivity of regolith, in feet squared per day	140 to 1,000	180 to 3,600	---
Estimated transmissivity of bedrock, in feet squared per day	1,000 to 40,000	92 to 330	200 to 3,200
Estimated streambed hydraulic conductivity, in feet per day	0.15 to 5.0	---	0.025 to 0.38
Ground-water withdrawals, in million gallons per day	About 6	0.96	1.1
Base-flow distribution	Losing upper stream reaches, gaining middle and lower reaches	Uniform across study area	Too little data to estimate distribution
Model			
Model area, in square miles	350	146	89
Grid spacing, in feet	1,320	500	500

Table 3. Comparison of selected characteristics of the three type areas and ground-water flow models in the Appalachian Valley and Piedmont Regional Aquifer-System Analysis study area.—Continued

Characteristics	Type areas		
	Cumberland Valley, Pa.	Indian Creek, N.C.	Stony Brook, N.J.
Number of active cells per layer	5,579	17,400	9,919
Anisotropy, row to column	1.33:1	Varies with topography	2:1, layer 1; 10:1, layer 2
Number of layers	5	11	2
Layer representation and thickness, in feet	Top 3 layers, regolith, bedrock, or both, 240, total; bottom 2 layers, bedrock, 410, total	Top layer, saprolite, 20 to 30; second layer, saprolite-bedrock transition, 25; lower 9 layers, bedrock, 800, total	Top layer, soil and weathered rock, 75 to 208; bottom layer, bedrock, 292 to 425
Lateral changes in transmissivity occur with	Each geologic unit	Three topographic settings	Faults or geologic unit by parts of study area
Boundaries	Primarily head-dependent flux, specified flux, and no flow	Primarily specified flux at boundary and interior streams	Primarily no-flow, and head-dependent flux and specified flux at interior streams
Recharge distributed by	Percent of distributed mean-annual precipitation	Uniform over study area	Base-flow estimates and geologic unit
Results			
Lateral flow in top layer	---	55 percent of recharge	94 percent of recharge
Travel time in top layer, in years	8 to more than 10	10 to 20	---
Interbasin flow	11.5 percent of one of two basin budgets	---	Less than 1 percent of any one of three basin budgets
Strong points of flow analysis	Detailed head data; distributed base-flow data; analysis of interbasin flow in karst by particle tracking; consideration of effects of diabase dike	Distributed base-flow data; discretization of transmissivity by topography; use of water-quality data to verify concept of flow	Discretization of transmissivity of dipping beds; consideration of the hydrologic effects of a normal fault

nitrate, and dissolved iron. Ground water in the Piedmont Physiographic Province, by contrast, has a smaller median dissolved-solids concentration (159 mg/L, fig. 8), is slightly acidic (median pH is 6.7), and is classified as moderately hard (median hardness is 65 mg/L as $CaCO_3$). Ground water in this province has large concentrations of sodium, potassium, chloride, silica, ammonia, phosphorus, total iron, and manganese. Ground water in the Blue Ridge Physiographic Province has the smallest median dissolved-solids concentration (73 mg/L, fig. 8), is slightly acidic (median pH is 6.6), and is classified as soft (median hardness is 29 mg/L as $CaCO_3$). Chemical quality of spring water in the study area is similar to that of water from wells, but more dilute (median dissolved-solids concentration is 136 mg/L). Chemical quality of surface water in the study area is similar to that of ground water, but like spring water, is more dilute. Median concentrations of dissolved solids in surface water (107 mg/L) indicates that surface water typically contains about 35 percent less dissolved solids than ground water and 21 percent less dissolved solids than spring water.

Typically, the order of abundance of major cations in ground water in all three provinces is calcium>magnesium>sodium; and for major anions, the order is bicarbonate>sulfate or chloride (table 4). For most water in the study area, the major dissolved ions are calcium, magnesium, and bicarbonate, which are produced by the dissolution of calcite and dolomite in the rocks. In parts of the Valley and Ridge Physiographic Province in Pennsylvania, the rocks contain significant amounts of either pyrite or gypsum, and sulfate becomes the dominant anion at higher ionic concentrations. Chloride typically is the third most abundant anion in water in the study area (the interquartile range in concentrations in ground water is 2.8 to 17 mg/L). The concentration of chloride and the variation in concentration in ground water is greatest in the Piedmont Physiographic Province. The geographic pattern, by county, of median chloride concentration in ground water (Briel, 1997, fig. 35) is similar to that for sodium (Briel, 1997, fig. 25). In addition, the geographic pattern of median chloride concentrations greater than 4.1 mg/L (Briel, 1997, fig. 35) is similar to the pattern of dense population distribution (greater than 100,000 per county; Swain and others, 1991, fig. 4), particularly in New Jersey, southeastern Pennsylvania, and the Atlanta, Georgia area.

Table 4. Typical proportions of major ions in ground water in the Appalachian Valley and Piedmont Regional Aquifer-System Analysis study area.

[Ca, calcium; Mg, magnesium; Na, sodium; HCO_3, bicarbonate; SO_4, sulfate; Cl, chloride]

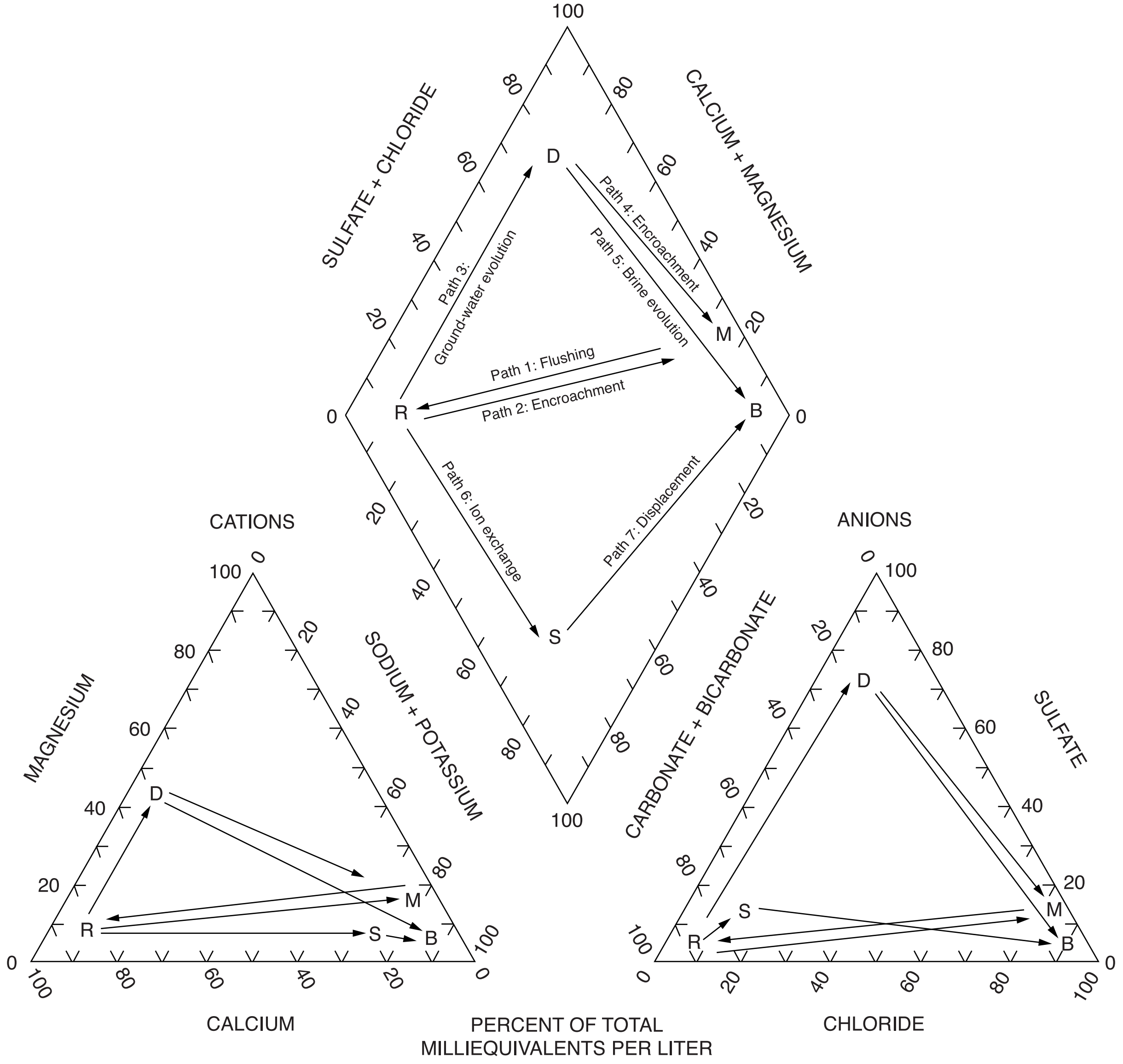
Physiographic province	Cation proportions Ca:Mg:Na	Anion proportions HCO_3:SO_4:Cl
Valley and Ridge	70:20:10	85:08:07
Blue Ridge	50:25:25	80:04:16
Piedmont	50:30:20	80:08:12

As part of the study of water chemistry in the APRASA study area, specific changes in the relative proportions of all major ions within the total concentration of solutes in water analyses are related to seven geochemical processes. These processes take specific reaction paths in a trilinear diagram (fig. 9). The most common reaction path (fig. 9, path 3) shows an evolutionary change in chemical composition of water that results from downgradient flow in recharge areas to deeper areas of more confined flow. Along this path, dissolved-solids concentration increases slightly, and chemical composition changes from a calcium-bicarbonate water to a mixed water containing calcium, magnesium, bicarbonate, and calcium sulfate. The dominant processes along this path involve the dissolution of dolomite and gypsum, and dedolomitization. Magnesium and sulfate concentrations increase, whereas calcium and bicarbonate concentrations remain constant. In the Blue Ridge and Piedmont Physiographic Provinces, secondary processes that affect water chemistry are represented by path 6 and path 2 (fig. 9). Along path 6, chemical composition changes as a result of the replacement of calcium and magnesium in the ground water by sodium ions loosely bound to clay minerals. Along path 2, chemical composition changes as a result of conservative mixing of freshwater with a sodium-chloride-sulfate water in areas of less vigorous ground-water circulation within the aquifer.

Ground-Water Development and Potential for Future Development

During development of the study area in the early 19th century, homes were located near streams and springs for transportation as well as water supply. Larger springs were developed for municipal supplies, and treatment plants eventually were constructed along streams to treat surface water. As population moved away from streams, shallow dug wells became a widespread source of household supply. Beginning in 1824 in New Brunswick, New Jersey (Carlston, 1943, p. 123), drilled wells began replacing dug wells as the main source of household supplies. Ground water withdrawn in 1985 for all uses in the study area was estimated in this study to be 1.7 Bgal/d. This represents only about 2 percent of the 90 Bgal/d estimated to be available from ground-water discharge.

Approximately 82 percent of the 1.7 Bgal/d is withdrawn from widely dispersed locations throughout the study area. Only 18 percent of the ground water used is withdrawn at pumping centers within a few counties (fig. 10). For the most part, unusual water-level declines in response to pumping in these centers have corresponded primarily with times of drought, and water levels have recovered during times of normal precipitation. As a consequence, much of the study area, including these pumping centers, could be developed for additional municipal and industrial ground-water supplies. Because ground-water flow paths in the study area are relatively shallow



EXPLANATION

CHEMICAL COMPOSITION

M MARINE WATER
R RECHARGE WATER
S SOFT WATER
D DOWNGRADIENT WATER
B BRINE

REACTION PATHS	DOMINANT PROCESS
Path 1 M → R	Recrystallization of aragonite to calcite. Selective dissolution of aragonite. Inversion of calcite from high-magnesium to low-magnesium. Cementation
Path 2 R → M	Simple mixing. Dissolution in dispersion zone
Path 3 R → D	Dissolution of dolomite and gypsum. Dedolomitization
Path 4 D → M	Dolomitization
Path 5 D → B	Dissolution of halite
Path 6 R → S	Ion exchange on clay sediments. Replacement of calcium and magnesium ions by sodium ions
Path 7 S → B	Displacement of soft water by mineralized water within a confined aquifer

Figure 9. Reaction paths for evolution of chemical composition of ground water in the Appalachian Valley and Piedmont Regional Aquifer-System Analysis study area. (Modified from Hanshaw and Back, 1979.)

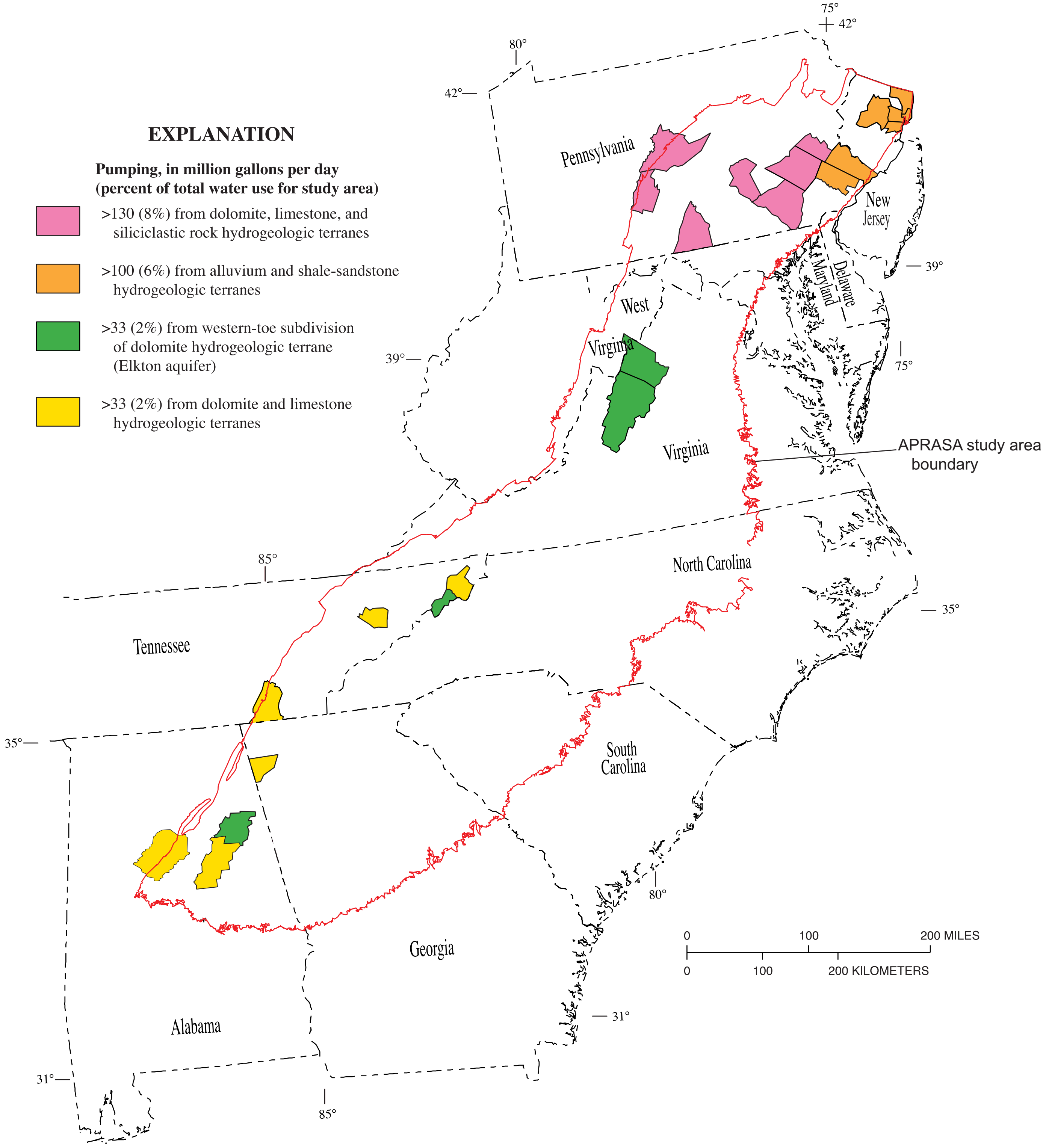


Figure 10. Estimated withdrawals at pumping centers, by county, in the Appalachian Valley and Piedmont aquifer system.

and short, however, ground-water interactions with surface water in regard to both water quantity and water quality are important constraints to consider in planning additional development.

Areas favorable for development of municipal and industrial ground-water supplies (fig. 11) may be summarized into four categories: (1) valley bottoms underlain by alluvium of glacial origin in New Jersey and Pennsylvania; (2) the Elkton aquifer along the southeastern edge of the Valley and Ridge Physiographic Province; (3) valley bottoms and rolling uplands underlain by relatively clay-free dolomite, limestone, and marble bedrock in all three physiographic provinces; and (4) the three (Mesko and others, 1999, fig. 1) northernmost Mesozoic basins in the study area. These areas were selected for their potential ability to provide municipal and industrial water supplies compared to other parts of the study area. Additionally, the northernmost Mesozoic basins were selected because of a large population with a rapidly growing need for water.

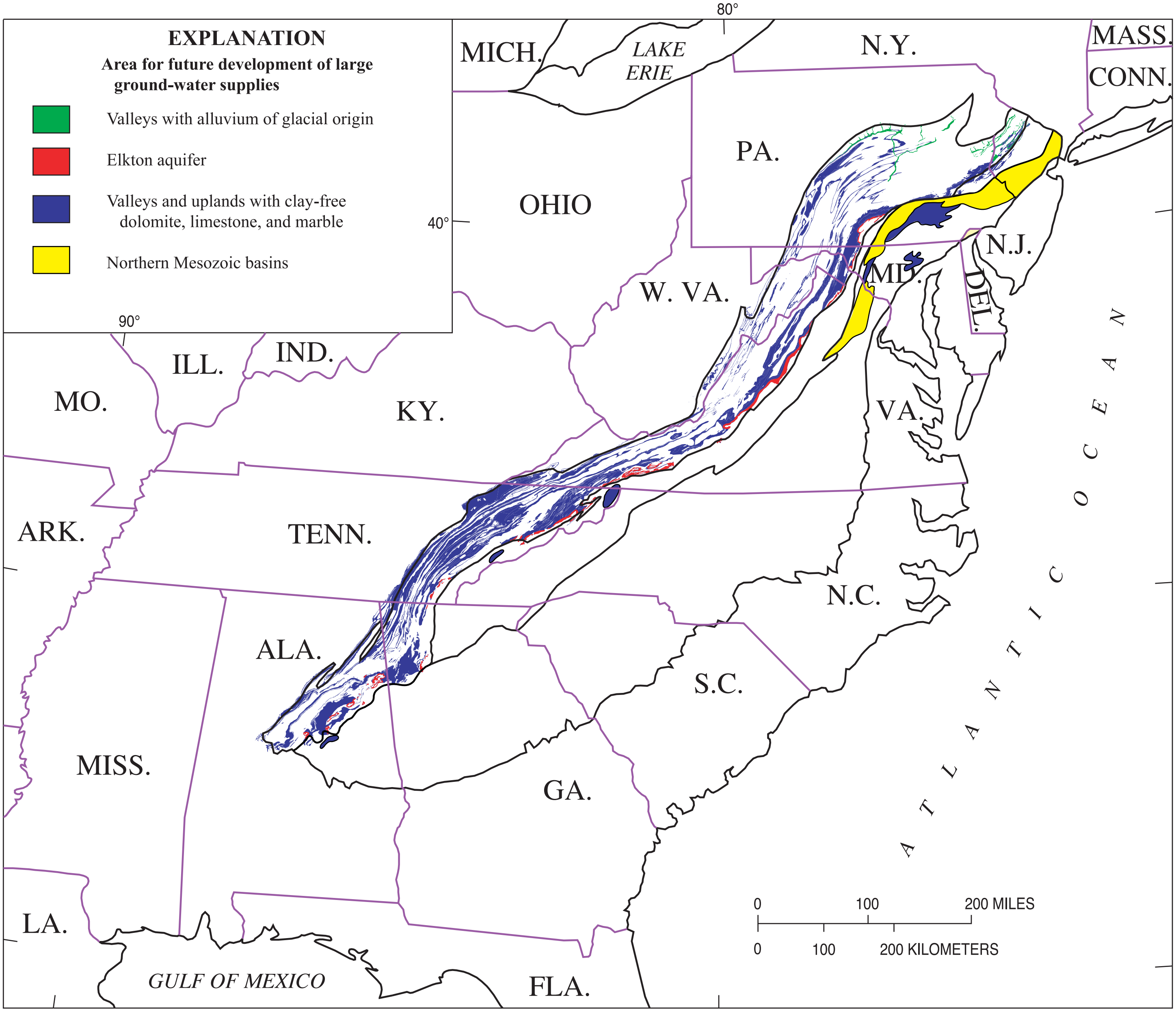


Figure 11. Areas where future development of municipal and industrial ground-water supplies from the Appalachian Valley and Piedmont aquifer system has good potential.

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