HYDROGEOLOGY OF, AND SIMULATION OF GROUND-WATER FLOW IN, A MANTLED CARBONATE-ROCK SYSTEM, CUMBERLAND VALLEY, PENNSYLVANIA

By Douglas C. Chichester

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.59	square kilometer
	Flow	
foot per day (ft/d)	0.3048	meter per day
gallon per minute (gal/min)	0.06308	liter per second
cubic foot per day (ft^3/d)	2,447	cubic meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute per foot (gal/min)/ft	0.207	liter per minute per meter

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

The U.S. Geological Survey conducted a study in a highly productive and complex regolith-mantled carbonate valley in the northeastern part of Cumberland Valley, Pa., as part of the Appalachian Valleys and Piedmont Regional Aquifer-System Analysis program. The study was designed to quantify the hydrogeologic characteristics and understand the ground-water flow system of a highly productive and complex, thickly mantled carbonate valley.

The Cumberland Valley trends east-northeast and is characterized by complexly folded and faulted Cambrian and Ordovician-age carbonate bedrock in the valley bottom, by shale and graywacke to the north, and by Triassic sedimentary redbeds and diabase rocks in the east-southeast. Near the southern valley hillslope, the carbonate rock is overlain by a wedge-shaped deposit of regolith, up to 450 feet thick, that is composed of residual material, alluvium, and colluvium. Residual material, composed mostly of weathered carbonate rock, is up to 200 feet thick. Alluvium and colluvium are composed of reworked residual material and siliciclastic materials derived from South Mountain, a resistant upland source of quartzite and schist to the south. Locally, saturated regolith is greater than 200 feet thick.

Seepage-run data indicate that stream reaches near valley walls are losing water from the stream, through the regolith, to the ground-water system. Most stream reaches in the lower and middle part of the basin are gaining water from the ground-water system. Results of hydrograph-separation analyses indicate that base flow in stream basins dominated by regolith-mantled carbonate, carbonate, and carbonate and shale bedrock are 81, 93, and 68 percent of total streamflow, respectively. The relatively high percentage for the regolith-mantled carbonate-rock basin indicates that the regolith provides for storage of precipitation and a slow, steady release of water to the carbonate-rock aquifer and streams to sustain streamflow as base flow.

Anomalies in water-table gradients and configuration are a result of topography and differences in the character and distribution of overburden material, permeability, rock type, and geologic structure. Most ground-water flow is local and discharges to nearby springs and streams. Regional flow is northeastward to the Susquehanna River.

Average-annual water budgets were calculated for the period of record from two continuous streamflow-gaging stations. Average-annual precipitation ranges from 39.0 to 40.5 inches, and averages about 40 inches for the modeled area. Average-annual recharge, which was assumed equal to the average-annual base flow, ranged from 12 inches for the Conodoguinet Creek to 15 inches for the Yellow Breeches Creek. The recharge rates represent 30 and 38 percent, and evapotranspiration represents 56 and 53 percent, of the average-annual precipitation for the Conodoguinet and Yellow Breeches Creek Basins, respectively.

The thickly mantled carbonate system was modeled as a three-dimensional water-table aquifer. Recharge to, ground-water flow through, and discharge from the Cumberland Valley were simulated. The model was calibrated for steady-state conditions by use of average recharge and discharge data. Aquifer horizontal hydraulic conductivity was calculated as geometric means from specific-capacity data for each geologic unit in the area.

Particle-tracking analyses indicate that interbasin and intrabasin flow of ground water occurs in the Yellow Breeches Creek Basin and from the Yellow Breeches to the Conodoguinet Creek Basin. The interbasin flow is 5.6 percent of the total budget and 11.5 percent of the total, calculated base flow of the Yellow Breeches Creek part of the modeled area.

The calibrated model was most sensitive to recharge and hydraulic conductivity of allochthonous deposits of the Martinsburg Formation and all of the Gettysburg-Newark Triassic Lowland Section in the east-southeast. The model was less sensitive to the specified flux off South Mountain and streambed hydraulic conductivity. The model was least sensitive to aquifer anisotropy.

INTRODUCTION

In 1978, the U.S. Geological Survey (USGS) began the Regional Aquifer-System Analysis (RASA) program to study and evaluate the Nation's major aquifer systems. The RASA program was initiated as a result of Congressional concern over the 1977 drought. This drought prompted a realization that there is a need to develop a better understanding of the Nation's regional ground-water flow systems so that these resources can be better and more efficiently used.

The purpose of the RASA program is to define regional geology and hydrology and to establish a framework of background information for the geology, hydrology, and geochemistry of the Nation's important aquifer systems (Sun, 1986; Sun and Weeks, 1991). The Nation's aquifers were divided into 28 regional aquifer systems for intensive study and analysis. These regional systems were designated on the basis of prior USGS appraisals of ground-water resources and economic and hydrologic considerations.

In 1988, the Appalachian Valleys and Piedmont Regional Aquifer-System Analysis (APRASA) project was selected for a 5-year study (Swain and others, 1991b). The APRASA study area is located in the Appalachian Highlands of the eastern part of the United States. This regional aquifer system is characterized by numerous aquifers that are independent of one another but have similar hydrogeologic properties and principles governing the occurrence and movement of ground water. Several areas were designated for intensive study to better understand and evaluate this complex region. These areas are local aquifers that are representative of other areas within the regional system. Information on hydrogeologic properties and principles derived from this study can then be transferred to other similar areas within the region.

The northeastern part of the Cumberland Valley is experiencing rapid population and industrial growth. In the fastest-growing parts of the valley, the demand for public-supply water is expected to nearly double between 1988 and 2013 (Pennsylvania American Water Company, written commun., 1988). Although the majority of the present demand is obtained by streamflow, at least 15 community water-supply systems use water from wells or springs (Becher and Root, 1981). With the increased development and demand for water in this area, a better understanding of the aquifer characteristics is necessary to use the ground-water resource efficiently.

As part of the APRASA project, the USGS conducted a study in northeastern Cumberland Valley, Pa. (fig. 1). The study was designed to quantify the hydrogeologic characteristics, improve understanding of the ground-water flow system, and provide a resource for planners to efficiently utilize the highly productive and complex regolith-mantled carbonate-rock aquifer on the northern flank of South Mountain. This study area is typical of thick, regolith-mantled carbonate-rock aquifers that are present in other areas along the southeastern margin of the Valley and Ridge Physiographic Province from Pennsylvania to Alabama (Swain and others, 1991a).

Purpose and Scope

This report presents the results of a study of the hydrogeologic framework of the Cumberland Valley and results from simulation of steady-state hydrologic conditions using a digital ground-water flow model. The purpose of the report was to identify and quantify the hydrogeologic properties and characteristics of a highly productive and complex thickly mantled carbonate valley.

Presented in the report are discussions of the following: (1) estimation of hydraulic properties of the regolith, carbonate aquifers, and streambeds; (2) assessment of the role of the regolith in storage and flow of ground water to the underlying carbonate aquifer; (3) assessment of the role of springs and a diabase dike in movement and discharge of water from the ground-water system; (4) assessment of the depth of the regional flow system and affects of fracturing on flow in the carbonate aquifer; (5) development of a water budget for the study area; (6) quantification of interbasin transfer of water; and (7) testing of the quantities, estimates, and assessments for reasonableness by means of a computer model of ground-water flow and mass (water) balance. The scope of the report includes a description and discussion of all the above topics.

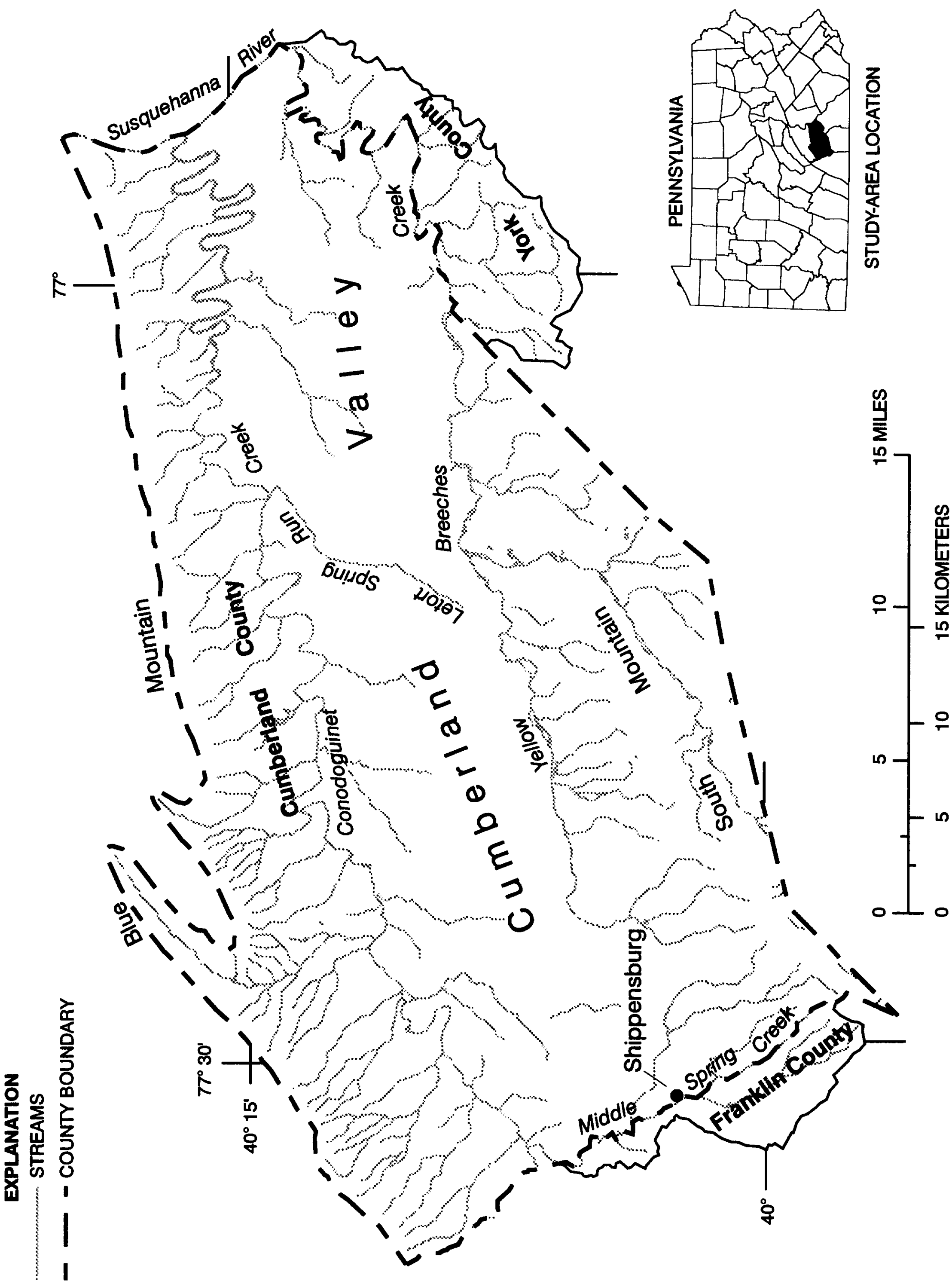


Figure 1. Location of the study area.

Description of Study Area

The study area includes parts of the Conodoguinet and Yellow Breeches Creek Basins, in the northeastern part of the Cumberland Valley, in south-central Pennsylvania (fig. 1). The area is bounded to the north by Blue Mountain, to the east by the Susquehanna River, to the east-southeast by the drainage-basin divide of the Yellow Breeches Creek, to the south by South Mountain, and to the west by the drainage-basin divide of Middle Spring Creek and the Cumberland County line. Surface water flows to the Conodoguinet and Yellow Breeches Creeks, both of which parallel the axis of the valley and drain northeastward into the Susquehanna River. The study area has approximately 30 springs, of which each discharges more than 1 ft^3/s in the valley. Land-surface elevations range from about 2,260 ft above sea level on Blue Mountain to about 300 ft above sea level at the Susquehanna River.

The study area is located in part of the Valley and Ridge, Piedmont, and Blue Ridge Physiographic Provinces (fig. 2). The northern and central part of the area is in the Great Valley Section of the Valley and Ridge Physiographic Province. Cumberland Valley, which extends from the Pennsylvania-Maryland border to the Susquehanna River, is in the central part of the Great Valley Section of the Valley and Ridge Physiographic Province. The section is characterized by low relief and subdued valleys and ridges. Land-surface elevations range from approximately 1,000 ft along the valley walls to 300 ft at the Susquehanna River. The province is underlain by Cambrian and Ordovician sedimentary rocks with Triassic diabase intrusions.

South Mountain is in the northern part of the Blue Ridge Physiographic Province. This area is characterized by subparallel ridges and valleys of moderate to high relief that typically trend northeast. Land-surface elevations range from approximately 600 ft at the valley walls to 2,060 ft at the highest point. The province is underlain by Precambrian to Ordovician sedimentary, volcanic, and metamorphic rocks.

The east-southeastern part of the study area is in the Gettysburg-Newark Lowland Section of the Piedmont Physiographic Province. This section is characterized by gently rolling topography of low to moderate relief with broad, shallow valleys and low ridges. Land-surface elevations range from 1,000 ft at the ridge tops to 300 ft at the Susquehanna River. The province is underlain by Triassic to Jurassic sedimentary rocks that have been intruded by numerous Triassic and Jurassic diabase dikes and sills.

The study area has a humid continental climate. Long-term average-annual precipitation at five National Oceanic and Atmospheric Administration stations in or adjacent to the study area ranges from 38.8 to 46.4 in. and averages approximately 40 in. for study area (table 1). Typically, because of orographic effects, precipitation amounts are greater on ridges and hilltops than on the valley floors. Precipitation is uniformly distributed throughout the year except during summer months when precipitation amounts increase slightly because of local storms.

Previous Investigations

All or parts of the study area have been the subject of several geologic and hydrologic investigations. The geology of parts of Cumberland and York Counties was described by MacLachlan and Root (1966) and Root (1977; 1978). The geology of parts of Cumberland and Franklin Counties was described by Fauth (1968). Root (1968; 1971) described the geology of parts of Franklin County. The geology and hydrogeology of Cumberland County was described by Becher and Root (1981). Flippo (1974) and Saad and Hippe (1990) compiled and summarized discharge of selected springs in the study area. White and Sloto (1990) analyzed base-flow-frequency characteristics for several streams in the study area. Knopman (1991) described factors controlling the water-yielding potential of rocks in the Valley and Ridge Physiographic Province of Pennsylvania. Gerhart and Lazorchick (1988) included the Cumberland Valley in a ground-water flow model of the lower Susquehanna River Basin. Chichester (1991) described the conceptual hydrogeologic framework of the valley. The hydrogeology of Franklin County was described by Becher and Taylor (1982).

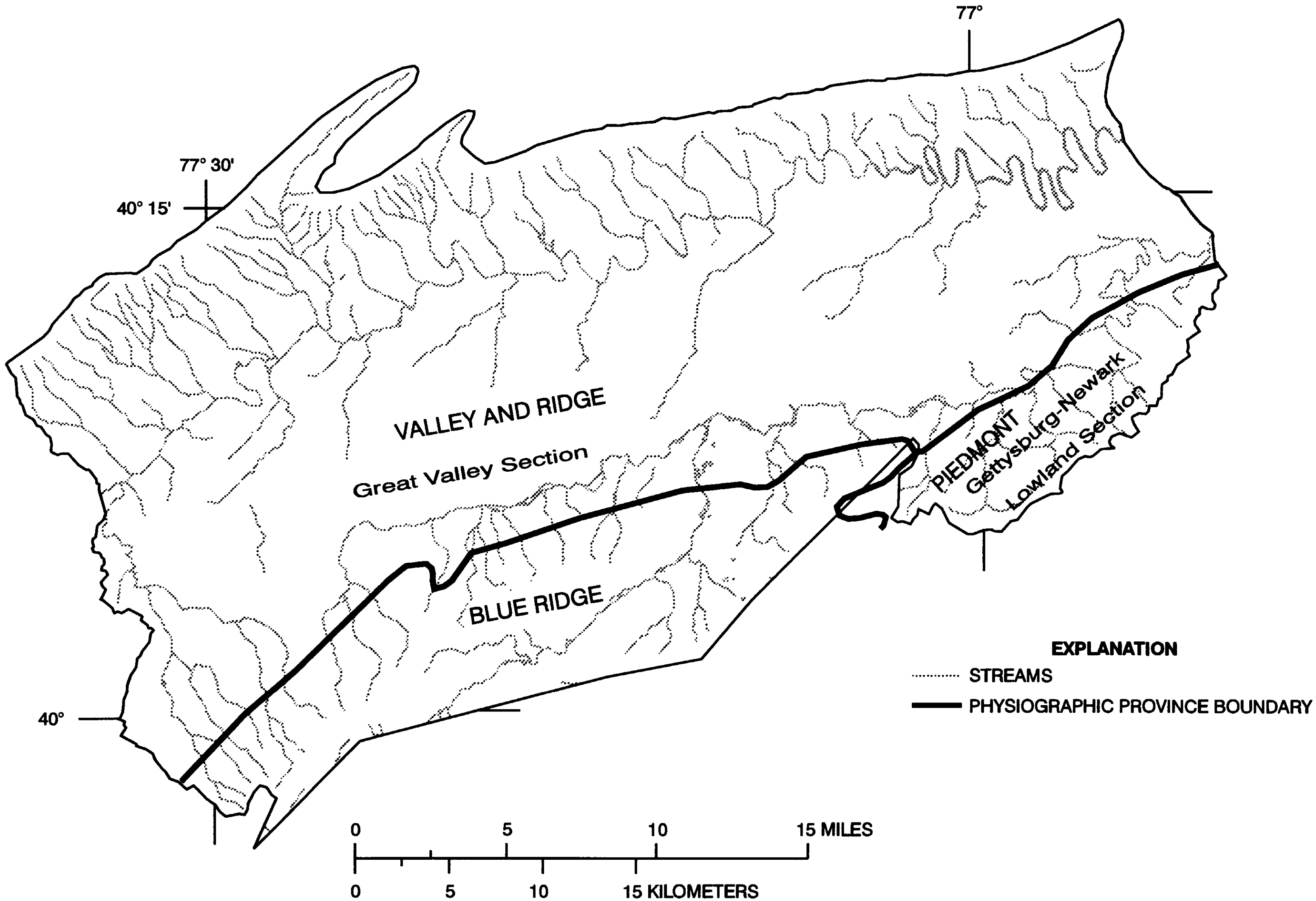


Figure 2. Physiographic provinces of the Cumberland Valley.

Table 1. Long-term average-annual precipitation data from selected National Oceanic and Atmospheric Administration stations in or near the study area, Cumberland Valley

Station name	Precipitation (in inches)	Years of record
Bloserville[1]	40.6	77
Capitol City[2]	39.1	103
Chambersburg[2]	40.6	95
Shippensburg[1]	38.8	61
South Mountain[2]	46.4	52

[1] U.S. Department of Commerce, 1989.
[2] U.S. Department of Commerce, 1990.

Data Availability, Collection, and Management

The APRASA project relies primarily on existing data, with supplemental data collection, to develop an understanding of the hydrogeologic characteristics of the local ground-water flow system. In addition to published reports listed in the previous investigations section, a substantial amount of data exists for the Cumberland Valley study area. These data include USGS Ground-Water Site Inventory (GWSI) well and spring data, Pennsylvania Water-Well Inventory (PAWWI) data, continuous water-level records from wells, aquifer-test information, seismic-refraction profiles, continuous streamflow records, precipitation records, and water-use records.

Field work for this study focused on obtaining additional measurements of ground-water levels and ground-water discharge to streams and springs. Ground-water levels were measured at a select well with a continuous recorder. For similar hydrologic conditions and time, the continuous-record data were then compared to water levels depicted in the map of the water table for November 1972 by Becher and Root (1981, pl. 1). The comparison was done to determine if the hydrologic conditions when the map for November 1972 was drawn are still valid at the present (1994). Seepage-run data were collected to improve the understanding of the relation between surface water and ground water in the study area, to refine the conceptual model, identify losing and gaining reaches, and to calibrate the ground-water flow model with respect to the direction and magnitude of water flow through streambeds.

A Geographic Information System (GIS) was used to compile, calculate, and store data; develop computer-simulation grids; input data to the model; and present simulation results. The following information is in the GIS data base: county, study-area, model-area, and drainage-basin boundaries; hydrography; topography; bedrock geology and structure; GWSI and PAWWI data; precipitation; recharge; thickness of unconsolidated and saturated regolith; horizontal hydraulic conductivity, aquifer top and bottom altitudes, and seepage-run data; and model-grid and node data necessary for use of the USGS ground-water flow model MODFLOW (McDonald and Harbaugh, 1988).

HYDROGEOLOGY

The geology and hydrology are strongly related in the Cumberland Valley. For example, in areas overlying carbonate rocks, karst features are reflected by sinkholes, closed depressions, and dry valleys. Shale and diabase bedrock cause locally greater topographic relief and raised water tables. A generalized north-south hydrogeologic section of the study area is shown in figure 3. This figure shows the general distribution of bedrock and regolith for an area typical of the central part of the study area and the area to be modeled.

Geology

The geology of the study area is composed primarily of the Cumberland Valley sequence in the north and south-central part, the Lebanon Valley sequence to the east, and rocks of the Gettysburg-Newark Lowland Section of the Piedmont Physiographic Province in the extreme east-southeastern part of the study area. In the southern part of the study area, the Cumberland Valley sequence is overlain by thick deposits of regolith comprised of alluvium, colluvium, and residuum. Table 2 shows the rocks units, stratigraphic relations, and time-stratigraphic equivalence of the rocks in each sequence for the study area.

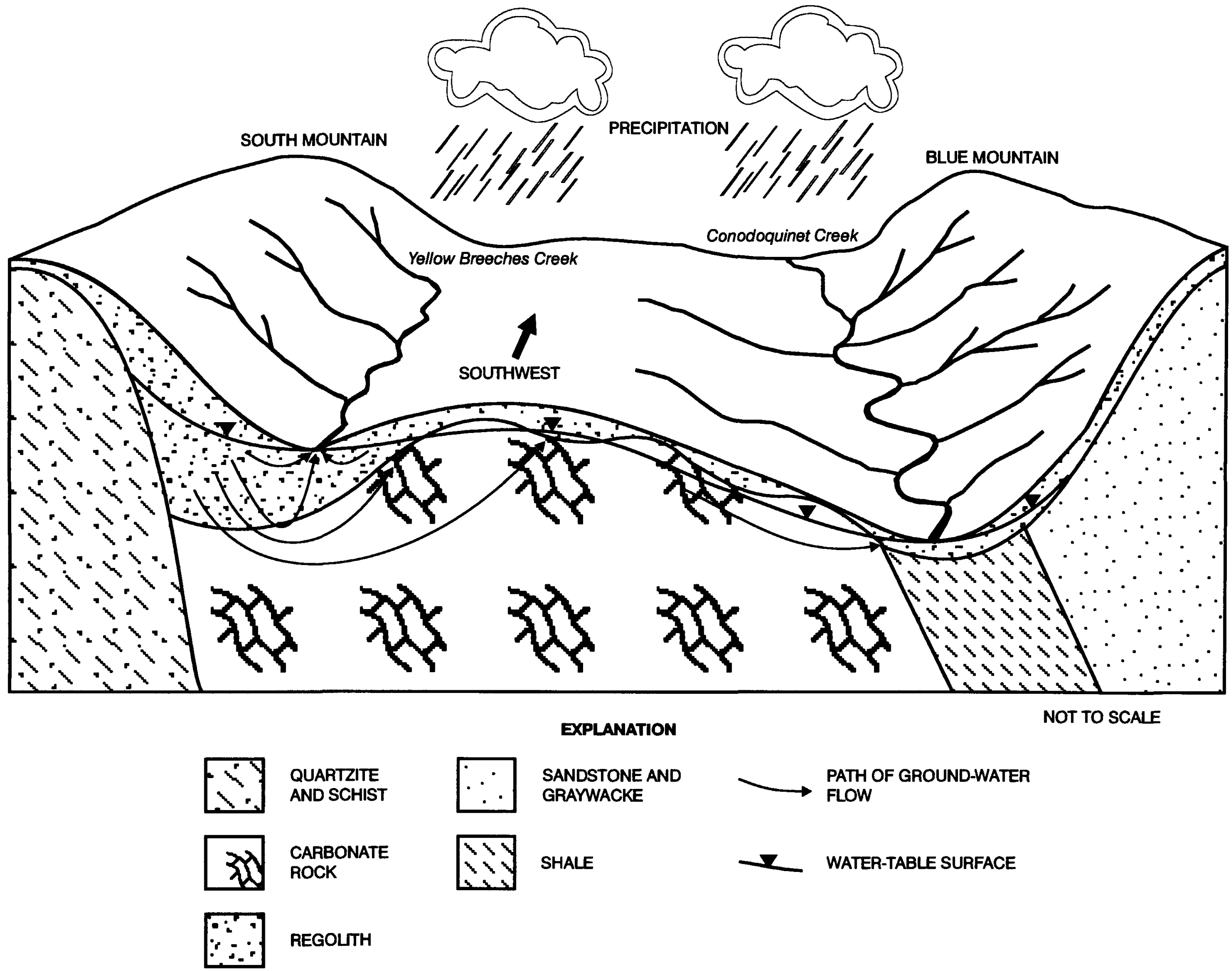


Figure 3. Generalized block diagram and hydrologic section of the Cumberland Valley.

Table 2. Stratigraphic relation of rock units in the Cumberland Valley (Modified from Becher and Root, 1981, fig. 3.)

System	Series	Group	Formation	Thickness (in feet)	Formation	Thickness (in feet)	Formation	Thickness (in feet)
Quaternary			Regolith	0 - 450			Regolith	Unknown
Triassic							Diabase	Unknown
Triassic							Gettysburg Formation	Unknown
Ordovician	Upper Ordovician		Martinsburg Formation ? Transported Martinsburg ?	Unknown	Martinsburg Formation ? Transported Martinsburg ?	Unknown		
Ordovician	Middle Ordovician		Chambersburg Formation	650	Myerstown Formation	Unknown		
Ordovician	Middle Ordovician		St. Paul Group	600 - 900				
Ordovician	Middle Ordovician ?	Beekmantown Group	Pinesburg Station Formation	175 - 300				
Ordovician	Lower Ordovician	Beekmantown Group	Rockdale Run Formation	2,000 - 2,500	Epler Formation	Unknown		
Ordovician	Lower Ordovician	Beekmantown Group	Stonehenge Formation	500				
Ordovician	Lower Ordovician	Beekmantown Group	Stofferstown Formation	0 - 200				
Cambrian	Upper Cambrian	Conococheague Group	Shadygrove Formation	800 - 1,000				
Cambrian	Upper Cambrian	Conococheague Group	Zullinger Formation	2,500 - 3,500				
Cambrian	Middle Cambrian		Elbrook Formation	3,500				
Cambrian	Lower Cambrian		Waynesboro Formation	1,000 - 1,500				
Cambrian	Lower Cambrian		Tomstown Formation	1,000 - 2,000				
			Cumberland Valley Sequence		Lebanon Valley Sequence		Gettysburg-Newark Lowland Section	

Lithology

The distribution and occurrence of generalized bedrock lithology that are included in the ground-water flow model are shown in figure 4. The geologic units generally trend east-northeast; older units are exposed in the south, and progressively younger units are exposed to the north-northwest. The geology north of the Conodoguinet Creek is characterized by shales and graywacke. Resistant sandstone forms Blue Mountain at the northern boundary of the study area. Between the Conodoguinet Creek and South Mountain, carbonate rocks predominate, although argillaceous carbonates, calcareous shales, and shales are common. In the eastern third of the area, a diabase dike that trends northward through the study area is exposed. In the east-southeastern part of the area, the geology is characterized by redbeds (red sedimentary rocks) and diabase intrusives (dikes and sills). Resistant quartzite and schist form South Mountain at the southern boundary of the study area.

In the eastern part of the study area, the Epler and Myerstown Formations of the Lebanon Valley sequence are exposed where they have been thrust over the Cumberland Valley sequence (fig. 5). Although the Lebanon and Cumberland Valley sequences are time-stratigraphic equivalents, the

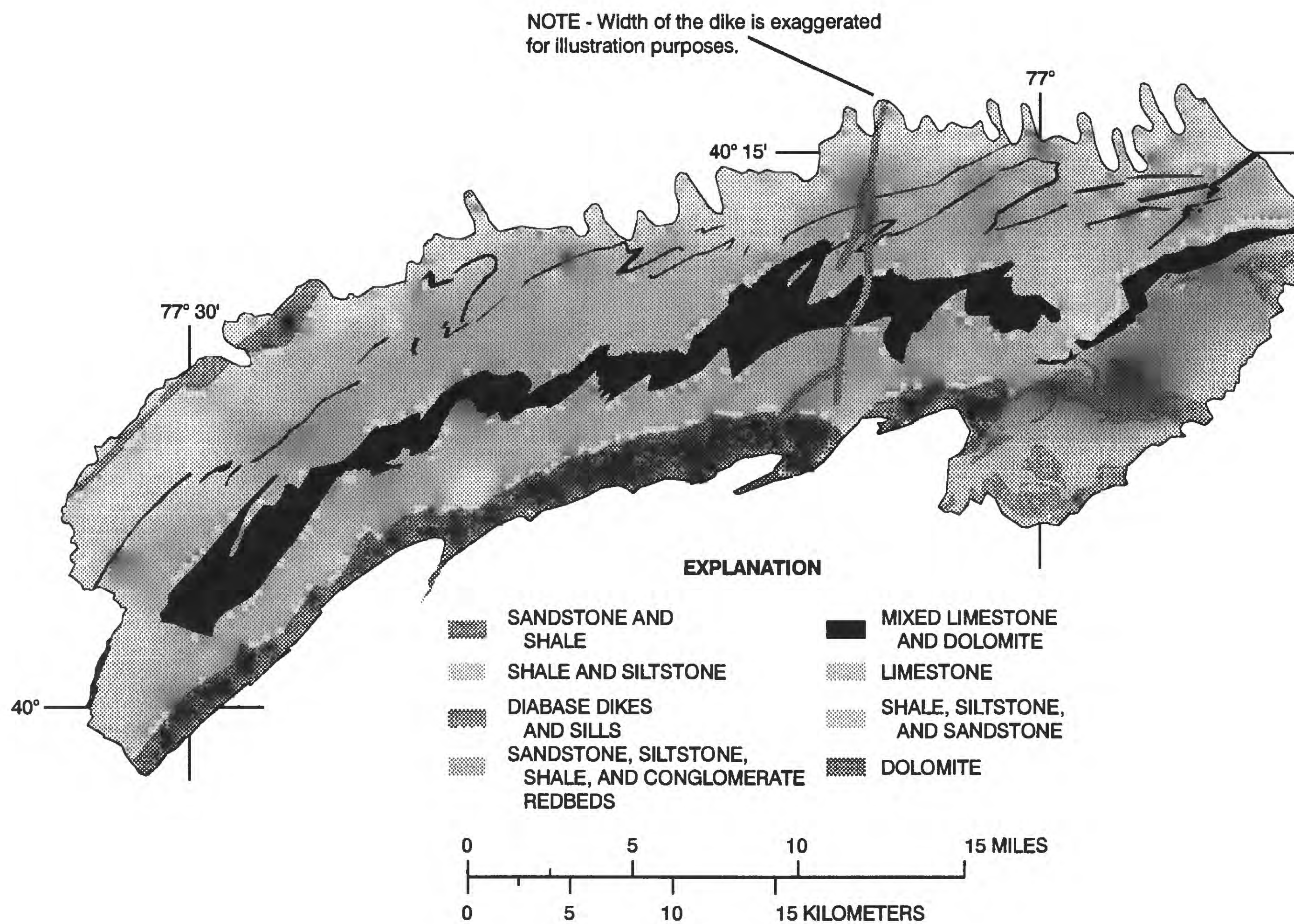


Figure 4. General bedrock geology of the modeled area of the Cumberland Valley. (Modified from Berg, Sevon, and Abel, 1984.)

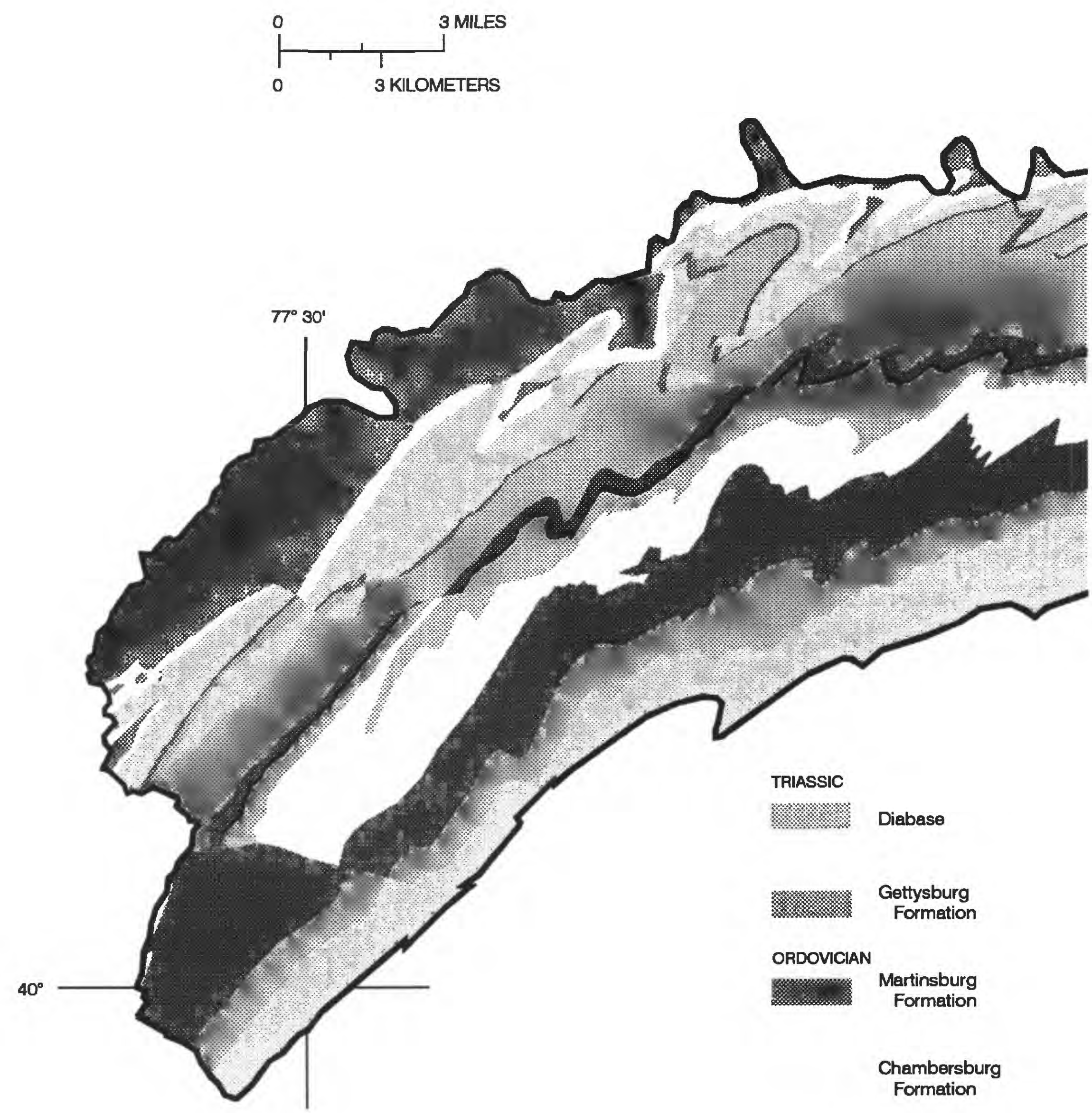
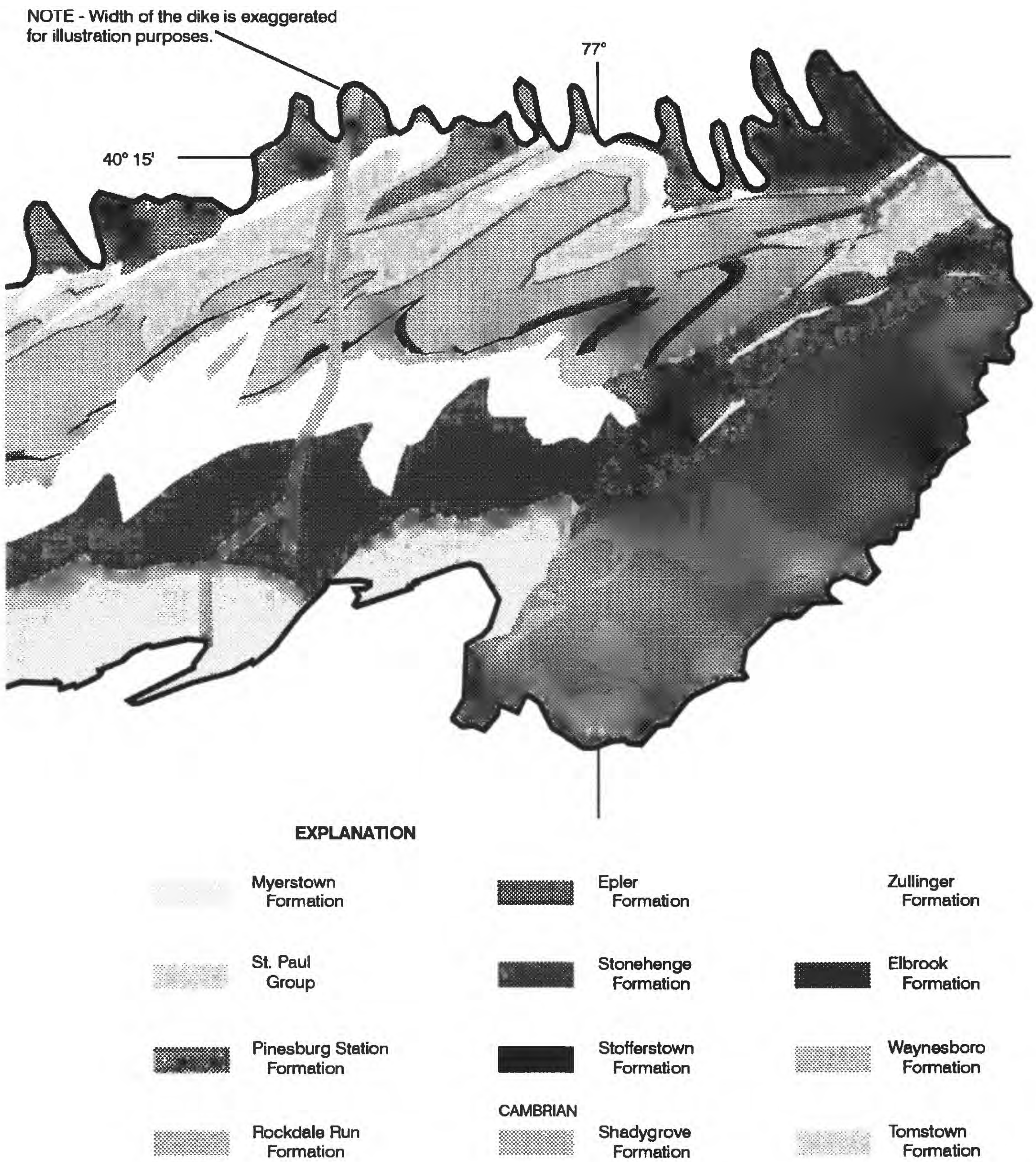


Figure 5. Bedrock geology of the modeled area of the Cumberland Valley. (Modified from Becher and Root, 1981, pl. 1.)


NOTE - Width of the dike is exaggerated for illustration purposes.
77°
40° 15'
EXPLANATION
Myerstown Formation
St. Paul Group
Pinesburg Station Formation
Rockdale Run Formation
Epler Formation
Stonehenge Formation
Stofferstown Formation
CAMBRIAN
Shadygrove Formation
Zullinger Formation
Elbrook Formation
Waynesboro Formation
Tomstown Formation

rock-stratigraphy for each is distinct and represents a different depositional setting (Root, 1977). The Lebanon Valley sequence is composed primarily of carbonate rocks with some shale and argillaceous limestone, whereas the Cumberland Valley sequence includes limestone, dolomite, shales, and graywacke.

Tomstown Formation.—The Tomstown Formation is a poorly exposed unit that parallels the flank of South Mountain. Exposures of the Tomstown are rare because of extensive overlying deposits of alluvium, colluvium, and residuum from weathered bedrock. The formation is composed of calcareous shale and limestone near the base of the formation, limestone in the middle, and massive beds of dolomite in the upper part (Becher and Root, 1981). The Tomstown Formation is of Lower Cambrian age and is 1,000 to 2,000 ft thick.

Waynesboro Formation.—The Waynesboro Formation is better exposed than the Tomstown Formation because overlying regolith is thin or absent. The formation grades from buff to sandy dolomite with interbands of limestone and dolomite at the base. The middle of the formation becomes more siliceous upwards, grading into a dark-red, reddish-brown, to purple sandy shale and siltstone (Becher and Root, 1981; Root, 1968). The Waynesboro Formation is of Lower Cambrian age and is 1,000 to 1,500 ft thick.

Elbrook Formation.—The Elbrook Formation is composed of predominantly calcareous shale and argillaceous limestone interbedded with purer limestone (Becher and Root, 1981). The Elbrook Formation is of Middle Cambrian age and is about 3,500 ft thick.

Zullinger Formation.—The Zullinger Formation comprises the base of the Conococheaque Group. The formation is composed of thick, predominantly siliceous, banded, dark-blue-gray limestone with interbeds of dolomite, and sandstone and chert beds at the base (Becher and Root, 1981). The Zullinger Formation is of Upper Cambrian age and is 2,500 to 3,500 ft thick.

Shadygrove Formation.—The Shadygrove Formation comprises the upper part of the Conococheaque Group. The formation is composed of light blue-gray to gray, thick to massive limestone with widely dispersed interbeds of dolomite (Becher and Root, 1981). The Shadygrove Formation is of Upper Cambrian age and is 800 to 1,000 ft thick.

Stoufferstown Formation.—The Stoufferstown Formation is composed of medium-gray, thin- to medium-bedded limestone comprised mostly of carbonate detrital (Becher and Root, 1981). The Stoufferstown Formation is of Lower Ordovician age and is 0 to 200 ft thick.

Stonehenge Formation.—The Stonehenge Formation is composed of medium-bedded, very fine to fine-grained, light- to medium-gray limestone with abundant zones of detrital and skeletal carbonate material with closely spaced, crinkled, siliceous dolomite laminae (Becher and Root, 1981). The Stonehenge Formation is of Lower Ordovician age and is about 500 ft thick.

Epler Formation.—The Epler Formation is part of the Lebanon Valley sequence and is a time-stratigraphic equivalent with the Rockdale Run Formation of the Cumberland Valley sequence. The formation is composed of predominantly medium-light gray, finely crystalline limestone with interbeds of medium-dark, finely crystalline dolomite (Becher and Root, 1981). The Epler Formation is of Lower Ordovician age and has an unknown thickness.

Rockdale Run Formation.—The Rockdale Run Formation is a time-stratigraphic equivalent of the Epler Formation of the Lebanon Valley sequence. The formation is composed of predominantly very light gray, very fine grained, pure limestone with the upper part consisting of medium- to thick-bedded, very fine grained, detrital and skeletal limestone (Becher and Root, 1981). The Rockdale Run Formation is of Lower Ordovician age and is 2,000 to 2,500 ft thick.

Pinesburg Station Formation.—The Pinesburg Station Formation is composed of light to medium gray, thick to massively bedded, laminated to banded dolomite (Becher and Root, 1981). The Pinesburg Station Formation is of Middle Ordovician age and is 175 to 300 ft thick.

St. Paul Group.—The St. Paul Group is composed predominantly of light- to medium-gray, thick bedded limestone and minor amounts of dolomite (Becher and Root, 1981). The St. Paul Group is of Middle Ordovician age and is 600 to 900 ft thick.

Myerstown Formation.—The Myerstown Formation is part of the Lebanon Valley sequence and is a time-stratigraphic equivalent with the Chambersburg Formation of the Cumberland Valley sequence. The formation is composed of medium-dark-gray to dark-gray, medium- to fine-grained, thin and regularly bedded limestone with very thin interbeds of dark-gray shale (Becher and Root, 1981). The Myerstown Formation is of Middle Ordovician age and has an unknown thickness.

Chambersburg Formation.—The Chambersburg Formation is a time-stratigraphic equivalent of the Myerstown Formation of the Lebanon Valley sequence. The formation is composed of dark-gray, thin-bedded, platy to nodular limestone (Becher and Root, 1981). The Chambers-burg Formation is of Middle Ordovician age and is about 650 ft.

Martinsburg Formation.—The Martinsburg Formation has exposures as part of both the Lebanon and Cumberland Valley sequences. The formation is composed primarily of shale with some graywacke sandstone and siltstone, argillaceous limestone, and calcareous shale (Becher and Root, 1981). Allochthonous exposures of the Martinsburg Formations are in the eastern part of the study area. The Martinsburg Allochthons are a coherent mass of transported material that has been thrust over the underlying material. The Martinsburg Formation is of Upper-middle Ordovician age and has an unknown thickness.

Gettysburg Formation.—The Gettysburg Formation is part of the Gettysburg-Newark Lowland Section of the Piedmont Physiographic Province and is not part of the Lebanon or Cumberland Valley sequences. The formation is composed of red and maroon, micaceous and silty mudstones and shales, locally calcareous with some thin red siltstone to very fine grained sandstone interbeds. The Gettysburg Formation is of Triassic age and possibly up to 15,000 ft thick (Root, 1977).

Diabase.—The exposures of diabase are Rossville- and York Haven-type plutons. The diabase is composed of medium- to coarse-grained, dark-gray diabase formed chiefly of plagioclase feldspar and black to green augite (Root, 1977; 1978). Diabase dikes and sills are present in the east-southeastern part of the study area. A diabase dike trending north through the east-central part of the study area (Ironstone Ridge) is 75 to 150 ft thick. The intrusions are of Triassic and Jurassic age.

Regolith.—Along the northern flank of South Mountain, an extensive deposit of regolith has formed on the carbonate rocks of the valley bottom. The regolith is a wedge-shaped, unconsolidated deposit thinning to the northwest, as thick as 450 ft (Becher and Root, 1981), consisting of residual material, alluvium, and colluvium. The residual material, which consists mainly of insoluble clastic material from weathered carbonate rocks, ranges from 170 (Pierce, 1965) to 200 ft thick (R.S. Hughes, Gannett Fleming, Inc., written commun., April 1991). Residual material covers nearly all the bedrock in the study area, from a few feet to several tens of feet, with the thickest deposits overlying carbonate rocks near South Mountain.

Thick deposits of alluvium and colluvium overlie the residual material. The alluvium consists of floodplain and alluvial-fan deposits that have coalesced to form thick alluvial slopes. Alluvial deposits are composed of reworked residual material, detrital debris, and siliciclastic material derived from upland sources on South Mountain. The alluvial deposits can be as thick as 200 to 300 ft in buried river channels incised in the carbonate rocks (Root, 1978). Colluvial deposits are interspersed in the alluvium and are composed of similar, yet coarser, siliciclastic material. The colluvial deposits can be greater than 100 ft thick in areas near the source material along South Mountain (Root, 1978).

Becher and Root (1981) have indicated that chemically aggressive water flowing off South Mountain has dissolved the carbonate rocks adjacent to South Mountain and produced the topographically low area presently occupied by Yellow Breeches Creek. Weathering of rock in place and mass movement of material from South Mountain into the topographically low area has resulted in thick accumulations of unconsolidated materials along the flank of the mountain.

Structure

The geologic structure of the area affects ground-water flow and the configuration of the water table in the study area. The general structural trend is to the east-northeast; the average trend is N. 70°E. Flow along strike is preferential and results in increased development of secondary porosity and permeability along strike. In addition, the structural contacts between lithologies of contrasting hydraulic properties can affect the flow of ground water. For example, diabase dikes form semipermeable boundaries that restrict flow and create a damming effect. Lithologies of contrasting hydraulic properties also affect the configuration and altitude of the water table.

The Cumberland Valley forms the northwest limb of an anticlinorium with its axis in South Mountain. The anticlinorium is a complex fold structure plunging moderately to the northeast with the nose at South Mountain. The rocks of the Cumberland Valley sequence comprise most of the units in the valley and are complexly folded and faulted into asymmetrical folds and steeply dipping faults that are subparallel to the valley trend. Thrust over the Cumberland Valley sequence are allochthonous units of the Martinsburg Formation from the Cumberland Valley sequence, and the Martinsburg, Myerstown, and Epler Formations from the Lebanon Valley sequence. The units of the Lebanon Valley sequence are even more intensively deformed than the Cumberland Valley sequence because of repeated movements along the thrust fault. In the east-central part of the study area, a Triassic diabase dike trends north across the valley. Triassic diabase dikes and sills are present in the extreme east-southeastern part of the study area. In addition, cleavage parallel to the fold structure and two joint sets parallel and perpendicular to the regional structure are common throughout the study area (Becher and Root, 1981).

Hydrology

Water enters the study area in Cumberland Valley as precipitation, streamflow, and through interflow and ground-water flow off South Mountain. Water leaves the study area as evapotranspiration, overland flow, and ground-water discharge to streams and springs. The Conodoguinet and Yellow Breeches Creeks are the main streams draining the study area. The streams flow predominantly east-northeast toward the Susquehanna River. The Conodoguinet Creek drains most of the study area and has a drainage area of 506 mi^2 in parts of Cumberland and Franklin Counties. The Yellow Breeches Creek drains 219 mi^2 from Cumberland, York, and Adams Counties.

Ground-Water/Surface-Water Relations

Two sets of seepage-run data were collected at selected reaches of the Conodoguinet and Yellow Breeches Creeks, their major tributaries, and springs. These data are used to quantify the ground-water discharge from the aquifer as well as to determine areas of losing and gaining reaches along the streams. To determine appropriate base-flow conditions for conducting the seepage investigations, median base-flow conditions were determined statistically by hydrograph-separation techniques (Pettyjohn and Henning, 1979) at three USGS continuous-record streamflow-gaging stations (fig. 6) (USGS Station IDs: 01571500 - Yellow Breeches Creek near Camp Hill, Pa.; 01570000 - Conodoguinet Creek near Hogestown, Pa.; and 01569800 - Letort Spring Run near Carlisle, Pa.). These median base flows were compared to actual streamflows at the streamflow-gaging stations to select the days when median base-flow discharges could be measured. On June 13 and 14, 1990, during near median base-flow conditions, seepage-run measurements were made at 81 sites in the study area (fig. 6) and were published in the Water-Resources Data for Pennsylvania (Loper and others, 1991, p. 194-199).

A second, low-flow, seepage-run data collection was performed during November 18-20, 1991 (Durlin and Schaffstall, 1992, p. 229-234). These measurements were made when streamflow was less than that during the June 1990 seepage run. These data were also used to quantify ground-water discharge and to compare and contrast areas of losing and gaining reaches during low, base-flow conditions with those measured during median-flow conditions.

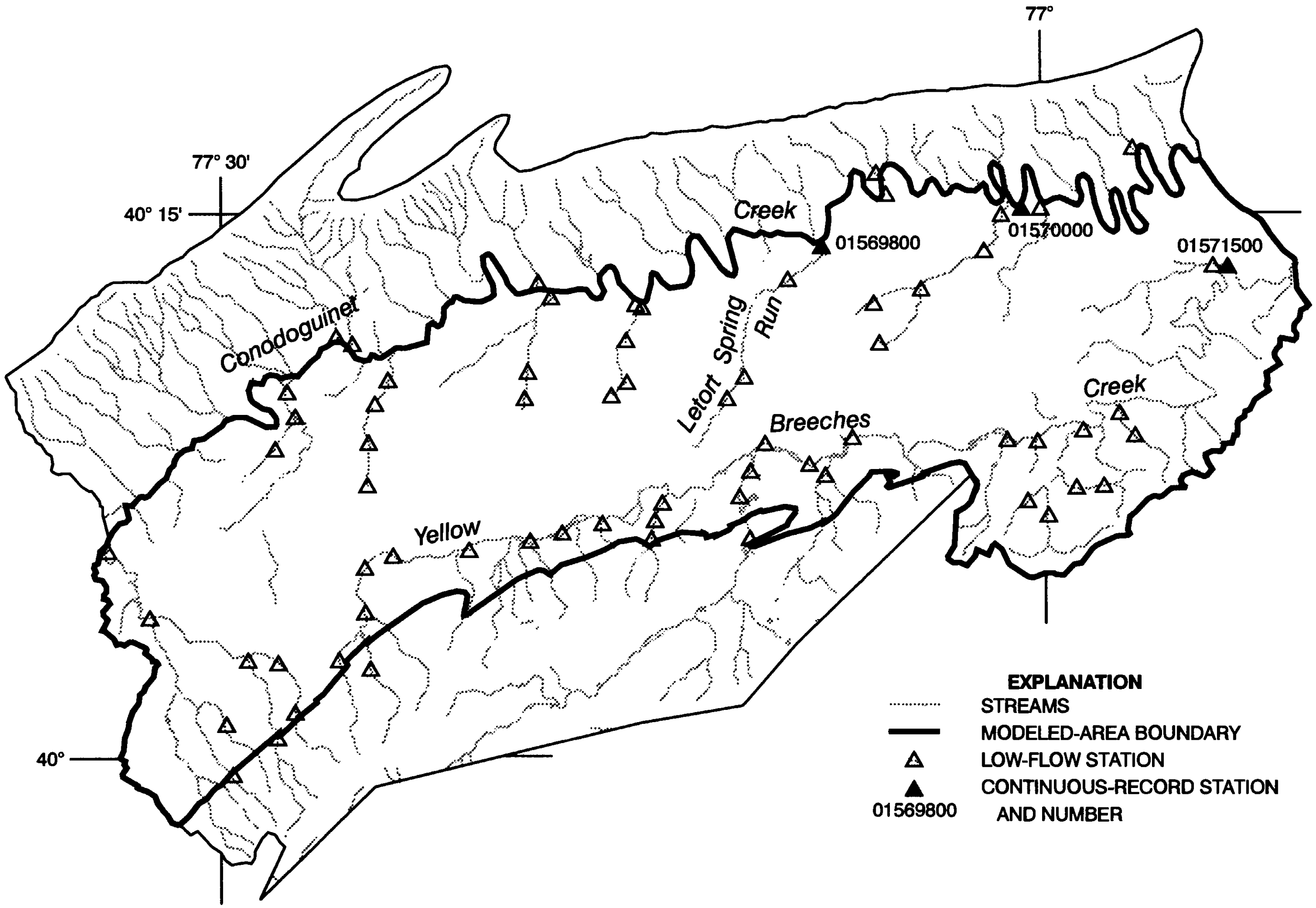


Figure 6. Location of streamflow-gaging stations and seepage-run sites in the Cumberland Valley.

The difference between the two sets of seepage-run measurements was most pronounced in the upper reaches of the streams and tributaries. At all but 1 of the 81 sites, flow was less during the second seepage-run measurement. One site had the same flow during both measurements, which was a result of regulation of discharge from a nearby fish hatchery. During the second seepage run, 14 sites were dry and the others had slightly or significantly lower flows.

Results of seepage-run measurements indicate that most stream reaches in the lower and middle part of the Conodoguinet and Yellow Breeches Creek Basins are gaining ground water. Data collected at tributaries along the northern flank of South Mountain indicate that many reaches are losing water. Indeed, some of these reaches go dry and only regain water in the lower reaches of the tributary. These reaches lose water because the tributary streams flowing near the hilltops of South Mountain have steeper gradients and flow over material of lower permeability (quartzite and schist) than do the streams near the valley walls and adjacent to the valley bottom. As a result, these hilltop streams lose little or no water to the ground-water reservoir. When these tributary streams flow over the valley wall areas, the low gradients and high streambed permeability (regolith) enable infiltration and percolation of surface water to the ground-water reservoir (fig. 3).

Ground Water

Ground water is recharged by precipitation and by infiltration of water from losing reaches of streams. The amount of recharge is a function of the amount and intensity of rainfall, evapotranspiration, rock type, soil type and antecedent moisture condition, depth to water table, and the location of streams within the ground-water recharge or discharge flow path. Along the flank of South Mountain, the ground-water system is recharged predominantly from losing streams and precipitation. Recharge as input to the model will be varied areally on the basis of the above factors.

Ground water discharges to springs, to gaining reaches of small streams and tributaries, and to the Conodoguinet and Yellow Breeches Creeks. The Conodoguinet and Yellow Breeches Creeks receive most of the discharge from the aquifer. The Susquehanna River also receives ground-water discharge and acts as the base level of the ground-water flow system for the study area and the area to be modeled.

A water-table map of the model area was constructed to help determine recharge and discharge areas, conceptualize ground-water flow, determine the effects of geology on the water-table configuration, enable the model to converge more quickly by use of the water table for starting heads, and to calibrate the ground-water flow model (fig. 7). The map was constructed, in part, from the map of the water table as drawn by Becher and Root (1981, pl. 1) for conditions in November 1972. In areas outside that mapped by Becher and Root, the water-table map was completed with GWSI and PAWWI data from a period of average ground-water conditions and from land-surface elevations at gaining reaches along streams.

The water-table configuration, gradient, and the resultant flow are strongly related to the underlying geology and structure and reflect a subdued representation of the general topography of the land surface. In areas where the bedrock has low permeability (for example, shale, diabase, or argillaceous limestone), the gradients increase and the contours closely follow the areal distribution of the particular rock type. Conversely, in areas where bedrock (for example, limestone and dolomite) has high porosity and permeability, the gradients decrease.

The east-southeastern part of the area is underlain by diabase dikes and sills and sedimentary rocks, including sandstone, siltstone, shale, and conglomerate (figs. 4 and 5). These rocks are characterized by low porosity and permeability and, in this area, have little secondary porosity. The water table in areas underlain by these rocks has gradients greater than 25 ft per 1,000 ft (fig. 7).

In the east-central part of the area, a diabase dike trends north-south across the valley. The water-table configuration shows a displacement and damming effect as the ground water tries to move around, over, and(or) through the lower porosity and permeable diabase dike (figs. 4, 5, and 7).

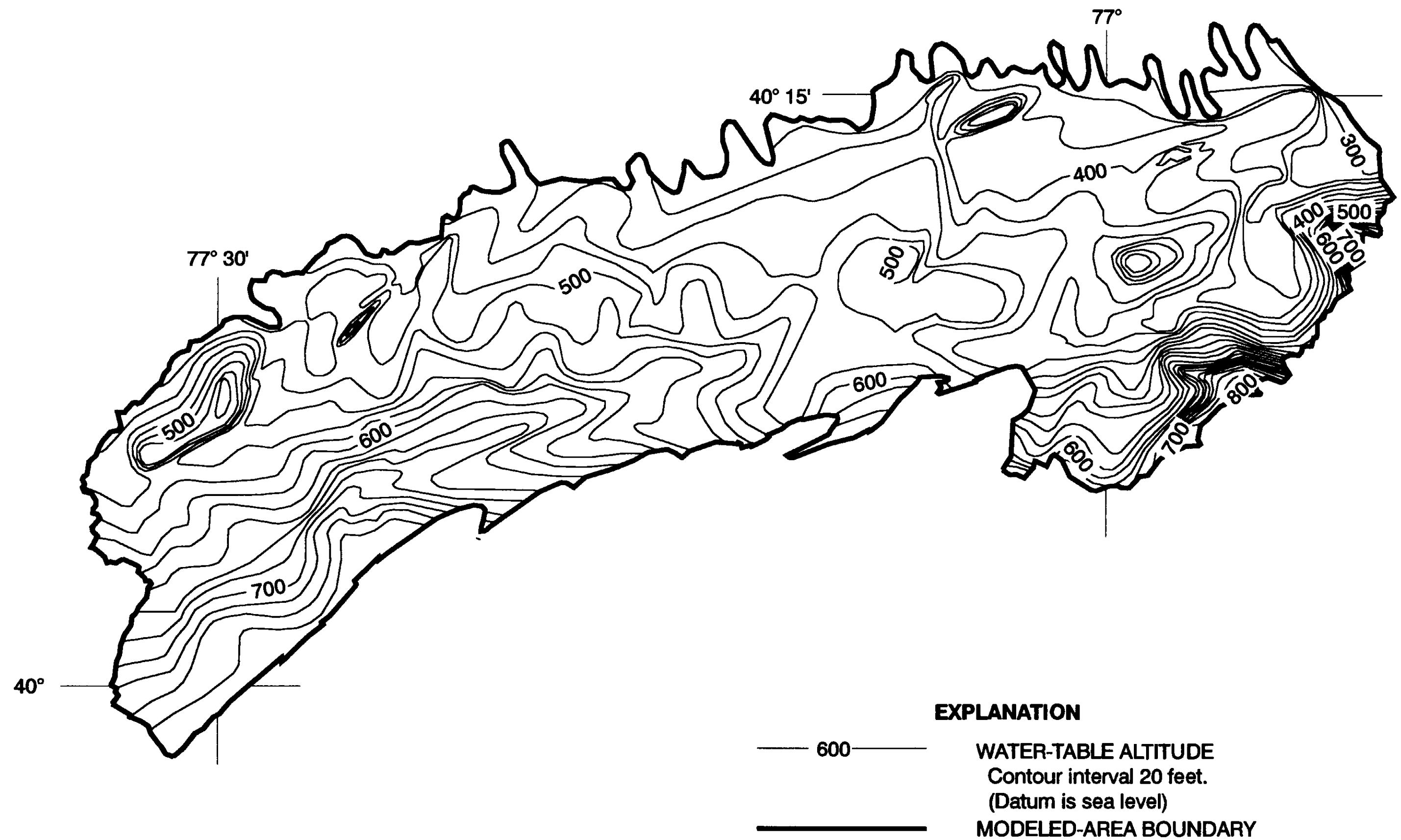


Figure 7. Altitude of water table within the modeled area of the Cumberland Valley. (Modified from Becher and Root, 1981, pl. 1.)

In the northwestern part of the area, the water-table contours reflect mounds of ground water in two places (fig. 7). These mounds overlie areas of shale bedrock, whose hydrologic characteristics contrast significantly with those of the surrounding carbonate rocks. Also, northeast of the diabase dike and in the east-central part of the study area, two other areas of shale have resulted in mounding of the ground water.

In the central part of the area, near Letort Spring Run, the underlying geology is characterized by limestone and dolomite that has high porosity and permeability because of dissolution by ground water. The water-table configuration in this area has low relief with gradients of approximately 4 ft per 1,000 ft (fig. 7).

In the southern part of the study area, along the flank of South Mountain, the water table has gradients of approximately 10 ft per 1,000 ft. This relatively steep gradient reflects not only the topography of the valley walls but also ground-water mounding caused by the large amount of recharge from infiltration of precipitation and water from losing stream reaches as they flow off the flank of South Mountain.

In the southern-southeastern part of the area, near Shippensburg, the water-table aquifer consists of saturated regolith as thick as 240 ft that overlies cavernous dolomite. From the saturated regolith, flow is downward to the underlying carbonate-rock aquifer, then laterally and upward to springs and streams (fig. 3).

In the center of Cumberland Valley, between the Yellow Breeches and Conodoguinet Creeks, the ground-water system is recharged largely by precipitation. Here, the aquifer is predominantly in carbonate rock because the regolith thins northward toward Conodoguinet Creek and locally is either unsaturated or discontinuous. Within the carbonate rock, which is folded and faulted, ground water flows through joints, fractures, bedding-plane separations, and cleavage openings that have been enlarged by dissolution. The water table in this area is relatively flat; its configuration is a subdued reflection of the general topography of the land surface.

Becher and Root (1981) indicated that, although most ground water discharges locally to nearby streams, there is intrabasin and interbasin flow of ground water within the valley. In the Yellow Breeches Creek Basin, interbasin flow occurs when water infiltrates into the aquifer south of the creek, flows under the creek, discharges to springs north of the creek, and then flows to the stream that the water had just flowed under (fig. 3). In addition, Becher and Root indicated that ground water flows from the Yellow Breeches Creek Basin to the Conodoguinet Creek Basin.

Water Budgets

The water budgets for the study area (table 3) were determined from precipitation data and use of stream-hydrograph-separation (Pettyjohn and Henning, 1979) and hydrograph-separation techniques (A.T. Rutledge, U.S. Geological Survey, written commun., Feb. 1991; Rutledge, 1991) for the period of record for each of three continuous-record streamflow-gaging stations. The results shown in table 3 are from hydrograph-separation techniques. These results are very similar to those calculated by Becher and Root (1981) by use of methods of Rorabaugh (1964).

The data in table 3, in particular the base-flow index, reflect the different lithologic and topographic characteristics of each surface-water basin. The Letort Spring Run base-flow index of 93 percent reflects a valley basin in carbonate terrane of low relief (approximately 200 ft). In this basin, only 7 percent of streamflow is surface runoff; the remainder is ground-water discharge. The ground-water system is drained predominantly by solution-enlarged conduits in the carbonate rock.

The Conodoguinet Creek base-flow index of 68 percent reflects a basin in carbonate and shale terrane with high relief (approximately 1,900 ft). In this basin, nearly one third of total streamflow is surface runoff; the remainder is ground-water discharge. Drainage of ground water is more through porous media in this basin than in the Letort Spring Run Basin.

Table 3. Major components of water budgets for Letort Spring Run, Conodoguinet Creek, and Yellow Breeches Creek

	Letort Spring Run 01569800 (21.6 square miles) (1977-1989)		Conodoguinet Creek 01570000 (470 square miles) (1912-1989)		Yellow Breeches Creek 01571500 (216 square miles) (1911-1989)	
	Inches per year	Percent	Inches per year	Percent	Inches per year	Percent
Surface runoff[1]	2	4	6	14	4	9
Ground-water discharge[1]	23	57 [2](93)	12	30 [2](68)	15	38 [2](81)
Evapotranspiration	16	39	22	56	21	53
Precipitation	40	100	40	100	40	100

[1] A.T. Rutledge, U.S. Geological Survey, written commun., February 1991.
[2] Base-flow index, or ground-water discharge as percentage of total streamflow.

The Yellow Breeches Creek base-flow index of 81 percent reflects a basin in quartzite, schist, and mantled-carbonate terrane with a basin relief slightly less than that of the Conodoguinet Creek Basin (approximately 1,700 ft). In the Yellow Breeches Creek Basin, the saturated regolith provides a large reservoir for storage of water and allows for a slow, steady release of water to the stream as base flow. Surface runoff is only about 19 percent of total streamflow; ground-water discharge comprises about 81 percent of the streamflow. The ground-water system is drained predominantly by flow through a porous media and solution-enlarged openings.

Aquifer Characteristics

The aquifer characteristics of well yield, specific capacity, and hydraulic conductivity are based on data from previous investigations and analyses of GWSI data. These data are summarized below and are used, in part, for conceptualization of the system and as input to the ground-water flow model.

Well Yields

Median reported yields of water from rock units in the area differ greatly—from less than 10 gal/min (Root, 1977, 1978) for the diabase intrusives in the east and east-southeast, to greater than 1,000 gal/min (Becher and Root, 1981) for cavernous dolomite underlying the regolith mantle along the flank of South Mountain. Median sustained yield for the regolith is 42 gal/min (Becher and Root, 1981).

Specific Capacity

The reported median specific capacity of wells in the study area ranges from 0.15 to 1.4 (gal/min)/ft of drawdown for shales, siltstones, and graywacke (Becher and Root, 1981). The low specific capacities are indicative of shale with few joints, fractures, and bedding-plane separations, whereas the higher specific capacities are indicative of calcareous shale or graywacke with extensive primary and secondary porosity and permeability. Median specific capacities of carbonate rocks range from 0.20 (gal/min)/ft of drawdown for argillaceous limestone to 19 (gal/min)/ft of drawdown for cavernous dolomite (Becher and Root, 1981). The water-yielding capacity of the regolith varies according to its composition. Becher and Root (1981) reported a median specific capacity of 1.4 (gal/min)/ft of drawdown for colluvium, and Hollyday and others (U.S. Geological Survey, written commun., Feb. 1991) reported a specific capacity of approximately 10 (gal/min)/ft of drawdown for alluvium throughout the Valley and Ridge Physiographic Province.

Hydraulic Conductivity

Horizontal hydraulic conductivity for each lithology was calculated from specific capacities obtained from the GWSI data base for wells in the study area. For some geologic units, GWSI data for all of the Great Valley of Pennsylvania were used to obtain a larger sample size. Only those specific-capacity tests that were an hour in length or longer were used in the calculations. The horizontal hydraulic conductivities were calculated on the basis of techniques described by Theis and others (1963). Table 4 lists the statistics on the calculated horizontal hydraulic conductivity of each geologic unit.

SIMULATION OF GROUND-WATER FLOW

Ground-water flow in the Cumberland Valley was simulated by use of the three-dimensional (3-D) finite-difference modular model (MODFLOW) computer program of McDonald and Harbaugh (1984), with the BCF2 module (McDonald and others, 1991) to allow for converting no-flow cells to variable-head cells. Recharge to, movement through, and discharge from the regolith-mantled carbonate rocks of the Cumberland Valley were simulated. Sources of water to the model area are areally-distributed recharge from precipitation and lateral recharge from upland sources along the flank of South Mountain. Discharges from the model area are by ground-water discharge to springs and streams.

Table 4. Statistics on horizontal hydraulic conductivity from Ground-Water Site Inventory data at wells in specific geologic units in the Cumberland Valley
[values in feet per day]

Geologic unit	Number of wells	Minimum	Maximum	Geometric mean	Arithmetic mean	Median
Regolith[1]	4	1.0	2,400	35	630	71
Gettysburg	7	.01	4.2	.21	1.2	2.9
Martinsburg	8	.01	4.4	.46	1.1	1.4
Chambersburg	7	.01	56	.36	9.1	7.7
Myerstown[1]	13	.02	23	.30	3.1	.13
St. Paul Group	20	.00	1,300	1.4	93	36
Pinesburg Station	4	.00	240	1.7	66	180
Rockdale Run	47	.01	19,000	16	630	150
Epler[1]	45	.02	1,900	3.6	110	3.9
Stonehenge	5	.03	39	.74	12	30
Stoufferstown[1]	2	.05	30	1.2	15	15
Shadygrove	8	.01	960	.41	120	5.6
Zullinger	13	.00	4,800	1.9	380	21
Elbrook	17	.00	3,300	2.1	230	58
Waynesboro	4	.02	89	3.7	36	79
Tomstown	10	1.4	2,300	38	360	470

[1] Statistics from Ground-Water Site Inventory data for all of the wells within the geologic unit for the Great Valley Section of the Valley and Ridge Physiographic Province of Pennsylvania.

Simplified Conceptual Model and Limitations

The conceptual ground-water flow model is based on the known information of the hydrogeologic properties of the geologic units, water-table surface and configuration, recharge and discharge rates, and the relation of the aquifer to the surrounding boundaries. If the conceptual model is accurate and the numerical model reflects the conceptual model, the simulated results will compare well with the observed data. Conversely, if the numerical model does not simulate the natural system well, then the conceptual model is inaccurate or needs to be revised in some fashion. The numerical model is a simplified mathematical representation of the complex hydrologic system in the basin. Certain assumptions regarding the hydrologic system were made to develop a simplified conceptual model. The model approximates the hydrologic system within the imposed constraints and limitations that are discussed below.

Continuum methods of ground-water-flow analysis, including most digital modeling, rely on the assumption that flow can be conceptualized as typical of flow through a porous medium, such that Darcy's Law is valid. The geologic units of Cumberland Valley have very small primary porosity; ground water flows mainly through secondary openings. However, because of the regional scale of the model, the aquifer was considered to sufficiently approximate a porous media to permit analysis by continuum methods. Secondary-opening density is sufficiently great at the regional scale to use a porous-media model. A block of aquifer material is assumed to have the equivalent properties of the same-size block of porous media. The water-table map of Becher and Root (1981) supports the view that ground-water flow is regional in the study area.

A simplified conceptual model of the complex hydrogeologic system was developed to analyze the ground-water flow system with use of a digital model. Numerical methods require that the conceptual model be simplified so that the characteristics are uniform over discrete space intervals. As a result, the conceptual model includes the following assumptions:

1. The geologic units in the Cumberland Valley act together as a single heterogenous water-table aquifer.
2. The lithologic contact between geologic units with depth is vertical.
3. Hydraulic conductivity is specified individually for each geologic unit. Hydraulic properties for each geologic unit vary spacially but are averaged for model simulation.
4. Streams are in direct hydraulic contact with the aquifer.
5. Ground-water flow below 650 ft is considered negligible. The lower limit of ground-water flow is 650 ft below land surface on the basis of analysis of GWSI data for water-bearing zones.
6. Recharge to the model area is distributed areally across the basin and is calculated on the basis of long-term average-annual precipitation data and stream hydrograph-separation techniques.
7. Under steady-state conditions, the total inflow to the aquifer is equal to the total outflow.

Model Discretization and Construction

Grid Design

Because of the extensive area considered for ground-water flow modeling, a uniform grid with square cells 0.25 mi (1,320 ft) on a side were used. The modeled area was discretized into a rectangular grid composed of 62 rows and 160 columns with the origin at the upper left of the grid. The cell location notation used in this report is (row, column). For example, cell (45, 153) is located in row 45 and column 153. The center of each cell is called a node. The number of active model cells was 5,579 per layer, covering a total modeled area of 350 mi^2 (fig. 8). The general structural trend is to the east-northeast. Because the system is anisotropic with largest hydraulic conductivity parallel to strike, the model grid is oriented with its rows parallel to the general trend of the geologic structure within the valley (N. 70°E.).

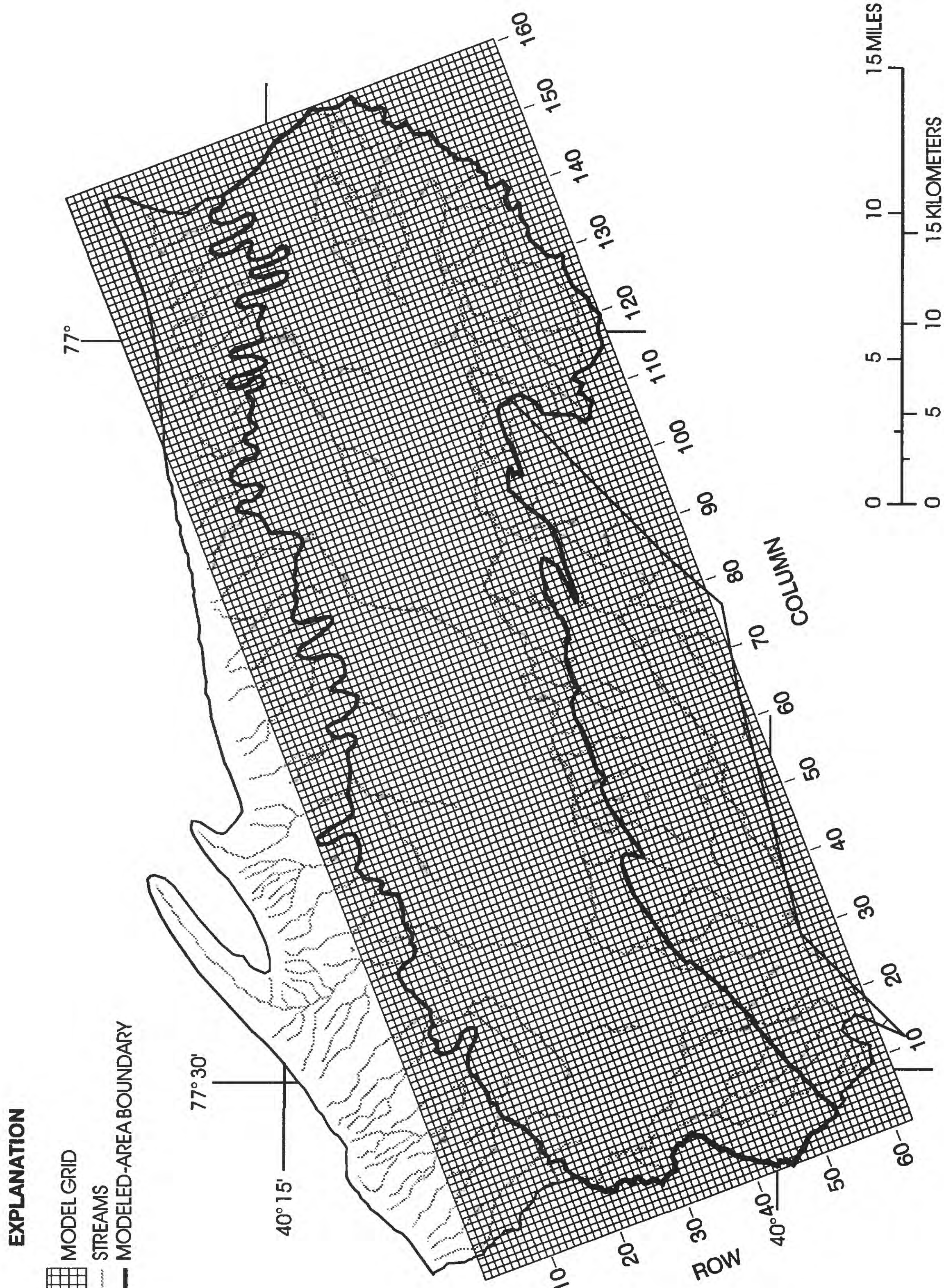


Figure 8. Study area, model grid, and active modeled area in the Cumberland Valley.

Vertical Discretization

The geologic units were simulated as a water-table aquifer for the top layer and as confined aquifers for the lower layers. Vertically, the modeled area is discretized into five layers. The top three layers contain cells representing either regolith or bedrock; cells in the bottom two layers represent bedrock only (fig. 9). The top of layer 1 is defined as the observed water-table surface as modified from Becher and Root (1981). The thickness of each layer is as follows: (1) 60 ft, (2) 60 ft, (3) 120 ft, (4) 160 ft, and (5) 250 ft. The total model thickness is 650 ft.

Layer 1 cells designated as regolith were defined as having thicknesses of saturated regolith of at least 5 ft and up to 60 ft. Cells with saturated regolith less than 5 ft in layer 1 were designated bedrock. For layer 2, the saturated regolith cells were defined as having regolith thickness of between 60 and 120 ft. Cells with less than 60 ft in layer 2 of saturated regolith were designated bedrock. Layer 3 regolith cells were defined as those having saturated regolith greater than 120 ft in thickness. Cells with less than 120 ft of saturated regolith in layer 3 were designated bedrock. The top three layers were discretized in the above manner to enable both vertical and horizontal flow between regolith and bedrock. This discretization more realistically represented the conceptual model of the flow system than a single layer representing all the regolith.

The bottom two layers, layers 4 and 5, are bedrock only. The bottom of layer 5 is defined as 650 ft below the water-table surface. Through statistical analysis of water-bearing zone data from the GWSI data base, the number of zones below 650 ft is very small.

Boundary Conditions

The model area is constrained by boundary conditions. Three types of boundary conditions are used for the model (fig. 10): (1) specified flux, (2) head-dependent flux, and (3) specified head. Where possible, natural hydrologic boundaries of the ground-water flow system were used as model boundaries.

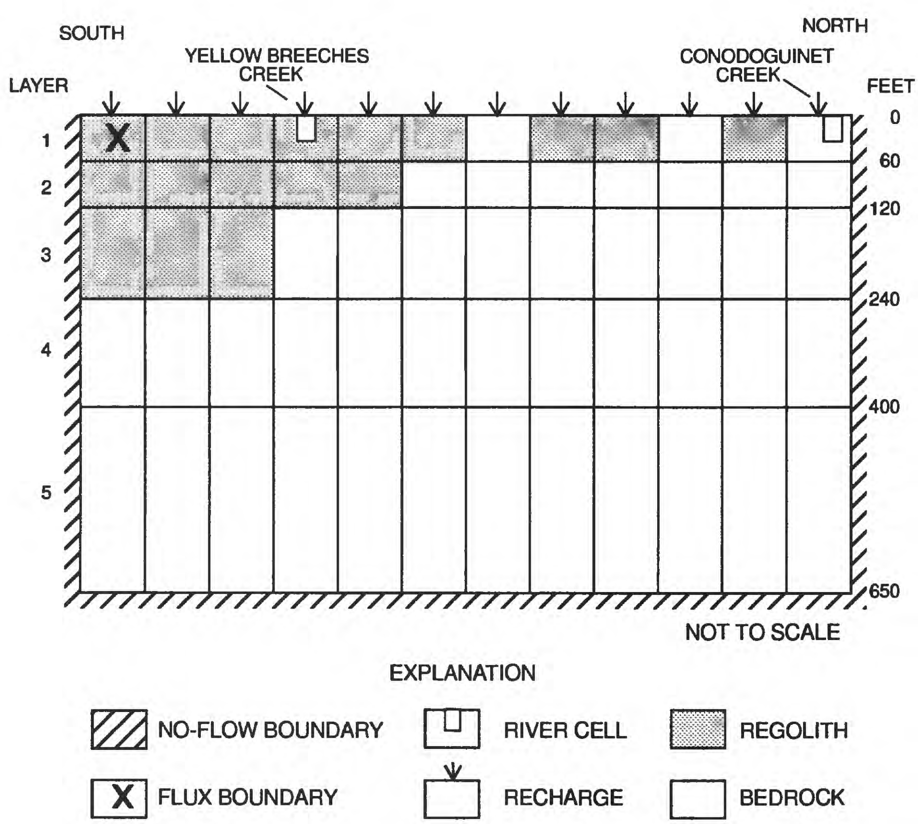


Figure 9. Schematic representation of general geology, model layers, and boundary conditions in the digital flow model.

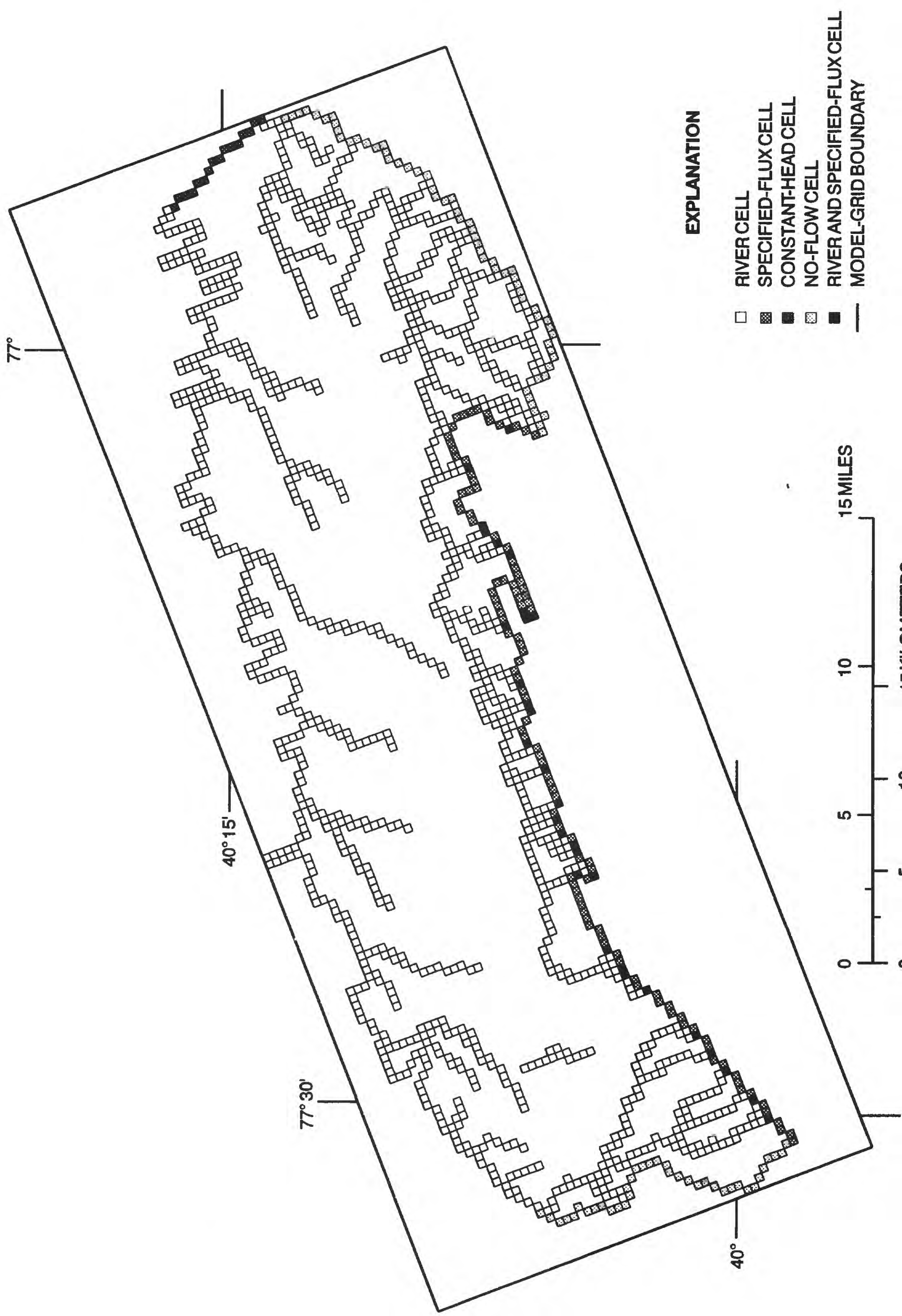


Figure 10. Model area and boundary conditions for the Cumberland Valley.

On the eastern side of the modeled area, the Susquehanna River is simulated as a constant-head boundary. The Susquehanna River is a regional sink and provides means of ground-water discharge for the Cumberland Valley. The head in the aquifer at each of the stream cells for the Susquehanna River was assumed to be equal to the river elevation. The cells in layer 1 for the Susquehanna River were modeled as constant-head cells. Cells in the other layers were modeled as no-flow boundaries.

On the north side of the modeled area, the Conodoguinet Creek is simulated as a head-dependent flux boundary. All stream cells within the model were also simulated as head-dependent flux cells (fig. 10). The upper boundary is simulated with 1,107 streams cells. Leakage to, or from, the streams (McDonald and Harbaugh, 1988) is approximated by the equation

$$Qr = (k'LW(hr-ha))/m, \quad (1)$$

where Qr is leakage, in cubic feet per day;
k' is streambed hydraulic conductivity, in feet per day;
L is length of stream reach, in feet;
W is stream width, in feet;
hr is stream stage, in feet;
ha is aquifer head, in feet; and
m is streambed thickness, in feet.

On the west side of the modeled area, the surface-water basin divide of Middle Spring Creek is simulated as a no-flow boundary.

On the southern side of the modeled area, the flank of South Mountain is simulated as a specified-flux boundary for layer 1. Water entering along this boundary is simulated by use of recharge wells. In addition, some cells along this boundary also were simulated as specified-head cells to represent upland streams entering the model area. This boundary represents recharge along the mountain front as a result of precipitation on the upland area adjacent to the modeled area.

On the east-southeastern side of the modeled area, the surface-water basin divide of the Yellow Breeches Creek is simulated as a no-flow boundary. The model bottom boundary and the lateral boundary of layers 2 through 5 also are simulated as a no-flow boundary.

The model upper boundary is the water table and is simulated as a specified-flux boundary. The flux is recharge varied areally on the basis of data from long-term average-annual precipitation and hydrograph-separation results on two continuous streamflow-gaging stations in the study area.

Hydraulic Conductivity

Hydraulic conductivity for the model was assigned by geologic unit. The hydraulic conductivity assigned to a particular cell was dependent on the geologic unit that the node of the cell occupied. The exception was the diabase dike trending northward across the valley. Cells along the dike were assigned a hydraulic conductivity representative of the dike whether the node of the cell fell on the dike or not, allowing for a continuous column of cells with lower hydraulic conductivity to follow the trend of the dike across the valley. A continuous column of cells improved the accuracy of simulation of the damming effect caused by the diabase dike. The initial hydraulic conductivities assigned for all layers of each individual geologic unit were based on geometric means calculated from GWSI data (tables 4 and 5).

Model Calibration

The ground-water flow model for the Cumberland Valley type-area study was calibrated under steady-state conditions. Average recharge, streamflow, water-table altitudes, and calculated hydraulic parameters were used to calibrate the model.

Approach

The calibration of the ground-water flow model involved the trial-and-error process of adjusting the initial estimates of aquifer properties until simulated hydraulic heads and water budgets were similar to the measured values. The initial estimates were adjusted within a range of measured values that are defined by the number and accuracy of the data on the local hydrogeologic properties. The accuracy of the final model simulation is affected by the amount and accuracy of the measured data, the complexity of the real system, and how well the conceptual model fits that system.

Table 5. Initial and calibrated horizontal hydraulic conductivity for all geologic units

Geologic unit	Horizontal hydraulic conductivity (in feet per day)	
	Initial	Final
Carbonate Regolith - Layer 1 [1]	35	75
Carbonate Regolith - Layer 2 [1]	35	25
Carbonate Regolith - Layer 3 [1]	35	15
Martinsburg Shale Regolith	35	7.5
Gettysburg-Newark Lowland Regolith	35	1.6
Diabase Dike - Layer 1	.03	.80
Diabase Dike - Layer 2	.03	.60
Diabase Dike - Layer 3	.03	.25
Diabase Dike - Layer 4	.03	.10
Diabase Dike - Layer 5	.03	.05
Diabase Sill - Layer 1	.20	.75
Diabase Sill - Layer 2	.20	.65
Diabase Sill - Layer 3	.20	.55
Diabase Sill - Layer 4	.20	.35
Diabase Sill - Layer 5	.20	.25
Gettysburg Formation - Layer 1	.21	.95
Gettysburg Formation - Layer 2	.21	.85
Gettysburg Formation - Layer 3	.21	.65
Gettysburg Formation - Layer 4	.21	.45
Gettysburg Formation - Layer 5	.21	.35
Martinsburg Formation	.46	2.5
Chambersburg Formation	.36	25
Myerstown Formation[1]	.30	2.5
St. Paul Group	1.4	55
Pinesburg Station Formation	1.7	31
Rockdale Run Formation	16	56
Epler Formation[1]	3.6	1.6
Stonehenge Formation	.74	26
Stoufferstown Formation[1]	1.2	6.7
Shadygrove Formation	.41	10
Zullinger Formation	1.9	.94
Elbrook Formation	2.1	.83
Waynesboro Formation	3.7	5.7
Tomstown Formation	38	28

[1] Statistics from Ground-Water Site Inventory data for all of the wells within the geologic unit for the Great Valley Section of the Valley and Ridge Physiographic Province of Pennsylvania.

The area to be modeled is not greatly affected by anthropogenic hydrologic stresses. Current withdrawals represent about 2-3 percent of the total water budget for the modeled area. Therefore, human-induced stresses were not simulated and calibration of this model represents natural, steady-state conditions.

Recharge

Model recharge plus specified-flux water entering the valley as upland recharge along South Mountain was assumed to be equal to the average-annual ground-water discharge for the area. Hydrograph-separation techniques were used to determine average base flows for the period of record at two continuous-record streamflow-gaging stations within the study area (fig. 6). These data were then converted to a percentage of the average-annual precipitation for the study area.

The initial estimate of recharge was based on a percentage of the areal distribution of precipitation for the model area. The percentage was based on the assumption that average-annual base flow, as calculated from hydrograph-separation techniques, is equal to the average-annual recharge. These initial estimates were based on the data for the continuous-record streamflow-gaging stations near the mouth of the Conodoguinet and Yellow Breeches Creeks (table 3) (figs. 6 and 11). For purposes of obtaining the initial estimate, recharge from losing stream reaches and interbasin flow were considered negligible.

The initial estimate for recharge, as a percentage of precipitation, was 30 and 38 percent for the Conodoguinet and Yellow Breeches Creek Basins, respectively. The percentages were then applied to each basin on the basis of the areal distribution of precipitation as shown in figure 11. Ground-water basins, delineated on the basis of the observed water-table map, were used as the areas to apply the basin-wide recharge. These areas were used instead of the surface-water basins because the percentages represent ground-water discharge and, therefore, are representative of the ground-water contributing areas not the surface-water basins. The initial and calibrated recharge amounts and percentages of precipitation as recharge for the

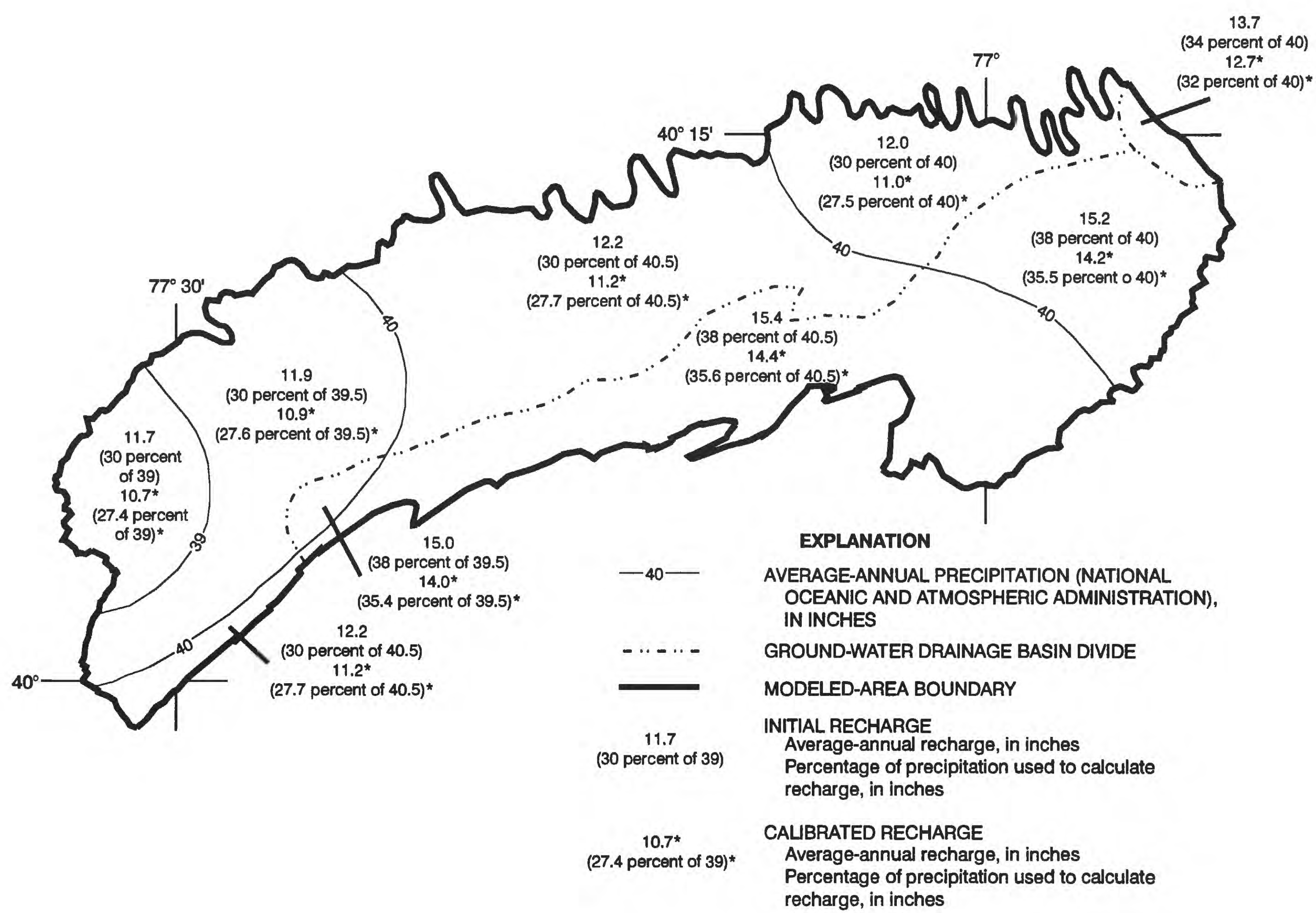


Figure 11. Average-annual precipitation and initial and calibrated average-annual recharge for the Cumberland Valley model area.

model area are shown in figure 11. The calibrated recharge amounts were 1 in. less than the initial estimate.

Aquifer Characteristics

Aquifer characteristics required for the model include the following: top and bottom altitudes for each layer; horizontal hydraulic conductivity for each geologic unit and regolith; vertical hydraulic conductance between layers; streambed hydraulic conductance; and aquifer anisotropy.

The top of layer 1 was defined, in part, as the water-table altitude mapped by Becher and Root (1981). The water-table surface was extended outward to include all the model area by the use of GWSI water-table altitude data and the land-surface elevation of gaining stream reaches as taken from 7-1/2-minute topographic maps. The subsequent top and bottom altitudes for the remaining layers were derived by subtracting the layer thickness, as defined earlier, from the altitude for the top of layer 1.

The hydraulic conductivities for each geologic unit were adjusted until the results of the simulated water budget matched the calculated budget, the simulated water-table configuration matched the observed configuration, and the root mean squared errors (RMSE) were minimized. The RMSE is the average of the squared differences in measured and simulated heads (Anderson and Woessner, 1992). The RMSE is calculated as

$$\left(\frac{\sum_{i=1}^{n} (h_m - h_s)^2}{n} \right)^{0.5} , \qquad (2)$$

where n is number of calibrated values,
i is individual nodes,
h_m is measured heads, and
h_s is simulated heads.

A statistical postprocessor to MODFLOW was used to calculate the RMSE following each model simulation (Scott, 1990). The RMSE calculations used the water-table map to represent measured heads at all active nodes and compared these values with the calculated heads. The hydraulic conductivity of entire geologic units was adjusted. Individual cells were only adjusted in one area of the model. This area was in the Gettysburg-Newark Triassic Lowland Section for cells (43, 152) and (43, 153). The cells in this area were adjusted individually to prevent persistent drying nodes and to improve the match between the calculated heads and observed heads. Table 5 shows the calculated and adjusted hydraulic conductivities for each geologic unit. The hydraulic conductivity for all geologic units in layer 5 was multiplied by a constant of 0.5 in the model input to represent reduced ground-water flow rates because of decreasing porosity and permeability with depth.

The saturated regolith was separated into three different zones of hydraulic conductivity to prevent drying of nodes and to better represent the physical system. The regolith was separated into zones on the basis of the bedrock it overlies—carbonate bedrock, Martinsburg shale, and rocks of the Gettysburg-Newark Lowland Section. The hydraulic conductivity of regolith overlying carbonate bedrock was adjusted individually by layer for layers 1 to 3. In areas where regolith overlies Martinsburg shale (in particular the allochthonous units), the hydraulic conductivity was adjusted lower than that for regolith overlying carbonate bedrock. The hydraulic conductivity of regolith in the Gettysburg-Newark Lowland Section area of the model also was adjusted individually and had the lowest hydraulic conductivities to prevent drying of nodes and to more accurately simulate the observed heads. Table 5 shows the calculated and adjusted hydraulic conductivities for regolith.

The vertical hydraulic conductance between layers was initially estimated and subsequently adjusted to improve the model simulation. The calibrated values for vertical hydraulic conductance (vcont) are as follows: (1) vcont between layers 1 and 2, 0.01; (2) vcont between layers 2 and 3, 0.005; (3) vcont between layers 3 and 4, 0.001; and (4) vcont between layers 4 and 5, 0.0005.

The aquifer exhibits anisotropic properties. The anisotropy is a result of increased secondary porosity and permeability development along bedding planes, joints, and cleavage parallel to strike. A calibrated column-to-row anisotropy value of 0.75 was used to minimize the RMSE for the simulated heads. The anisotropy value resulted in a horizontal hydraulic conductivity along strike (row) that was 1.33 times greater than that across strike (column).

Comparison of Simulated and Measured Water Levels

The water-table surface produced by model simulation at the end of the calibration process for layer 1 is shown in figure 12. These data can be compared with the observed water-table surface as shown in figure 7. The RMSE of the observed heads is 25.0 ft for the entire model area and 19.9 ft for the model area minus cells that lie in the Gettysburg-Newark Lowland Section. The observed water-table surface was used in the calculation of the RMSE, not discrete water-level measurements at wells.

Areas where errors in simulated heads occur are predominantly caused by geologic and possibly structural factors. Figure 13 shows the differences between observed and simulated heads. Contrasting hydraulic properties between adjacent lithologies or a fault may result in poorly simulated heads. The allochthonous units of the Martinsburg Formation and the Lebanon Valley sequences also are areas where simulated heads poorly match observed heads. These errors may result from the presence of thin thrust sheets that overlie lithologies with contrasting hydraulic properties.

Additionally, problems simulating heads in the extreme east-southeastern part of the model may be a result of contrasting lithologies and differing hydraulic properties with depth. In the Gettysburg-Newark Lowland Section area, the assumption that the contact between lithologies is vertical may not be a valid assumption. Here, the diabase sills may be vertically discontinuous units and may be overlain or underlain by different lithologies with contrasting hydraulic properties.

The simulated head data for lower layers were compared qualitatively. Observed data for wells open to these layers are very sparse, and for many wells there is uncertainly about which layer the well represents, so comparing and contrasting observed and simulated heads in lower layers quantitatively was not possible. However, looking at simulated heads in different layers supports the vertical discretization of the model and ground-water flow from the recharge to discharge areas of the system.

Compariston of Simulated and Measured Base Flow

Measured base-flow data was adjusted prior to model calibration. Because the modeled area does not include all of the surface-water drainage-basin area for the Conodoguinet and Yellow Breeches Creeks, subtraction of flow outside of the modeled area was necessary. Subtraction of flow was necessary for the upper part of the Conodoguinet Creek Basin that extends westward into Franklin County, for south flowing tributaries off shale bedrock to the Conodoguinet Creek, and for tributaries flowing off South Mountain to the headwaters of the Conodoguinet and Yellow Breeches Creeks.

Seepage-run measurements were made at select surface-water drainage basins in the areas outside the modeled area. The discharge and surface-water drainage-area data for these sites were then plotted to determine a regression relation. This relation was then used to subtract flow from all the tributary surface-water drainage-basin areas outside the model that flowed into the Conodoguinet and Yellow Breeches Creeks. The resultant base flow was used to determine the values to target in the simulated water budgets of the Conodoguinet and Yellow Breeches Creeks and the entire modeled area.

Initial streambed hydraulic conductivities were arbitrarily set to 0.25 ft/d for all stream cells in the Conodoguinet and Yellow Breeches Creek Basins. Subsequently, the streambed hydraulic conductivity was adjusted individually for the Conodoguinet and Yellow Breeches Creek Basins.

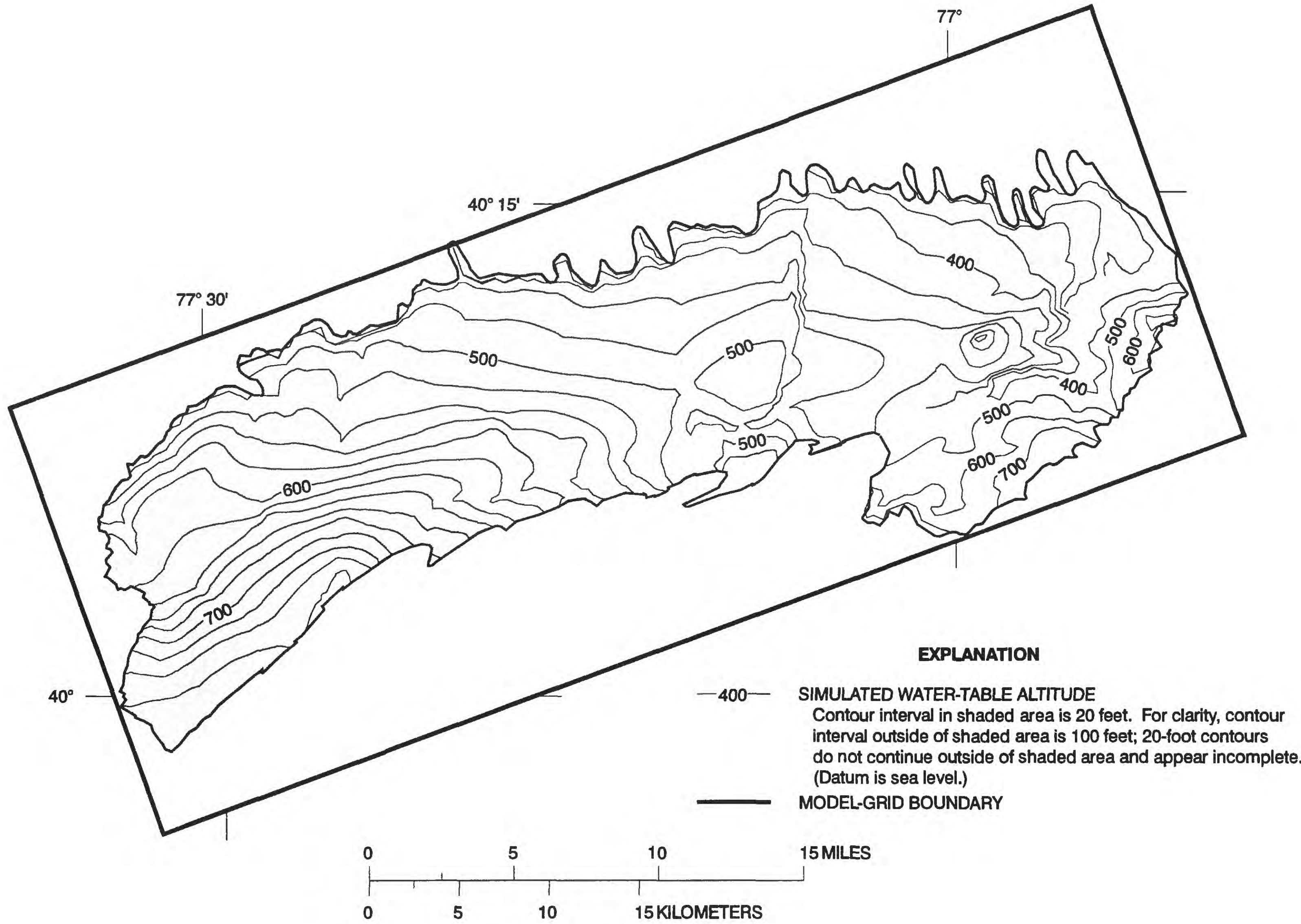


Figure 12. Simulated altitude of water table within the Cumberland Valley model area.

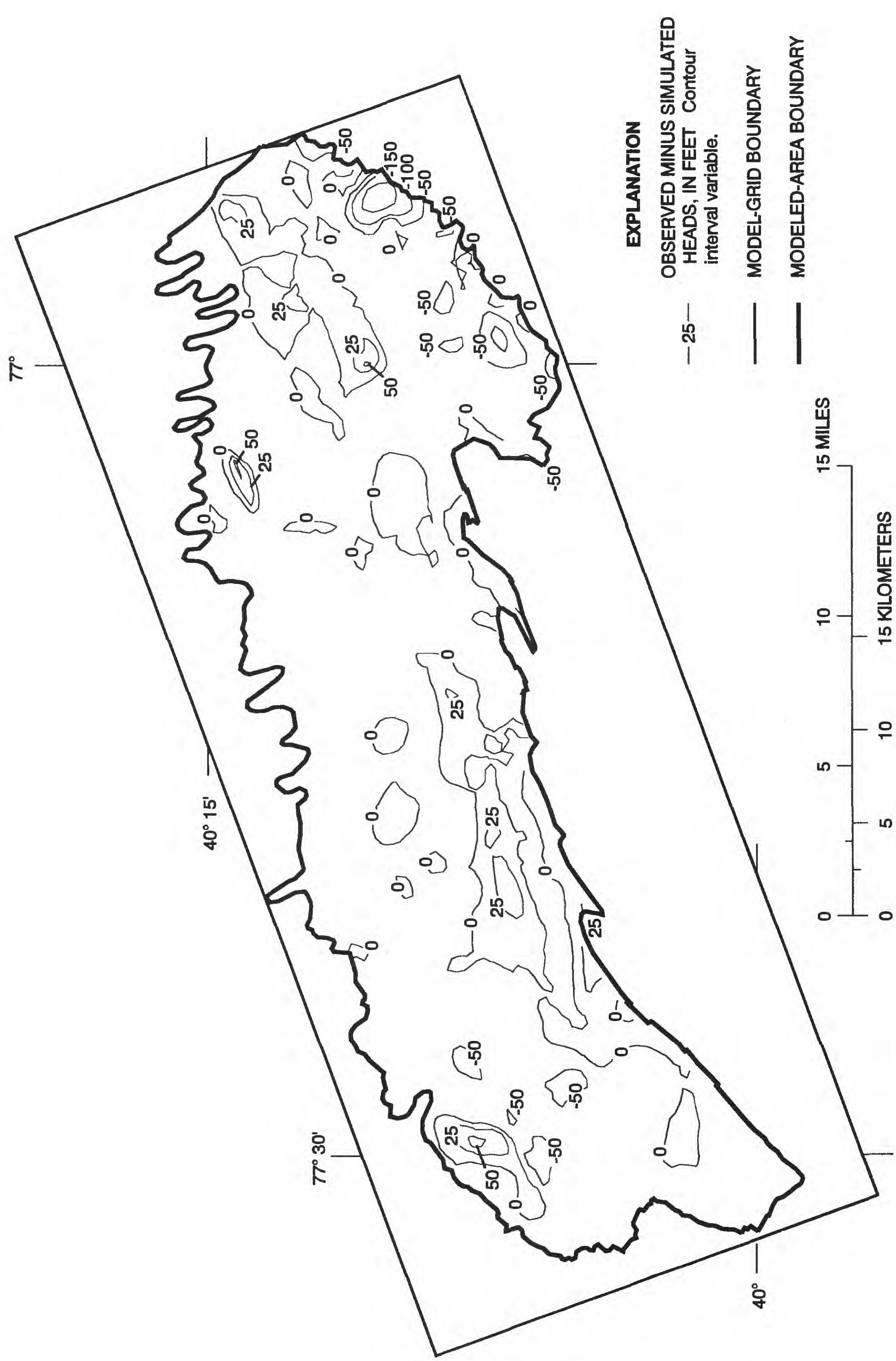


Figure 13. Difference in altitude of observed and simulated water table.

The streambed hydraulic conductivity was not adjusted for individual reaches or on the basis of the underlying bedrock. During the calibration process, streambed conductivities were adjusted to minimize the RMSE as well as to match the calculated discharge for the individual basin budgets. The calibrated streambed hydraulic conductivities were 0.15 and 5.0 ft/d for the Conodoguinet and Yellow Breeches Creek Basins, respectively. The large difference in streambed hydraulic conductivities are most likely a result of streamflow over bedrock in the Conodoguinet Creek Basin and over unconsolidated materials in the Yellow Breeches Creek Basin.

Sensitivity Analysis

Sensitivity analyses of the model involved changing a single parameter while holding all others constant. The effect of changing a parameter on the simulated water budget and water table was determined by varying the values being tested over a reasonable range. In this way, any changes in the simulated water budget and water table can be attributed to the changes in the value of the parameter being tested. If the change in a variable results in a large change in the simulated water budgets, the model is said to be sensitive to that variable. Conversely, if the change results in only small differences in the simulated results, the model is insensitive to that parameter. The sensitivity of the model can give some indication as to what additional information could improve the calibration of the model and improve the understanding of the ground-water flow system.

The degree of sensitivity was based on the changes in RMSE for head data between model simulations. Changes in the RMSE of a few tenths of a foot or less were called either sensitive or insensitive. Changes in the RMSE of several tenths of a foot or more, or changes resulting in failure of the model to converge, drying of nodes, or some other effect causing difficulties in running the model were termed very sensitive.

Numerous sensitivity analyses were performed during the calibration of the model. The variables that were tested for sensitivity analyses were aquifer horizontal and vertical hydraulic conductivities, streambed hydraulic conductivity, recharge rate, specified flux along South Mountain, and aquifer anisotropy. These parameters were individually tested over a reasonable range of values. For example, the horizontal hydraulic conductivities were tested within the range of maximum and minimum values for each lithology; however, they typically were tested within the range of the median and means for the lithology. Results of final sensitivity analyses, after model calibration, are discussed below in relative order from the most sensitive to least sensitive parameter.

Model sensitivity to changes in aquifer hydraulic conductivity ranged from very sensitive to sensitive. Very sensitive areas of the model included allochthonous Martinsburg Formation in the north and northwest and all of the Gettysburg-Newark Lowland Section in the east-southeast. Calibrating the model in these areas was difficult because of drying nodes and inaccurate simulation of heads. Model areas representing other lithologies were sensitive to changes in hydraulic conductivity with fluctuating heads. The simulated position and distribution of the ground-water divide between the Conodoguinet and Yellow Breeches Creek Basins was sensitive to changes in hydraulic conductivity of lithologic units in the vicinity of the basin divide. Model sensitivity to changes in recharge was also very sensitive. Changes in the recharge rate within normal climatic ranges produced large and discernible effects in simulated water budgets for both basins as well as in simulated heads throughout the modeled area.

The model was less sensitive to changes in streambed hydraulic conductivity and specified flux representing water flow off South Mountain and was sensitive to insensitive to changes in vertical hydraulic conductivity and anisotropy. Effects of the model to changes in streambed hydraulic conductivity were discernible in the simulated basin budgets and, to a lesser extent, in the simulated heads. The simulated heads were not sensitive to changes in the specified flux along South Mountain; however, simulated basin water budgets were sensitive. In particular, the simulated streamflow in the water budget for the Yellow Breeches Creek Basin was sensitive to changes in specified flux off South Mountain. Model sensitivity to vertical hydraulic conductivity was discernible in water budgets and simulated heads. Sensitivity analyses indicated that simulated water budgets were insensitive to changes in aquifer anisotropy. However, simulated head distributions and the ground-water basin divide location is sensitive to changes in anisotropy.

Evaluation of Hydrologic Characteristics and Flow System

Estimated and Simulated Parameters

The initial estimates for hydraulic conductivities are similar to the final values used in the model (table 5) and are within the range of measured values for individual geologic units (table 4). The hydraulic conductivity for individual units was adjusted so that simulated heads would better agree with the measured values (i.e., reduce the RMSE). For example, in areas where simulated heads were too high, hydraulic conductivities were adjusted higher to allow water to flow more readily downward and laterally to lower simulated heads. Most lithologies in the model had to be adjusted in this manner. Although recharge values could be adjusted to minimize the RMSE, the hydraulic conductivities were adjusted because they are relatively unknown and it was assumed that recharge was a known parameter.

The calculated estimates of base flow (see earlier section on the comparison of simulated and measured base flows) were 15.4×10^6 and 15.0×10^6 ft^3/d for the modeled areas of the Conodoguinet and Yellow Breeches Creek Basins, respectively. The simulated base flow for the same area is 17.2×10^6 and 15.2×10^6 ft^3/d for the Conodoguinet and Yellow Breeches Creek Basins, respectively. The estimated and simulated base flow for the Yellow Breeches Creek Basin are very similar. The simulated base flow for the Conodoguinet Creek is 10.5 percent higher than the estimated base flow. The total modeled area estimated and simulated base flow were 30.4×10^6 and 32.7×10^6 ft^3/d, respectively. The simulated base flow for the modeled area is 7.0 percent greater than the calculated base flow. The discrepancy in base flow for the Conodoguinet Creek and for the total modeled area may be a result of ground-water flow into or out of the aquifer from the streams outside, north, of the modeled area. Subtraction of surface-water flow was taken into account, but flow directly from the aquifer to and from the stream was not. A more accurate simulation of base flow, and thus model simulation, may be realized with the use of the streamflow-routing package to MODFLOW written by Prudic (1989).

The initial estimate of recharge was a percentage of average precipitation for the entire model area. This estimate did not agree with the basin budgets for the Conodoguinet and Yellow Breeches Creek Basins. The next estimate of recharge was a percentage of average precipitation for each basin on the basis of hydrograph-separation techniques. This second estimate greatly reduced errors in basin water budgets. The third and final estimate was to use a percentage of the areal distribution of average-annual precipitation for each basin. This third estimate not only improved the basin water budget but also improved the simulated head distributions for the model area (i.e., reduce the RMSE).

Flow-Path Analysis and Flow Budget

The computer programs MODPATH and MODPATH-PLOT (Pollock, 1989) were used to compute path lines and to track particles for ground-water flow. Figure 14 shows backtracking of particles from three springs in the model area. Backwards tracking of particles along their path lines from the springs enables determination of recharge areas for the springs. The particle tracking for the western-most spring, Big Spring, supports Becher and Root's (1981) findings that there is interbasin transfer of water from the Yellow Breeches Creek Basin to the Conodoguinet Creek Basin at Big Spring.

The computer program ZONEBUDGET (Harbaugh, 1990) was used to calculate subregional water budgets from model results. The subregional water budgets were used to estimate the simulated amount of interbasin transfer of water, if any, between the Conodoguinet and Yellow Breeches Creek Basins. On the basis of the surface-water basin drainage divides, 1.72×10^6 ft^3/d of interbasin flow occurs from the Yellow Breeches Creek Basin to the Conodoguinet Creek Basin. The interbasin flow amounts to 5.6 percent of the calculated annual water budget

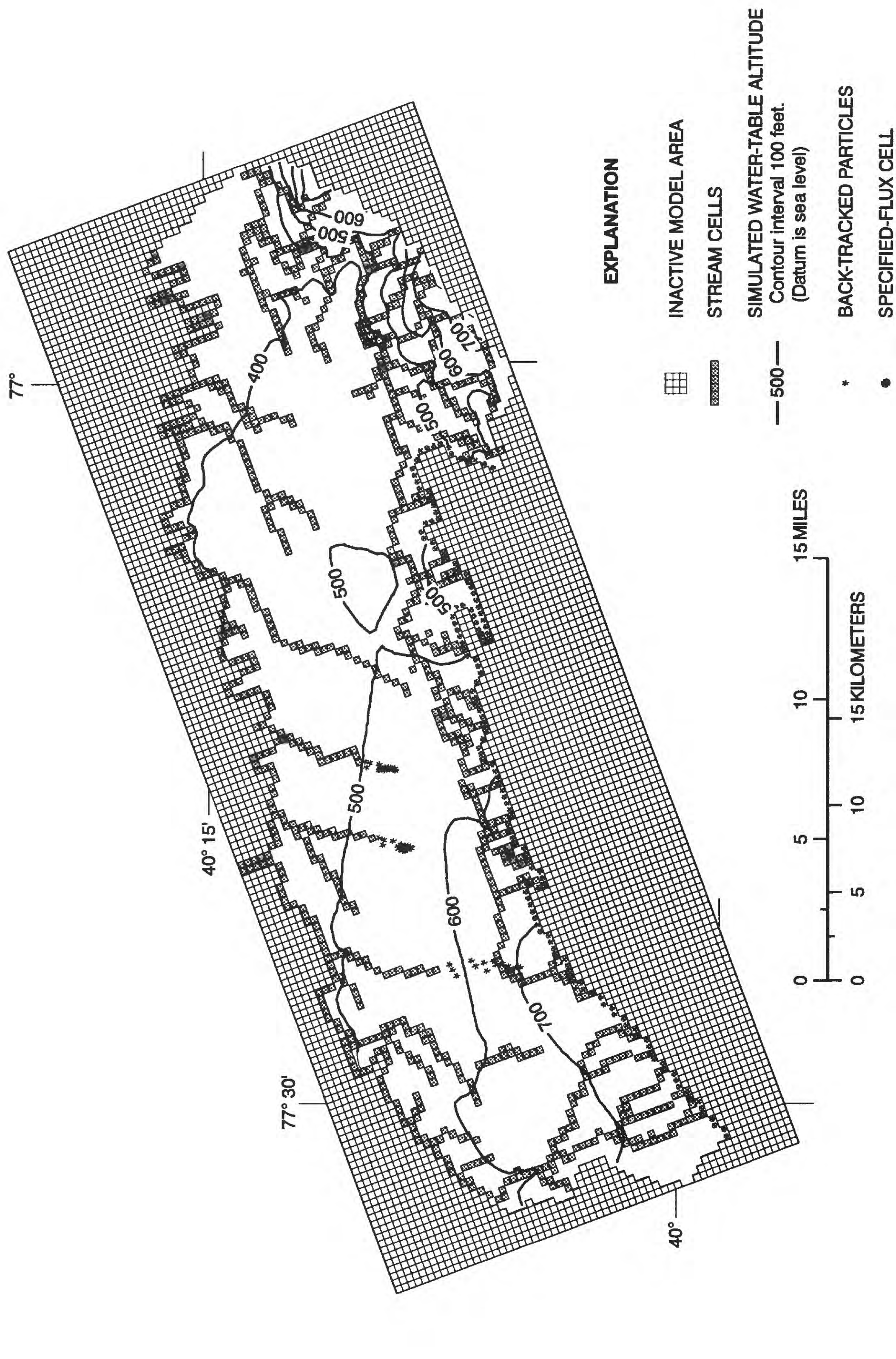


Figure 14. Back-tracking flow particles from selected locations.

for the modeled area and 11.5 percent of the calculated estimate of the flow for the Yellow Breeches Creek; this compares with a value of 8 percent of the flow for the Yellow Breeches Creek as calculated by Becher and Root (1981).

On the basis of the ground-water basin divides, 1.42×10^6 ft^3/d of interbasin flow occurs from the Yellow Breeches Creek Basin to the Conodoguinet Creek surface-water drainage basin. The interbasin flow amounts to 4.7 percent of the calculated annual water budget for the modeled area and 9.5 percent of the calculated estimate of the flow for the Yellow Breeches Creek.

The interbasin transfer of ground water accounts, in part, for recharge to the part of the Yellow Breeches Creek surface-water drainage basin that lies within the Conodoguinet ground-water basin. In addition, the interbasin transfer includes water that is lost from stream reaches in the upper part of the Yellow Breeches Creek Basin that lies within the ground-water basin of the Conodoguinet Creek surface-water drainage basin.

Boundary Conditions

The physical boundary conditions were not adjusted during the calibration process, so no quantitative evaluation can be made concerning the boundaries used for the model. However, improvements in the accuracy of the simulations may be realized with additional measurements of mountain-front recharge entering the model for the specified-flux boundary along the flank of South Mountain and additional streamflow data for the head-dependent flux boundary along the Conodoguinet Creek.

Also, if the boundaries were moved to the headwaters surface-water basin divides for the Conodoguinet and Yellow Breeches Creeks in the north and south, simulation results may improve. However, the model area would nearly double in size and additional data would be needed to determine hydraulic properties of the bedrock and streambed material in these areas.

Applications to Similar Areas

The qualitative results and the approach for analysis and study can be applied to other similar areas along the Great Valley Section of the Valley and Ridge Physiographic Province. However, the quantitative results of this study are not transferable to other areas.

The results of sensitivity analyses for this study area also may be transferable to other similar areas. The sensitivity data can be used to determine where additional data collection may be necessary or would help to improve model simulations. Also, the types of additional data that would be most beneficial could be determined. This will help streamline and reduce costs for future work as well as provide valuable information for present or future studies in other similar areas of this physiographic province.

SUMMARY AND CONCLUSIONS

The thickly mantled carbonate-rock aquifer of the Cumberland Valley in Pennsylvania is a highly productive and complex aquifer. The aquifer is characterized by complexly folded and faulted carbonate bedrock in the valley bottom, and locally in the north and east by shale, graywacke, and red-sedimentary and diabase rocks. Near the southern valley hillslope, the carbonate rock is overlain by wedge-shaped regolith (up to 450 ft thick) consisting of residual material, alluvium, and colluvium. Residual material, comprised mostly of weathered carbonate rock, is up to 200 ft thick. Alluvium and colluvium consist of reworked residual material and siliciclastic materials derived from a resistant upland source of quartzite and schist to the south. Locally, the thickness of saturated regolith exceeds 240 ft. The topographic relief of the carbonate (Letort Spring Run), carbonate and shale (Conodoguinet Creek), and regolith-mantled carbonate (Yellow Breeches Creek) basins are approximately 200, 1,900, and 1,700 ft, respectively.

In general, the water-table surface is a subdued representation of the land surface. Anomalies in the water-table gradient and configuration are a result of topography and differences in the character and distribution of overburden material and bedrock, permeability, and geologic structure. Locally, ground water is mounded, has steep gradients, and its flow is diverted by adjacent rocks of low permeability as a result of a fault or lithologic contact. In areas of solution-affected carbonates, as in the Letort Spring Run Basin, the water-table gradient is low. Regional ground-water flow is generally east-northeast toward the Susquehanna River.

Seepage-run data indicate that stream reaches near valley walls are losing water from the stream, through the regolith, to the ground-water system. Most stream reaches in the lower and middle part of the Conodoguinet and Yellow Breeches Creek Basins are gaining water from the ground-water system. Results of hydrograph-separation techniques indicate that base flow in stream basins dominated by carbonate, carbonate and shale, and regolith-mantled carbonate bedrock is 93, 68, and 81 percent of total streamflow, respectively.

An average-annual water budget was calculated for the study area above the continuous-record streamflow-gaging stations for the Conodoguinet and Yellow Breeches Creeks. Average-annual precipitation ranges from about 39.0 to 40.5 in. and averages about 40.0 in. for the entire study area. Average-annual direct surface runoff was 5.7 and 3.5 in. for the Conodoguinet and Yellow Breeches Creek Basins, respectively. Average-annual evapotranspiration was 22 and 21 in. for the Conodoguinet and Yellow Breeches Creek Basins, respectively. Average-annual base flow was 12 and 15 in., which is 68 and 81 percent of the ground-water discharge as a percentage of total streamflow for the Conodoguinet and Yellow Breeches Creek Basins, respectively. Average-annual recharge varied areally and was 29 and 37 percent of the total precipitation for the Conodoguinet and Yellow Breeches Creek Basins, respectively.

A conceptual model was developed on the basis of known information of the hydrogeologic properties of the rock units, water-table surface and configuration, recharge and discharge rates, and the relation of the aquifer to the surrounding boundaries. This model was used as the basis for the construction and discretization of the finite-difference ground-water flow model.

A finite-difference ground-water flow model was used to simulate the thickly-mantled carbonate aquifer in the Cumberland Valley. The valley was modeled as a three-dimensional water-table aquifer. Recharge to, ground-water flow through, and discharge from the Cumberland Valley were simulated. Input to the model includes areally varied recharge and an applied specified flux along the flank of South Mountain. Discharge from the model includes ground-water discharge to Susquehanna River and to the Conodoguinet and Yellow Breeches Creeks and their tributaries.

The model boundaries used natural hydrologic boundaries where possible. The eastern boundary is the Susquehanna River, which is a regional ground-water sink. To the north, the Conodoguinet Creek is modeled as a specified-head boundary. To the west, the drainage-basin divide of Middle Spring Creek is a no-flow boundary. To the south, the flank along South Mountain is modeled as a specified-flux boundary. The upper boundary is modeled as a water-table surface and streams. The lower model boundary is a no-flow boundary 650 ft below the water-table surface. A model grid was constructed with the rows oriented at N. 70°E., which is approximately parallel to the general strike of the geologic structure for the study area. The grid was discretized at 0.25 mi (1,320 ft) grid spacing with 62 rows and 160 columns. The active model area includes 5,579 nodes and is 350 mi^2 in area.

Initial estimates of hydraulic properties for the model area were calculated from statistical analyses of specific-capacity data from the GWSI data base. Geometric mean statistics were used to define the hydraulic conductivity for each geologic unit. Horizontal hydraulic conductivity is greater in the direction parallel to the strike of the formations than in the direction parallel to the dip of the formations. In the digital model, the ratio used to simulate this anisotropy was 1.33:1.

Model-calibrated streambed vertical hydraulic conductivity was adjusted individually for the Conodoguinet and Yellow Breeches Creek Basins. Calibrated values are 0.15 and 5.0 ft/d for the Conodoguinet and Yellow Breeches Creek Basins, respectively.

Average simulated base flow for the entire model is 7 percent greater than the calculated estimate of the observed base flow. The simulated base flow is 10.5 and 1 percent greater than the calculated observed base flow for the Conodoguinet and Yellow Breeches Creek Basins, respectively.

The average water budget for the model area was approximated by steady-state simulation. Particle-tracking analyses using MODPATH-PLOT indicate that interbasin flow of ground water occurs within the Yellow Breeches Creek Basin and between the Yellow Breeches and Conodoguinet Creek Basins. Simulated interbasin flow, based on the surface-water drainage-basin area, is 1.72×10^6 ft^3/d from the Yellow Breeches Creek to the Conodoguinet Creek Basin. The interbasin flow is 5.6 percent of the total budget and 11.5 percent of the total, calculated base flow of the Yellow Breeches Creek part of the model area.

The calibrated model was most sensitive to recharge and hydraulic conductivity of allochthonous deposits of the Martinsburg Formation and all of the Gettysburg-Newark Triassic Lowland Section in the east-southeast. The model was less sensitive to the specified flux off South Mountain and streambed hydraulic conductivity. The model was least sensitive to aquifer anisotropy.

The quantitative results of this study area are not transferable to other similar type areas. However, the qualitative results and the approach for analysis and study can be applied to other similar areas along the Great Valley Section of the Valley and Ridge Physiographic Province. This information can supply valuable information to address ground-water quantity and quality issues during the present and in the future.

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