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Scientific Investigations Report 2009–5153

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per day (m^3/d)	264.2	gallon per day (gal/d)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
	Hydraulic conductivity	
meter per day (m/d)	3.281	foot per day (ft/d)
	Transmissivity*	
meter squared per day (m^2/d)	10.76	foot squared per day (ft^2/d)

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

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

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience and expressed in the metric equivalent of square meters per day (m^2/d).

Hydrogeologic Setting and Ground-Water Flow in the Opequon Creek watershed area, Virginia and West Virginia

By Mark D. Kozar and David J. Weary

Abstract

Due to increasing population and economic development in the northern Shenandoah Valley of Virginia and West Virginia, water availability has become a primary concern for water-resource managers in the region. To address these issues, the U.S. Geological Survey (USGS), in cooperation with the West Virginia Department of Health and Human Services and the West Virginia Department of Environmental Protection, developed a numerical steady-state simulation of ground-water flow for the 1,013-square-kilometer Opequon Creek watershed area. The model was based on data aggregated for several recently completed and ongoing USGS hydrogeologic investigations conducted in Jefferson, Berkeley, and Morgan Counties in West Virginia and Clarke, Frederick, and Warren Counties in Virginia. A previous detailed hydrogeologic assessment of the watershed area of Hopewell Run (tributary to the Opequon Creek), which includes the USGS Leetown Science Center in Jefferson County, West Virginia, provided key understanding of ground-water flow processes in the aquifer.

The ground-water flow model developed for the Opequon Creek watershed area is a steady-state, three-layer representation of ground-water flow in the region. The primary objective of the simulation was to develop water budgets for average and drought hydrologic conditions. The simulation results can provide water managers with preliminary estimates on which water-resource decisions may be based.

Results of the ground-water flow simulation of the Opequon Creek watershed area indicate that hydrogeologic concepts developed for the Hopewell Run watershed area can be extrapolated to the larger watershed model. Sensitivity analyses conducted as part of the current modeling effort and geographic information system analyses of spring location and yield reveal that thrust and cross-strike faults and low-permeability bedding, which provide structural and lithologic controls, respectively, on ground-water flow, must be incorporated into the model to develop a realistic simulation of ground-water flow in the larger Opequon Creek watershed area.

In the model, recharge for average hydrologic conditions was 689 $m^3/d/km^2$ (cubic meters per day per square kilometer) over the entire Opequon Creek watershed area. Mean and median measured base flows at the streamflow-gaging station on the Opequon Creek near Martinsburg, West Virginia, were 604,384 and 349,907 m^3/d (cubic meters per day), respectively. The simulated base flow of 432,834 m^3/d fell between the mean and median measured stream base flows for the station. Simulated base-flow yields for subwatersheds during average conditions ranged from 0 to 2,643 $m^3/d/km^2$, and the median for the entire Opequon Creek watershed area was 557 $m^3/d/km^2$.

A drought was simulated by reducing model recharge by 40 percent, a rate that approximates the recharge during the prolonged 16-month drought that affected the region from November 1998 to February 2000. Mean and median measured streamflows for the Opequon Creek watershed area at the Martinsburg, West Virginia, streamflow-gaging station during the 1999 drought were 341,098 and 216,551 m^3/d, respectively. The simulated drought base flow at the station of 252,356 m^3/d is within the range of flows measured during the 1999 drought. Recharge was 413 $m^3/d/km^2$ over the entire watershed during the simulated drought, and was 388 $m^3/d/km^2$ at the gaging station. Simulated base-flow yields for drought conditions ranged from 0 to 1,865 $m^3/d/km^2$ and averaged 327 $m^3/d/km^2$ over the entire Opequon Creek watershed.

Water budgets developed from the simulation results indicate a substantial component of direct ground-water discharge to the Potomac River. This phenomenon had long been suspected but had not been quantified. During average conditions, approximately 564,176 m^3/d of base flow discharges to the Potomac River. An additional 124,379 m^3/d of ground water is also estimated to discharge directly to the Potomac River and represents approximately 18 percent of the total discharge to the Potomac River.

Introduction

The study area for this investigation is the Opequon Creek watershed area in the northern Shenandoah Valley of Virginia and West Virginia and the Eastern Panhandle of West Virginia. The study area (fig. 1) encompasses approximately 1,013 km^2 and includes both the Opequon Creek watershed (855 km^2) and those of several smaller, mostly unnamed tributary streams that discharge directly to the Potomac River in the northern portion of the study area (158 km^2). The region has experienced rapid population growth and associated economic development over the last 20 years. This increased growth has placed an ever-increasing demand on available ground- and surface-water resources. Local, county, and State water managers have recognized the importance of effective management of the abundant but finite ground-water resources of the region. Effective management of ground-water resources requires a thorough knowledge of the availability of ground-water resources not only during average climatic conditions but also, more importantly, during the critical low-water-table and streamflow conditions that occur during droughts. The 16-month drought that affected the region from November 1998 through February 2000 exposed the limits of water availability and was a driving force behind the need for accurate assessments of water resources in the region.

Purpose and Scope

This report presents results of a steady-state simulation of ground-water flow in the Opequon Creek watershed area in the northern Shenandoah Valley of Virginia and West Virginia. The model was developed by extrapolating the conceptual model (Kozar and others, 2007) of ground-water flow developed for the smaller Hopewell Run watershed area (52 km^2) (fig. 1) to the much larger Opequon Creek watershed area (1,013 km^2). The resulting model was used to develop a budget of available ground-water resources and to assess the potential effects of drought on water availability within the watershed. The report describes the hydrogeology of the study area, documents the development of the ground-water flow model, presents the results of water-budget analyses, and quantifies simulated streamflow under both average and drought conditions.

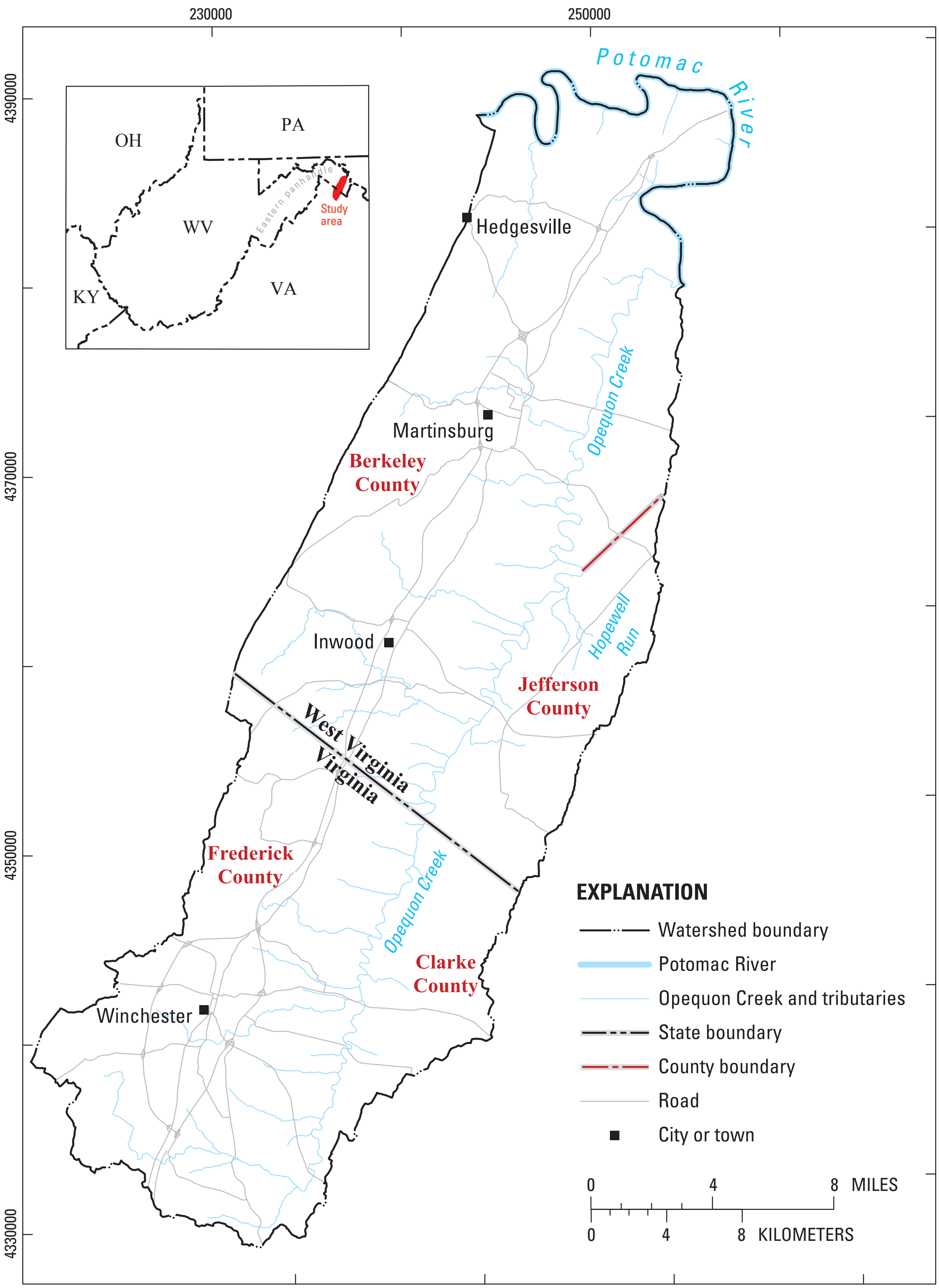
Approach

Various methods were used to develop the numerical ground-water flow model of the Opequon Creek watershed area. Extensive aquifer tests conducted in Berkeley and Jefferson Counties, West Virginia (McCoy and others, 2005a, 2005b), and in a recent investigation completed at the USGS Leetown Science Center (Kozar and others, 2007, 2008) provided the hydraulic data (transmissivity, hydraulic conductivity, and storativity) and the conceptual model of ground-water flow needed to develop and calibrate a numerical ground-water flow model of the area. Eight USGS streamflow-gaging stations (table 1) provided base-flow data to aid in calibrating simulated ground-water flows in the model. Base-flow surveys conducted in the region in 2005 and 2006 (Evaldi and Paybins, 2006a, 2006b) helped to identify potential gaining and losing reaches in the watershed and subwatersheds with either abnormally high or low base-flow yields. Base flow is streamflow provided by ground-water discharge. Recharge to the study area was estimated by analyzing streamflow hydrographs (Rutledge, 1998) for the eight gaging stations in the watershed and provided the primary input to the model. Ground-water levels measured at 420 wells in the study area were retrieved from the USGS Ground-Water Site Inventory (GWSI) database and used for calibration of ground-water levels in the model. Aquifer tests conducted in the area as part of previous studies (McCoy and others, 2005a, 2005b) provided data on the hydraulic properties of the aquifer needed for model development and calibration.

The computer software package Visual MODFLOW, version 4.0.0.131 (Waterloo Hydrogeologic, Inc., 2004), was used to develop a steady-state ground-water flow model of the Opequon Creek watershed area. Visual MODFLOW is a commercially derived graphical user interface to the USGS MODFLOW 2000 three-dimensional finite-difference ground-water modeling software (Harbaugh and others, 2000) and to MODPATH (Pollock, 1998), a USGS particle-tracking software package. MODFLOW was used to simulate ground-water levels and develop a water budget for the Opequon Creek watershed area.

Description of Study Area

The study area is an approximately 1,013-km^2 region of the northern Shenandoah Valley in Virginia and West Virginia (fig. 1). The region is part of the broader Great Valley of the Valley and Ridge Physiographic Province (Fenneman, 1938), which extends from New York to Alabama. Therefore, it is assumed that methods developed and tested for this and previous studies in the area are transferable to the broader Great Valley region. Major population centers in the region include Martinsburg, West Virginia, and Winchester, Virginia (fig. 1). The major tributary draining the study area is Opequon Creek (drainage area of 855 km^2), which discharges to the Potomac River. Numerous smaller tributaries, including Hopewell Run, drain to Opequon Creek, and a few smaller streams (drainage areas totaling 158 km^2) drain directly to the Potomac River. Elevation in the study area ranges from a maximum of approximately 390 m along North Mountain in the western part of the study area to a minimum of 130 m at the mouth of Opequon Creek.



Base from U.S. Geological Survey digital data, Universal Transverse Mercator Projection, Zone 18, NAD 83.

Figure 1. Location of the Opequon Creek watershed area in Virginia and West Virginia. (Opequon Creek forms the boundary between Berkeley and Jefferson Counties in West Virginia and between Clarke and Frederick Counties in Virginia.)

Hydrogeologic Setting

The study area is dominated by karst terrain, consisting of Cambro-Ordovician-age limestones and dolomites in a broad synclinal trough, which is bisected by the younger late-Ordovician-age Martinsburg Formation. This unit is a predominantly brown shale, which crops out in the center of the valley (fig. 2a). Siliciclastic rocks border the study area along a series of high-angle thrust faults along North Mountain to the west. Bedrock ridges form in the low-permeability Conococheague Limestone on the eastern side of the syncline. Although the study area is karstic, sinkholes are sparse and typically are small, less than 10 m in diameter. Caves are also sparse and limited in length and width. Within the karst aquifer system, diffuse components of ground-water flow provide most of the storage.

Previous Hydrogeologic Investigations

The relation between geology and ground-water supply and quality in the study area was first discussed by Jeffords (1945a, 1945b). Graeff (1953) and Beiber (1961) explained the lithologic control of carbonate units on the quality and quantity of ground water, and on the direction of flow in the aquifers of Jefferson and Berkeley Counties, West Virginia. Large springs discharging more than 545 m^3/d (1,000 gal/min) from these carbonate units were correlated with the faults in the area by Hobba and others (1972). Taylor (1974) concluded that systematic fracturing of the carbonate bedrock, attributed to a four-phase deformation history, is partially evident from topographic analysis of the area. He found that well yields and spring locations in lowland areas are related to structural features, such as joints, faults, and fractures, that allow large quantities of ground water to flow downgradient. Seasonal and annual fluctuations in ground-water storage and base-flow discharge to streams associated with these features can be large (Hobba, 1976, 1981). Estimates of aquifer transmissivity for the fractured carbonate rocks from Kozar and others (1991) and Shultz and others (1995) ranged over four orders of magnitude (0.1–2,000 m^2/d). Preferential flow in the direction of strike was verified by the dye-tracing work of Jones (1991), Kozar and others (1991), and Shultz and others (1995). Previous dye-tracing work in the Hopewell Run watershed area by Jones and Deike (1981) led to the conclusion that the aquifer is characterized by steeply dipping bedding planes with a diffuse network of fractures that may retard travel times and force circulation to depths below those common in other karst systems. McCoy and Kozar (2007b) found that vertical flow of ground water in the Great Valley was downgradient along continuous interconnected fractures in the direction of bedding. Ground water is eventually forced to the surface along structural offsets perpendicular to strike. Structural geologic features, especially thrust faults and cross-strike faults, are important controls on ground-water flow and coincide with many of the larger solution conduits in the region (Kozar and others, 2007, 2008). Lithologic controls, especially low-permeability units such as the Conococheague Limestone and Martinsburg Formation, are equally important, as they act as barriers to ground-water flow, forcing water to flow along solutionally enlarged bedding planes, thrust faults, and cross-strike faults. In nearby Frederick County, Virginia, Harlow and others (2005) modified the conceptual model of Wolfe and others (1997) to describe the influence of structural features on karst development at moderate depths. An equivalent-porous-medium (EPM) finite-difference model for the Opequon Creek watershed was first developed by Early (2005), but simulation of discharge at springs by use of pumping nodes produced unrealistic cones of depression around the springs. The effort did, however, illustrate the potential utility of EPM simulations for assessing regional water budgets. A regional ground-water flow model developed for the entire Shenandoah River watershed (Yager, 2008) was used to evaluate the effect of complex geologic structure on regional patterns of ground-water flow to production wells. Dealing with different geologic structure in various ways produced slightly different zones of contribution to simulated production wells, but overall water budgets were similar.

Ground-water flow patterns in the Great Valley are complex. The once flat-lying sedimentary rocks have been folded, faulted, and intensely weathered such that a variably thick layer of regolith overlies steeply dipping, deformed bedrock units. Recharge in the form of infiltration of precipitation initially moves into the regolith, where much of it is stored. Water moves to the underlying bedrock by way of leakage to open fractures, faults, and bedding planes or by direct runoff into surficial karst features. Flow in the bedrock is controlled by the orientation and connectivity of the fracture system and the location of solution-enlarged conduits. Relict structure in the regolith and continuous bedding planes apparently force flow parallel to regional gradients (Jones, 1991). Frazier and others (1988) conducted a detailed surface-water assessment at the USGS Leetown Science Center and adjacent property in the Hopewell Run watershed using watershed models to assess flooding potential and long-term stability of engineered ponds proposed for construction.

Geologic History

The sedimentary rocks in the Opequon Creek watershed area were deposited in chiefly shallow marine environments over about a 200-million-year (m.y.) period of relative tectonic quiescence from the Late Cambrian (about 540 m.y. ago) into the Mississippian Period (about 340 m.y. ago). From about 340 m.y. to about 280 m.y. ago, continental collision between North America and Africa, the Alleghenian orogeny, produced most of the folds, faults, and joints seen in the Great Valley today. Earlier episodes of tectonism seen in rocks east of the Blue Ridge, such as the Taconic and Acadian orogenies, apparently did not affect the rocks of the Great Valley (Southworth and others, 2006). Post-Paleozoic erosion has removed younger sediments to expose Cambrian- and Ordovician-age rocks at the land surface today.

Geology

Lithology and bedrock structure are important controls on ground-water flow. Low-permeability lithologic units such as the Martinsburg Formation and Conococheague Limestone act as barriers to ground water flowing across the strike of the bedding. This retardation of cross-strike flow is especially pronounced where the bedding dips at steep angles or where the lower permeability formations crop out. Geologic structures that disrupt the rocks in cross-strike directions, especially highly permeable fault and fracture zones, provide avenues through which ground water can flow laterally across or through strata with low primary permeability. Solution conduits form along strike-parallel thrust faults, especially where downgradient flow is forced into these features by lower permeability bedrock. These structural features act as drains for the broader network of diffuse-flow fractures in the aquifer and are especially prominent along the geologic contacts between carbonate strata and the much lower permeability Martinsburg Formation.

Bedrock Lithologic Units

The bedrock of the Opequon Creek watershed area (fig. 2a) is composed of predominantly fractured limestone and dolomite of the Upper Cambrian Elbrook Formation and Lower Ordovician and Upper Cambrian Conococheague Limestone; the Lower Ordovician Stonehenge Limestone, Rockdale Run Formation, and Pinesburg Station Dolomite; and the Middle Ordovician New Market and Chambersburg Limestones. A large portion of the Opequon Creek watershed area is underlain by clastic rocks of the Upper and Middle Ordovician Martinsburg Formation, the youngest bedrock lithologic unit in the model area. A thin band of Silurian and Devonian clastic rocks crops out along much of the northwestern boundary of the watershed in the Little North Mountain fault zone. The stratigraphic relations, lithologies, and relative thicknesses of the Cambrian and Ordovician rock units are shown in figure 2b.

The Elbrook Formation, the oldest unit exposed in the Opequon Creek watershed area, is found in a thick outcrop belt that parallels the western edge of the study area (fig. 2a). The Elbrook is composed of interbedded limestone, dolostone, and shale. The limestone, which may be thinly to moderately bedded, contains algal bioherms, intraformational conglomerates, and dolomite mottling. The dolostone is commonly moderately bedded; a distinctive yellowish weathering of thinly bedded laminated dolostone appears shaly in weathered outcrops. The Elbrook Formation in the watershed is about 700 m thick.

The Conococheague Limestone is exposed in a thick outcrop belt along the western side and in several folds in the northern and eastern part of the Opequon Creek watershed area (fig. 2a). The Conococheague Limestone is chiefly thick-bedded, light-gray limestone deposited in upward-shallow peritidal cycles capped by laminated dolomite beds. Typical cycle thicknesses range from 2 to 12 m. Some beds contain rip-up clasts, forming flat-pebble, edgewise conglomerates. The quartz-sandstone-rich, basal Big Springs Station Member of the Conococheague Limestone is resistant to weathering and produces prominent topographic ridges that serve as markers for the contact with the underlying Elbrook Formation, which is commonly obscured by soil. Conodont biostratigraphy suggests that the Cambrian-Ordovician boundary is within the Conococheague Limestone near the upper formational contact (Harrris and others, 1994). The Conococheague Limestone is about 850 m thick in this part of the Great Valley.

The Ordovician Stonehenge Limestone occurs in outcrop belts in approximately the center of each of the east and west limbs of the Massanutten synclinorium in the Opequon Creek watershed area (fig. 2a). The Stonehenge Limestone is a thick to massive-bedded (with thin interbeds), dark-gray, siliceous limestone. The silt is concentrated in wispy laminae that commonly weather in raised-relief natural exposures. The silt content of the rock has allowed a pervasive axial planar cleavage, related to Alleghenian folding, to be produced. In some exposures the cleavage is so penetrative that it has obscured or obliterated the bedding planes. In such areas, the cleavage probably has a greater effect on the hydrologic properties of the rocks than the bedding. The lower part of the Stonehenge Limestone is the Stoufferstown Member. This member is distinguished by the anastomosing, crinkly, siliceous laminae permeating the limestone, and commonly forms distinct strike-parallel linear ridges and fins in outcrop. The Stonehenge Limestone is about 198 m thick.

The Rockdale Run Formation and the superjacent Pinesburg Station Dolomite were treated as one unit for this study. The Rockdale Run Formation is composed of thick and medium-bedded, light-gray limestone and dolomite in cyclic, peritidal deposits that resemble those in the Conococheague Limestone. It is commonly lighter in color and less cleaved than the underlying Stonehenge Limestone. The Pinesburg Station Dolomite is thick-bedded and weathers light gray to buff. It ranges from 0 to 122 m thick, whereas the Rockdale Run Formation is commonly about 460 m thick in this part of the Great Valley (Dean and others, 1990).

Because of the regional scale of this study, the relatively thin Middle Ordovician limestones overlying the Pinesburg Station Dolomite were combined into one map unit (Oeln). In Virginia, these units are the New Market, Lincolnshire, and Edinburg Limestones. In West Virginia, the facies that defines the Lincolnshire is absent, and the rocks above the New Market Limestone that are equivalent to the Edinburg lithology are called the Chambersburg Limestone. These limestones are exposed in two belts flanking the core of the Massanutten synclinorium, which is occupied by the superjacent shales and sandstones of the Martinsburg Formation (fig. 2a). The New Market Limestone lies unconformably above the Pinesburg Station Dolomite. The New Market Limestone is a very pure, dove-gray, lime mudstone. It is quarried extensively at various locations in the region. The New Market is the most soluble

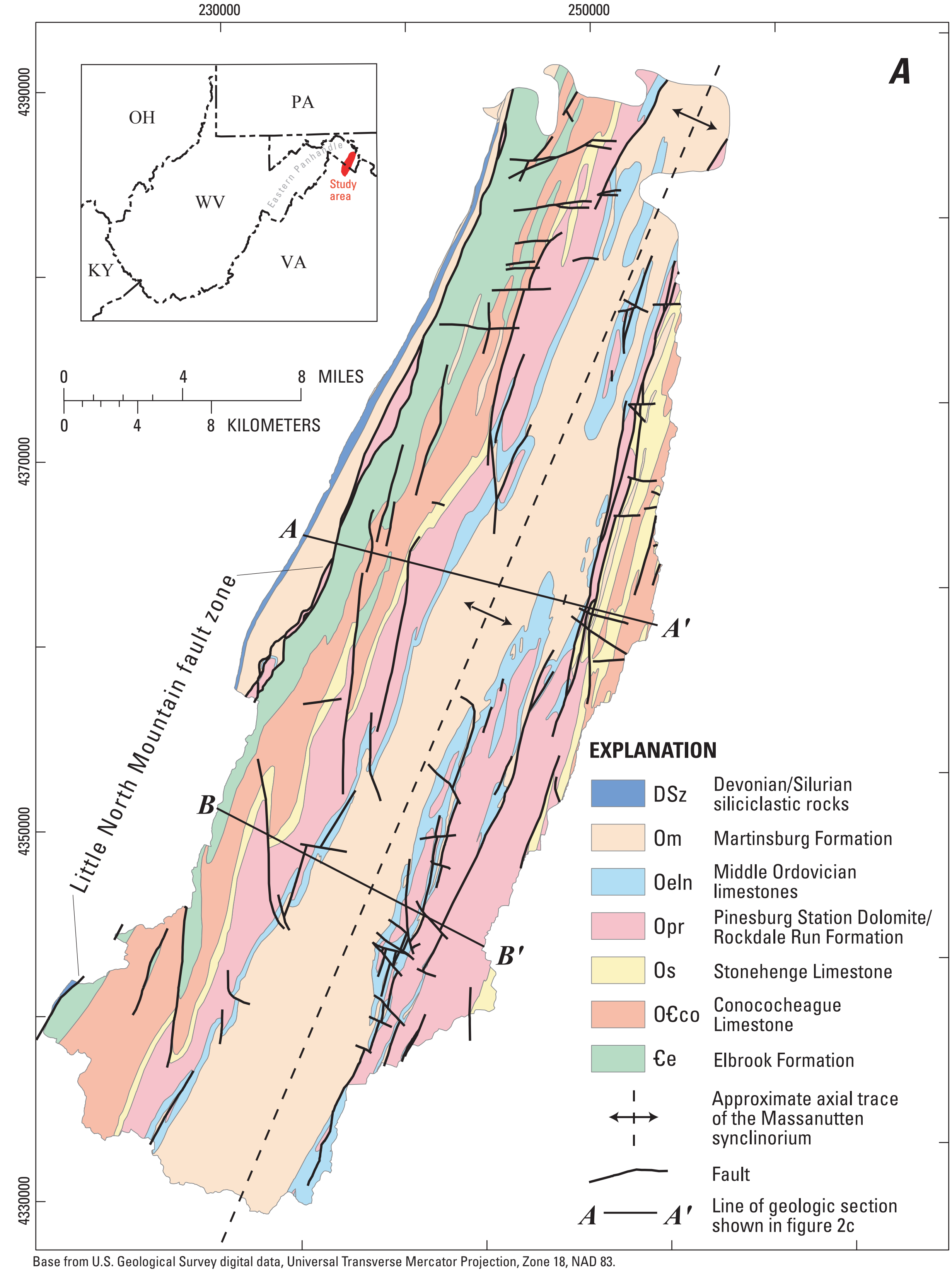


Figure 2. (*A*) Geologic map of, (*B*) lithologic column for, and (*C*) geologic sections *A-A′* and *B-B′* through the Opequon Creek watershed area, Virginia and West Virginia.

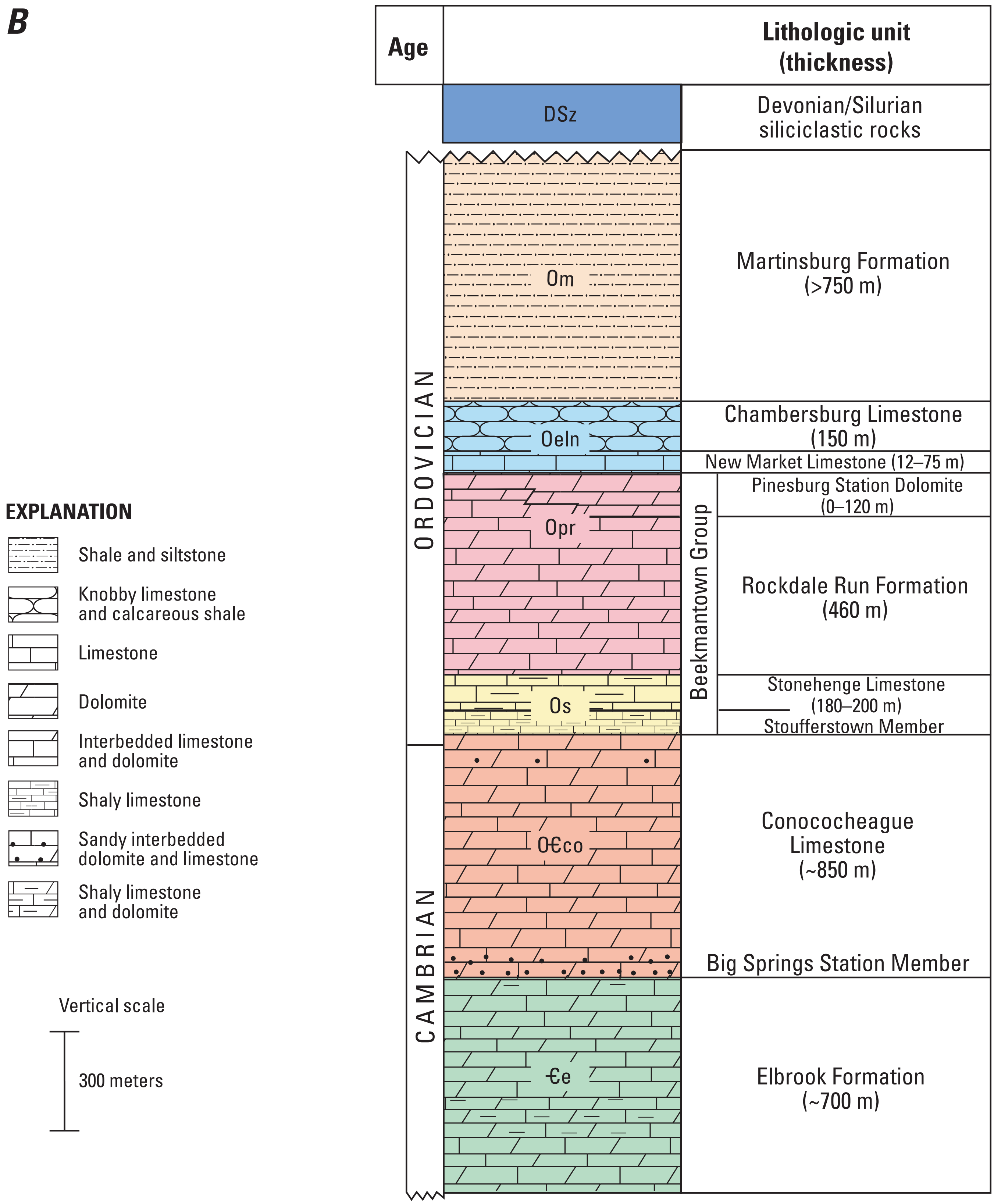


Figure 2. (*A*) Geologic map of, (*B*) lithologic column for, and (*C*) geologic sections *A-A′* and *B-B′* through the Opequon Creek watershed area, Virginia and West Virginia.—Continued

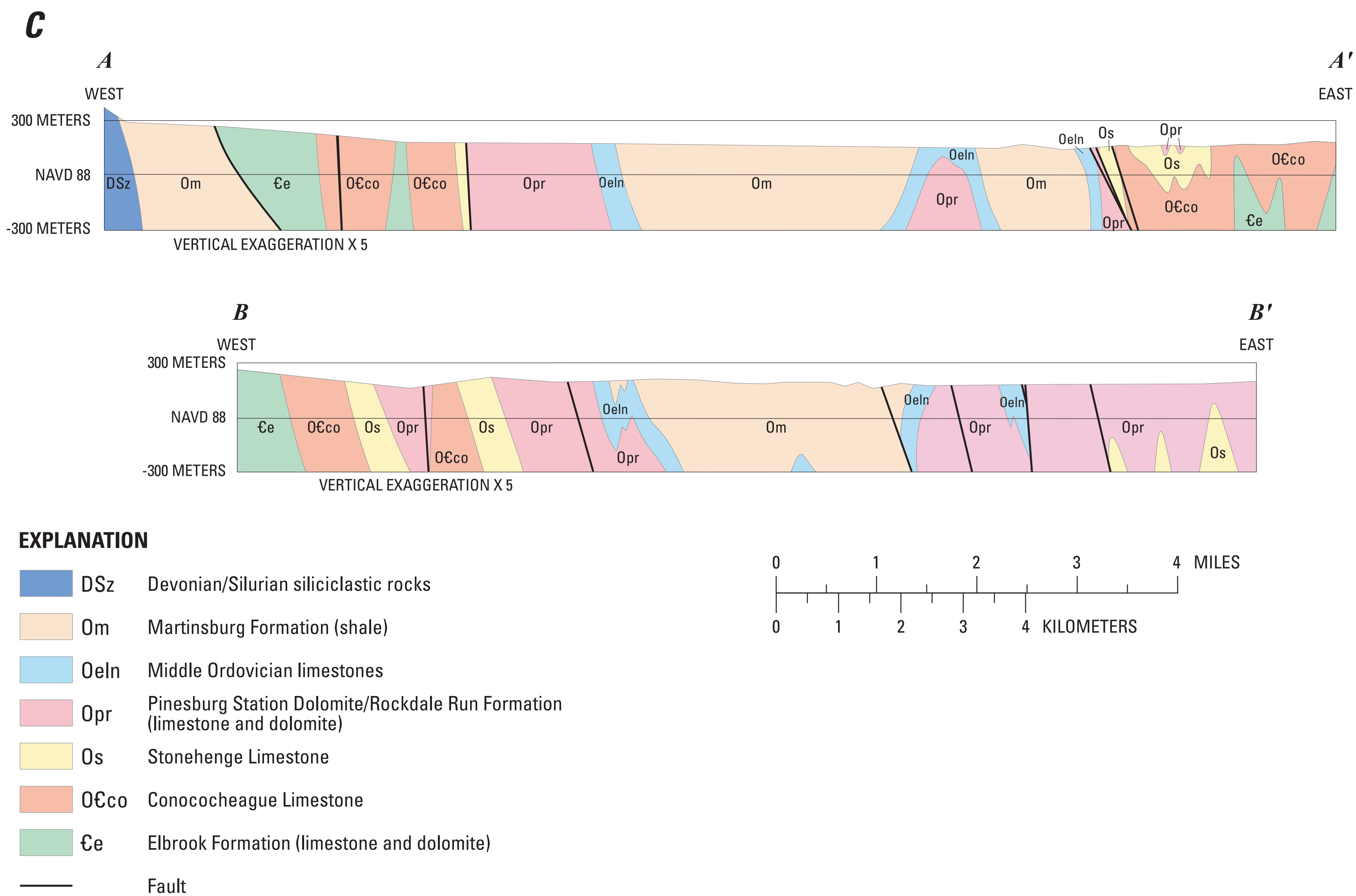


Figure 2. (*A*) Geologic map of, (*B*) lithologic column for, and (*C*) geologic sections *A-A′* and *B-B′* through the Opequon Creek watershed area, Virginia and West Virginia.—Continued

unit in the study area and is the most likely to develop karst features. The other Middle Ordovician limestones, although less soluble than the New Market, constitute a highly soluble outcrop belt between the Pinesburg Station Dolomite below and the shale of the Martinsburg Formation above. The Middle Ordovician limestones are about 200 m thick.

The Martinsburg Formation, the youngest stratigraphic unit in the study area, chiefly occupies a large area along the axis of the Massanutten synclinorium (fig. 2a, 2c). A large outcrop belt also exists along the western margin of the Opequon Creek watershed area in the Little North Mountain fault zone. Several thin belts along narrow thrust-fault-truncated synclines also occur in the east-central part of the watershed area (fig. 2a, 2c). The Martinsburg Formation contains medium-gray to dark-gray and light-olive-gray shale and siltsone, commonly weathering to a light yellowish or orange-brown color. The lower several hundred meters may be composed of calcareous shales of the Stickley Run Member (Orndorff and others, 1999). The Martinsburg Formation also contains beds of medium-gray to olive-gray graywacke. Graywacke is more abundant and more thickly bedded higher in the section, where it forms conspicuous ribs in creek beds and may comprise as much as 30 percent of some intervals that are several hundred meters thick. This occurs more commonly in the southern part of the watershed, where the Massanutten synclinorium is plunging to the south. Axial planar cleavage is well developed along folds and in places obscures the bedding. As a primarily siliciclastic unit, the Martinsburg Formation is the only bedrock unit in the study area that does not have karst features. The total thickness of the Martinsburg Formation in the study area exceeds 760 m. The youngest rocks in the study area are a thin belt of undifferentiated clastic rocks of Silurian and Devonian age that are exposed along Little North Mountain at the western edge of the Opequon Creek watershed area. These rocks are chiefly quartz arenites, orthoquartzites, and shales.

Structural Geology

The geologic structure of the Opequon Creek watershed area is complex, with numerous thrust faults oriented parallel or subparallel to the regional bedrock strike and fault traces trending approximately N. 20° E. Cross-strike longitudinal and oblique faults also occur, with traces at attitudes of approximately N. 80° W. and N. 65° E., respectively. The rocks are tectonically deformed, and the numerous upright and overturned folds in the area affect ground-water flow.

Structurally, the Opequon Creek watershed area lies almost entirely within the Massanutten synclinorium, a mega-scale downfold with many small folds and faults superimposed upon it, which locally forms the Great Valley. Within the watershed, the synclinorium plunges gently toward the south and is slightly asymmetrical, with the eastern limb steeper than the western. Most of the main stem of Opequon Creek is located just east of the fold axis, flowing north-northeast near or on the contact between the clastic rocks of the Martinsburg Formation and the carbonates of the Middle Ordovician limestones (see geologic map and cross sections, figures 2a and 2c). East of the synclinorium axis, beds tend to dip steeply and are overturned in some areas. The overturned folds verge to the northwest with limbs dipping steeply toward the southeast (fig. 2c). Folds on the western limb of the synclinorium tend to plunge toward the southwest; those on the eastern limb plunge toward the northeast.

Thrust faults, which moved rocks from the southeast up and over rocks to the northwest, form the dominant fracture pattern in the Opequon Creek watershed area. They are more common in the carbonate rocks on the eastern side of the synclinorium (fig. 2a, 2c); on the western side, most thrust movement has occurred along the Little North Mountain fault zone.

A series of several south-to-north-trending faults are important features found on the west side of the synclinorium. These are reverse faults associated with large, failed folds and may focus ground-water flow out of the large southward-plunging synclines to the south and across the structural grain toward the axis of the synclinorium.

Although many cross-strike faults have been mapped both on the eastern and western sides of the watershed, they are more common on the eastern side (fig. 2a). These faults are commonly only a few miles in extent, but are probably important for guiding ground-water flow across the strike of bedding and possibly across thrust faults. They can be either normal or reverse faults and most are near vertical in attitude. (See Orndorff (1992) for a discussion of cross-strike faults in the Great Valley.) There are probably a number of faults of each style in the belt of Martinsburg Formation exposed along the axis of the synclinorium, but they are unmapped because they are not exposed and lack good marker horizons within the Martinsburg Formation.

The pattern of distinct cross-strike faults, clearly seen in the topographic expression of the weathered land surface over the Martinsburg Formation, suggests that the core of the Massanutten synclinorium in this part of the Great Valley (north of Massanutten Mountain and south of the Potomac River) achieves its apparent southward plunge through many normal faults, which step down to the south. This is also manifested by the relative widening of the map pattern of the synclinorium to the south.

At a local scale, bedding planes and joints are the dominant fracture type in the Opequon Creek watershed area. The predominant trends for bedding attitude are strikes to the north-northeast and dips to the southeast or northwest. On the eastern side of the Massanutten synclinorium the dip is mostly steep and to the northwest, although some areas are overturned and dip very steeply to the southeast. On the western side of the synclinorium the dip tends to be to the southeast and, on average, less steep than on the eastern side.

Joints—fractures in the rock produced by tectonic stress—are found in all of the bedrock units in the Opequon Creek watershed area. The most common joint-plane attitudes are (1) oriented approximately normal to the strike of bedrock (dip joints), (2) oriented approximately parallel to the strike of bedrock (longitudinal joints), and (3) oriented in the directions of shear (at acute angles bisected by the plane of the dip joints). Most of the joints are non-throughgoing—that is, they do not penetrate continuously across lithologic boundaries. Locally, some joints are throughgoing, and may be important avenues for ground-water flow.

Hydrology

Ground water in the study area occurs predominantly in diffuse fractures. Water that flows through the intricate network of lower permeability diffuse fractures is collected over a broad area in higher permeability conduit drains that primarily coincide with the major thrust, normal, and cross-strike faults of the region. Earlier investigators who developed conceptual models of ground-water flow in the area (Kozar and others, 1991; Shultz and others, 1995) recognized the importance of solutionally enlarged bedding planes in governing ground-water flow. The importance of cross-strike faults or other complex geologic structures, such as overturned or tightly folded structures, in controlling ground-water flow was not fully realized until it was viewed in the context of recent work (McCoy and others, 2005a, 2005b), and of the data collected for this investigation. The conceptual model of ground-water flow in the region was more fully documented in recent investigations completed in the Hopewell Run watershed area (Kozar and others, 2007, 2008).

Ground-Water Levels

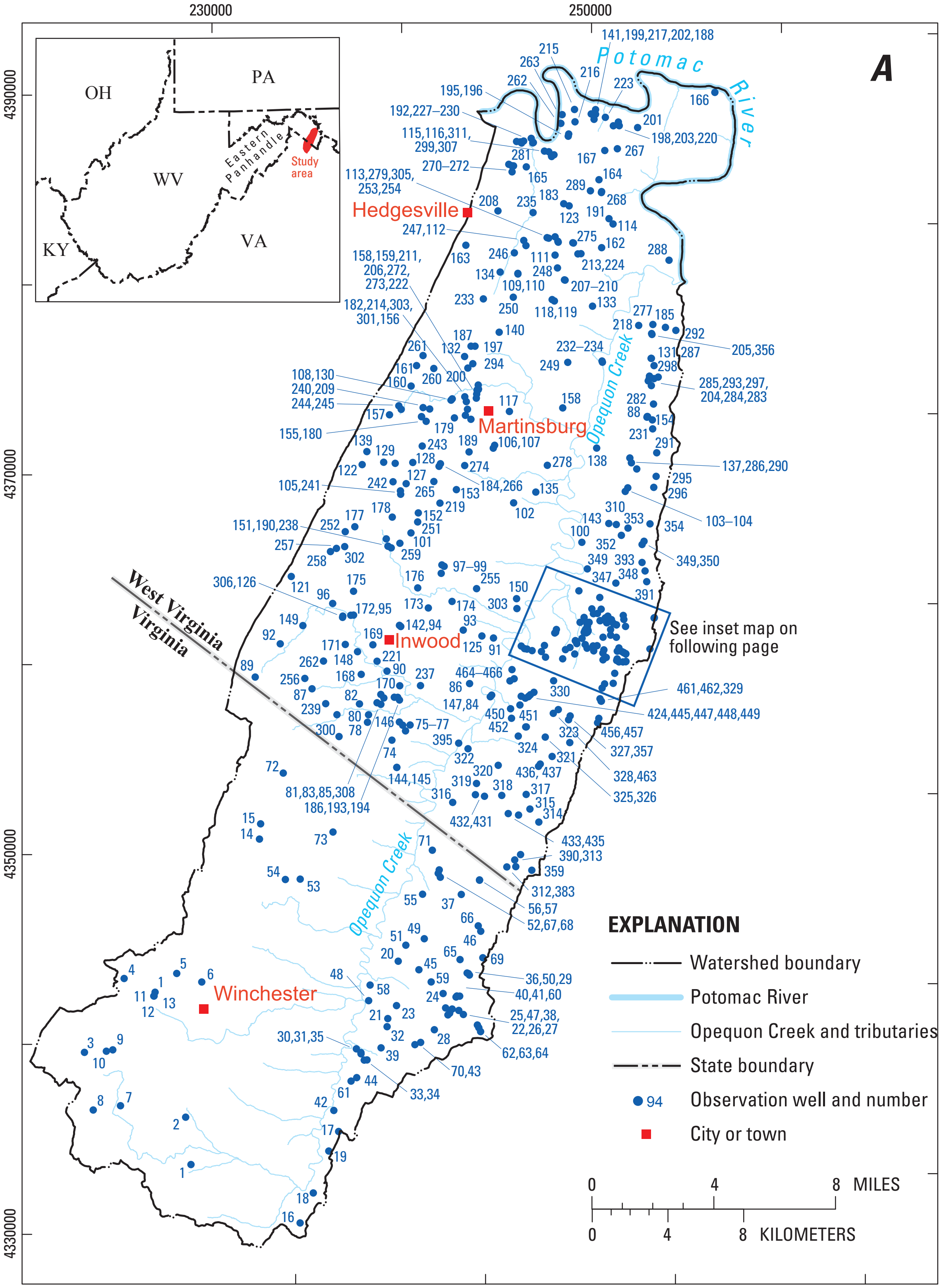
A search of ground-water levels available for the study area was made by querying the GWSI database. A total of 513 water levels were available for development and calibration of the ground-water flow model of the Opequon Creek watershed area. Unfortunately, the data were collected over a 40-year period that includes both high and low ground-water-level conditions. Also, some of the data were considered to be questionable as a result of poor location information, pumping prior to measurement of the water level, poor well yield, or other factors. After approximately 10 percent of obvious outlier data were eliminated, 470 sites (app. 1) remained for final calibration and development of the ground-water flow model. The data provided good areal coverage of the Opequon Creek watershed area (fig. 3a), and overall provided a large data set of ground-water levels to which the ground-water flow model could be calibrated. Because the data represented measurements over a broad range of hydrologic conditions, the ground-water flow model was calibrated to the average ground-water level represented by the data throughout the range of altitude for the watershed. Production wells within the Opequon Creek watershed area are shown in figure 3b.

Ground-Water Recharge

An accurate assessment of ground-water recharge in the study area is needed to develop a realistic ground-water flow model. Streamflow data for the Opequon Creek watershed area were obtained from eight USGS streamflow-gaging stations (fig. 3b). Hydrographs of the streamflow data from six of the gaging stations were analyzed using the Rorabaugh method (Rutledge, 1998) to estimate effective ground-water recharge rates for the watershed. Effective recharge was estimated using the USGS hydrograph analysis software RORA and RECESS (Rutledge, 1998). Recharge ranged from 123 to 420 mm/yr (table 1). The variability in recharge is primarily a function of the composition of bedrock within the respective watersheds for which the estimates are made. Recharge in the model was assigned on the basis of analyses of streamflow records but was modified on the basis of model-calibration results to account for differences in lithology and density of cross-strike faults.

Recharge rates tend to be lower in areas dominated by shale than in areas with a higher proportion of limestone, especially the more permeable limestones such as those of the Stonehenge Limestone, the Rockdale Run Formation, and the Middle Ordovician limestone formations (fig. 2). As a result, three different recharge rates were used to simulate ground-water flow in the model representing this variability in recharge for the region. The highest recharge rate (390 mm/yr) was applied to the northern part of the study area, north of Martinsburg (fig. 4). This area has experienced intensive downcutting of bedrock by the Potomac River and is characterized by a higher density of cross-strike faults (fig. 2) than other areas within the watershed. The higher density of cross-strike faults along with the downcutting results in greater depths to ground water and greater ground-water recharge than in other parts of the watershed. A recharge value of 280 mm/yr was assigned to carbonate bedrock formations within the model; a value of 150 mm/yr was assigned to the area underlain by the Martinsburg Formation.

Precipitation records (National Oceanic and Atmospheric Administration, 2002a, 2002b) from five National Oceanic and Atmospheric Administration (NOAA) weather stations and from the airport at Winchester, Virginia, indicate long-term average annual precipitation of 925 to 1,026 mm/yr (table 2). The long-term average precipitation for the region was used to develop the water budget for the Opequon Creek watershed area. Precipitation is the major input of water into the study area. The only interbasin transfer of water into the watershed occurs as a result of the wastewater-treatment return flow from Winchester, Virginia, which obtains water from an intake on the Shenandoah River. Although the interbasin transfer of water is negligible in relation to the recharge from precipitation, it was factored into the water budget and accounted for by the streamflow data from USGS streamflow-gaging stations.



Base from U.S. Geological Survey digital data, Universal Transverse Mercator Projection, Zone 18, NAD 83.

Figure 3. Location of (*A*) water-level observation wells used for development and calibration of the ground-water flow model of, and (*B*) large-capacity production wells, U.S. Geological Survey streamflow-gaging stations, and wastewater-treatment-plant outfalls in, the Opequon Creek watershed area, Virginia and West Virginia.

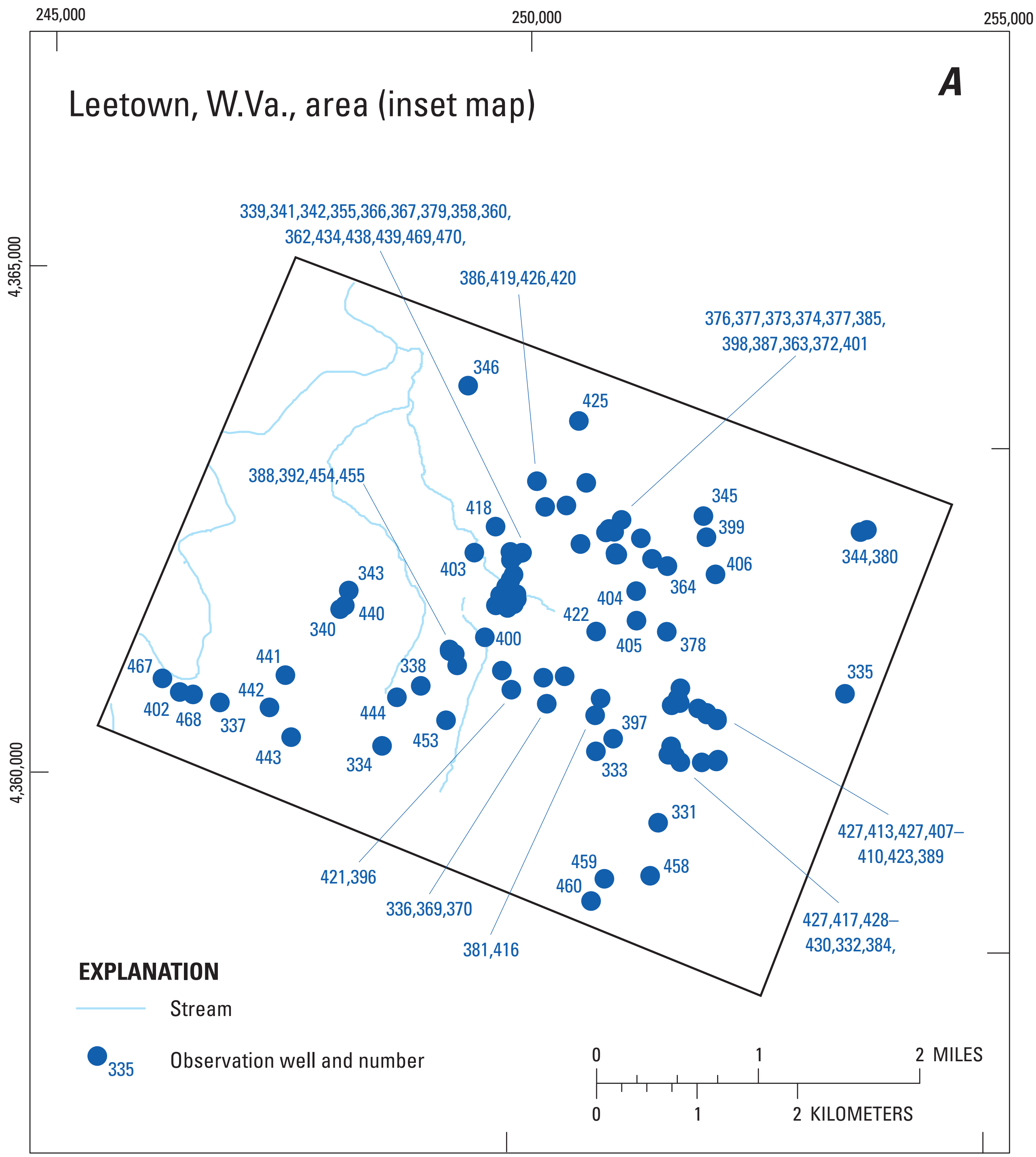


Figure 3. Location of (*A*) water-level observation wells used for development and calibration of the ground-water flow model of, and (*B*) large-capacity production wells, U.S. Geological Survey streamflow-gaging stations, and wastewater-treatment-plant outfalls, in the Opequon Creek watershed area, Virginia and West Virginia.—Continued

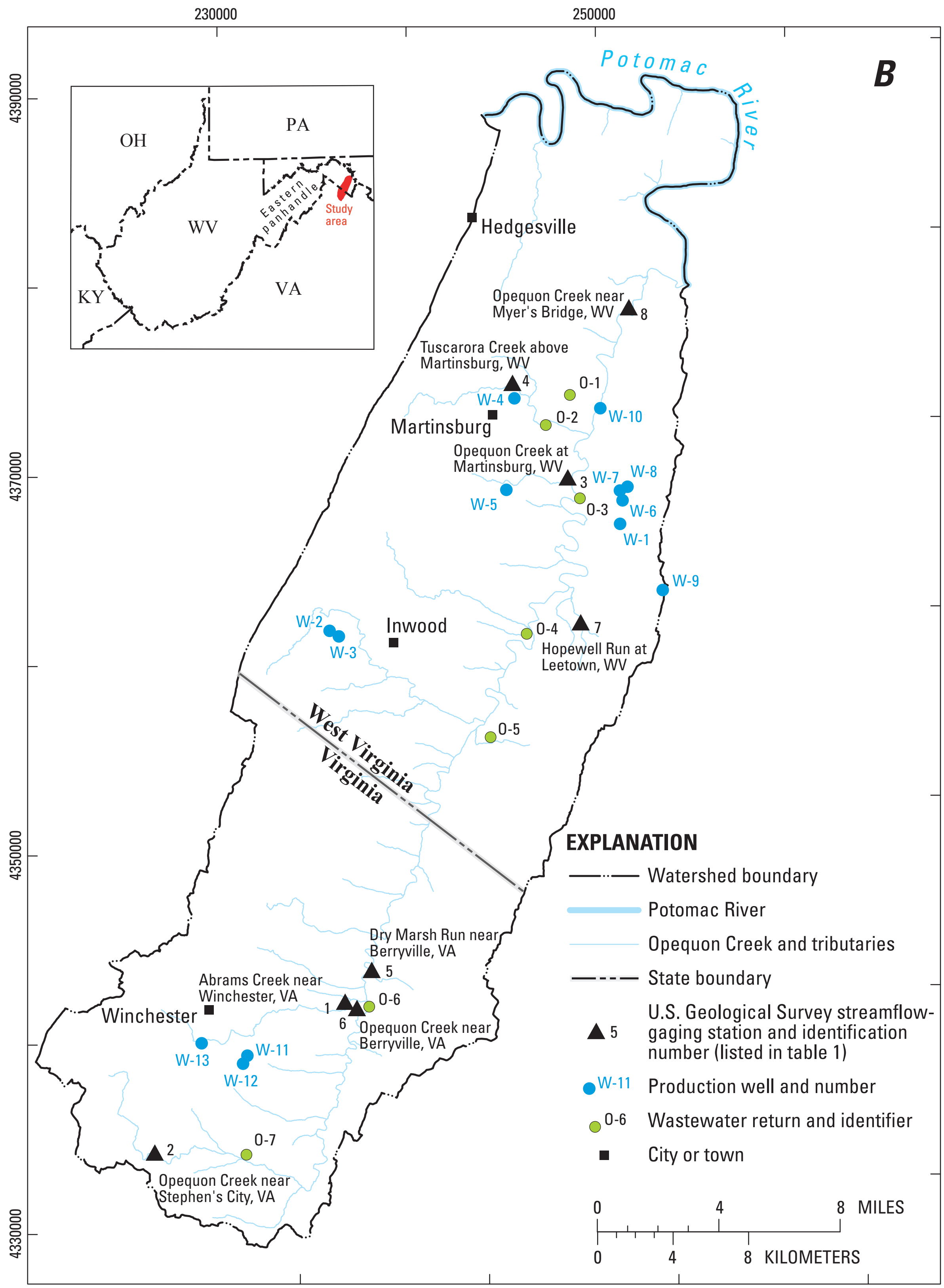


Figure 3. Location of (*A*) water-level observation wells used for development and calibration of the ground-water flow model of, and (*B*) large-capacity production wells, U.S. Geological Survey streamflow-gaging stations, and wastewater-treatment-plant outfalls, in the Opequon Creek watershed area, Virginia and West Virginia.—Continued

Table 1. (*A*) Effective-recharge estimates and (*B*) mean base flow for eight streamflow-gaging stations in the Opequon Creek watershed area, Virginia and West Virginia.

[m, meters; UTM, Universal Transverse Mercator projection; km², square kilometers; m, meters; mm/yr, millimeters per year; s, second; m³/s, cubic meter per second; n/d, not determined]

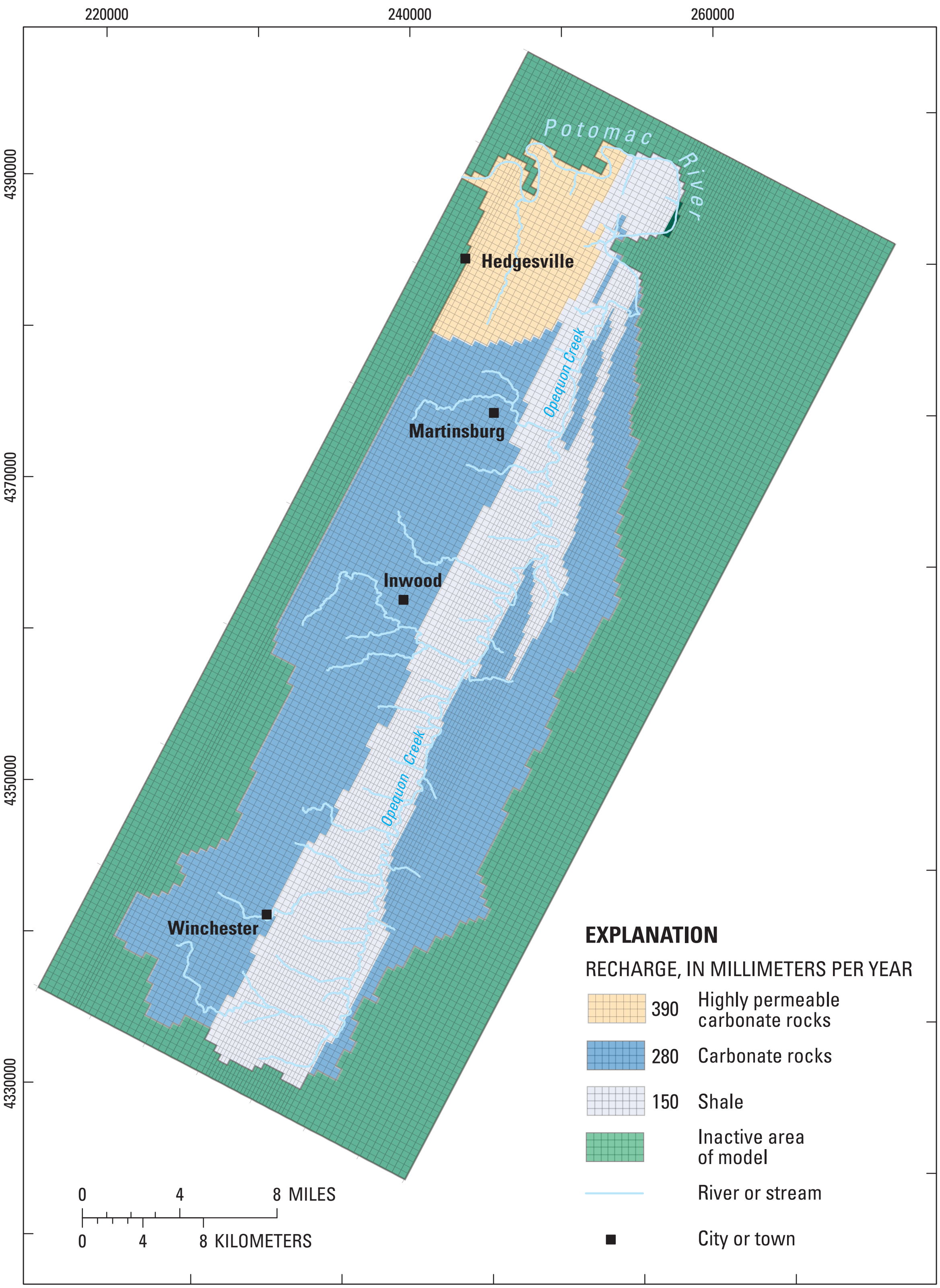
A

U.S. Geological Survey station name and map number in figure 3b	U.S. Geological Survey station number	UTM Zone 18 Easting (NAD 83)	UTM Zone 18 Easting (NAD 83)	Surface altitude (m)	Drainage area (km²)	Measured base flow (m³/s)	Measurement date	Period of record	Effective recharge (mm/yr)	Mean daily streamflow (m³/s)
Abrams Creek near Winchester, VA (1)	01616000	223,460	4,341,053	160.5	44.0	n/d	7/26/2005	1949–60, 1979–94	372	0.609
Opequon Creek near Stephens City, VA (2)	01614830	222,870	4,333,764	214.9	39.4	0.142	7/26/2005	2001–06	n/d	0.243
Opequon Creek near Martinsburg, WV (3)	01616500	247,044	4,367,919	108.2	707.1	3.172	7/26/2005	1947–06	241	6.976
Tuscarora Creek above Martinsburg, WV (4)	01617000	244,389	4,373,100	137.0	29.3	0.091	7/26/2006	1948–77, 2006	290	0.310
Dry Marsh Run near Berryville, VA (5)	01616100	234,977	4,342,635	164.6	28.5	0.127	7/26/2005	2002–06	393	0.372
Opequon Creek near Berryville, VA (6)	01615000	234,072	4,340,681	153.4	150.7	0.396	7/26/2005	1943–2006	123	1.338
Hopewell Run at Leetown, WV (7)	01616425	247,225	4,360,238	137.2	23.2	0.119	7/26/2005	2003–06	420	0.316
Opequon Creek near Myers Bridge, WV (8)[1]	01617020	250,868	4,376,674	103.6	n/d	3.936	7/26/2005	2004–05	n/d	8.847

B

U.S. Geological Survey station name and map number in figure 3b	U.S. Geological Survey station number	Monthly mean daily base flow for U.S. Geological Survey streamflow-gaging stations for the period of record (m³/s)											
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Abrams Creek near Winchester, VA (1)	01616000	0.538	0.708	0.878	0.850	0.736	0.595	0.481	0.481	0.425	0.510	0.510	0.595
Opequon Creek near Stephens City, VA (2)	01614830	0.244	0.249	0.340	0.312	0.252	0.249	0.204	0.133	0.218	0.167	0.235	0.312
Opequon Creek near Martinsburg, WV (3)	01616500	8.043	9.742	12.744	10.677	7.845	6.287	4.050	3.852	4.021	4.276	5.098	7.080
Tuscarora Creek above Martinsburg, WV (4)	01617000	0.340	0.425	0.538	0.538	0.368	0.312	0.218	0.167	0.164	0.178	0.193	0.283
Dry Marsh Run near Berryville, VA (5)	01616100	0.425	0.425	0.623	0.538	0.396	0.453	0.272	0.164	0.195	0.221	0.269	0.481
Opequon Creek near Berryville, VA (6)	01615000	1.699	2.011	2.577	1.841	1.359	1.104	0.623	0.623	0.821	0.821	1.048	1.529
Hopewell Run at Leetown, WV (7)	01616425	0.280	0.340	0.312	0.566	0.425	0.425	0.261	0.193	0.224	0.210	0.221	0.340
Opequon Creek near Myers Bridge, WV (8)[1]	01617020	10.535	7.986	19.201	15.180	7.590	4.758	5.069	3.370	2.764	4.305	10.139	15.264

[1] The discharge record for the Opequon Creek at Myers Bridge was estimated based on approximately 9 months of continuous stream-discharge data collected over an 11-month period. Data for missing periods were estimated based on a linear regression with data available for the nearby Opequon Creek at Martinsburg streamflow-gaging station. The R^2 correlation coefficient between streamflow at the Myers Bridge and Martinsburg stations was 99.1.



Base from U.S. Geological Survey digital data, Universal Transverse Mercator Projection, Zone 18, NAD 83.

Figure 4. Model grid and recharge for the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.

Table 2. (*A*) Monthly and annual mean precipitation data for five weather stations in the Opequon Creek watershed area for the period 1971–2000 and (*B*) historical long-term mean precipitation for Martinsburg, West Virginia, and Winchester, Virginia.

[Monthly values in millimeters per month; annual values in millimeters per year]

A Weather station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
Martinsburg Regional Airport, WV	69.3	61.0	89.2	79.8	106.4	88.6	94.7	86.4	89.4	86.4	79.8	69.6	1,001
Kearneysville, WV	74.9	64.5	84.1	83.8	104.6	97.8	99.3	85.1	87.1	90.4	80.0	74.4	1,026
Berryville, VA	70.9	59.2	80.0	77.2	94.0	89.9	104.9	84.8	84.1	86.4	77.7	63.0	972
Winchester (3ESE), VA	69.6	54.6	87.6	73.2	92.7	92.7	77.5	71.6	85.1	75.2	81.0	63.8	925
Winchester (7 SE), VA	67.6	61.0	84.6	76.5	99.8	104.1	93.0	91.4	91.2	80.3	77.7	66.0	993
Mean precipitation	**70.7**	**59.8**	**84.1**	**77.7**	**97.8**	**96.1**	**93.7**	**83.2**	**86.9**	**83.1**	**79.1**	**66.8**	**979**
Median precipitation	**70.2**	**60.1**	**84.3**	**76.8**	**96.9**	**95.3**	**96.1**	**85.0**	**86.1**	**83.3**	**78.9**	**64.9**	**983**

B Weather station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
Martinsburg Regional Airport, WV 1926–2007	63.0	59.4	84.1	82.0	84.2	89.2	88.4	92.7	82.3	82.6	72.6	69.1	960
Winchester (3ESE), VA 1912–2007	61.5	56.9	80.8	79.2	94.5	99.1	96.5	93.7	82.0	78.7	70.6	63.8	957
Mean precipitation	**62.3**	**58.2**	**82.5**	**80.6**	**89.4**	**94.2**	**92.5**	**93.2**	**82.2**	**80.7**	**71.6**	**66.5**	**958**

Streamflow data for the Opequon Creek near Martinsburg streamflow-gaging station for the period of record were analyzed as part of developing the ground-water flow model of the Hopewell Run watershed area (Kozar and others, 2007, 2008). The long-term average recharge for the part of the Opequon Creek watershed area draining to Opequon Creek near Martinsburg was estimated to be 250 mm/yr (Kozar and Mathes, 2001). Meteorological records (Cornell University, 2008) indicate the most recent drought in the area occurred from November 1998 to January 2000. This was the fourth most severe drought on record, dating back to 1895, and was the longest, lasting for approximately 16 months. Estimated ground-water recharge for the Opequon Creek near Martinsburg drainage area for the 16-month drought was 145 mm/yr (Kozar and others, 2007, 2008), or approximately 60 percent of the average recharge rate for the watershed. Recharge for the 16-month drought was simulated by decreasing the effective recharge rates for each of the three zones used to develop the steady-state model by approximately 40 percent.

Hydraulic Properties

The hydraulic properties of aquifers that are used to develop a ground-water flow model include aquifer transmissivity, hydraulic conductivity, saturated thickness, and specific yield (storativity). Transmissivity in square meters per day (m^2/d) is a measure of an aquifer's ability to transmit water and generally is defined as the rate at which water is transmitted through a unit width of aquifer under a unit hydraulic gradient (Gary and others, 1973). Saturated thickness in meters (m) is the thickness of the aquifer that is saturated with ground water. Hydraulic conductivity in meters per day (m/d) is equal to transmissivity divided by the saturated thickness of the aquifer. Storativity is the volume of water released from storage per unit decline in head. Specific yield is a measure of the capacity of an unconfined aquifer to store water and is defined as the ratio of the volume of water a given mass of saturated aquifer will yield by gravity to the volume of that mass (Gary and others, 1973). For an unconfined aquifer, storativity is approximately equal to specific yield. These hydraulic properties were determined by conducting many single- and multi-well aquifer tests in the bedrock units of the Opequon Creek watershed area. The same units crop out at the surface over a broad area in both Jefferson and Berkeley Counties. Aquifer-test data were obtained from two previous investigations (McCoy and others, 2005a, 2005b), that include data for the Leetown area and a recent hydrogeologic investigation completed in Morgan County, West Virginia (Boughton and McCoy, 2006), and were used to determine the typical hydraulic properties of the geologic formations in the model area. Statistical analyses of these data indicate that two of the eight geologic formations that are exposed at the surface in the study area have characteristically low (<0.8 m/d) hydraulic conductivities (table 3). These formations are the Martinsburg Formation and the Conococheague Limestone. Hydraulic conductivities are 0.6 m/d for all three layers of the Martinsburg Formation and range from 0.2 to 0.8 m/d for the Conococheague Limestone. The low hydraulic conductivity of these units (table 3) means that they control ground-water flow in the study area by acting as barriers to flow. Solution enlargement of fractures along major fault zones (simulated hydraulic conductivity ranging from 30 to 120 m/d) results in enhanced permeability along these features, allowing them to act as drains for water to flow easily through or across the less permeable units. The cross-strike faults and some of the oblique faults, both of which cross bedrock strike at high angles, are especially effective as conduit drains for ground water.

Ground-Water Withdrawals

The major ground-water withdrawals (fig. 3b) in the watershed are primarily from large-capacity production wells for public water supplies or for commercial or industrial activities related to quarry and aggregate operations. Large withdrawals are not common; the few large water withdrawals are tabulated in table 4. Individual domestic withdrawals were not simulated in this model and it was assumed that most of the water withdrawn from residential wells is returned to the aquifer through septic-system return flows. Several large springs in the study area are also used as a source of water for public supply.

Structural and Lithologic Controls on Ground-Water Flow

The conceptual model of ground-water flow described above is derived primarily from the work conducted as part of the hydrogeologic assessment of the Hopewell Run watershed area near Leetown, West Virginia (Kozar and others, 2007, 2008). Although the geology of the Opequon Creek watershed area is nearly identical to that of the Hopewell Run watershed area, the structural and lithologic controls on ground-water flow in the Opequon Creek watershed area have not been fully documented. To ensure that the conceptual model developed for the Hopewell Run watershed area is applicable to the Opequon Creek watershed area, an assessment was conducted in the Opequon Creek watershed area of the locations of known springs in relation to known faults and the contacts between carbonate bedrock and the low-permeability shale bedrock of the Martinsburg Formation.

This assessment was conducted as part of a GIS analysis by plotting on a map the locations of all known springs along with the contact of the carbonate rocks with the Martinsburg Formation and the location of all known mapped faults in the region (fig. 5). A 300-m buffer zone was placed around all known faults on the GIS map, and springs were divided into three groups based on measured discharge: less than 545 m^3/d (less than 100 gal/min), 545 to 5,449 m^3/d (100 to 999.9 gal/min), and greater than 5,450 m^3/d (greater

Table 3. Measured values of transmissivity for geologic formations, faults, and fracture zones, and estimated values of hydraulic conductivity assigned to specific layers in the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.

[m/d, meters per day; m^2/d, square meters per day; na, not applicable]

Geologic formation or zone	Geologic formation identifier (fig. 2)	Measured median transmissivity[1] (m^2/d)	Estimated median hydraulic conductivity[2] (m/d)	Model-calibrated upper layer hydraulic conductivity[3] (m/d)	Model-calibrated middle layer hydraulic conductivity[3] (m/d)	Model-calibrated lower layer hydraulic conductivity[3] (m/d)
Faults and fracture zones	na	7,000	70.0	120	60.0	30
Silurian/Devonian siliciclastic rocks	DSz	7.0	0.15	0.1	0.1	0.1
Martinsburg Formation	Om	18.3	0.4	0.6	0.6	0.6
Middle Ordovician limestones	Oeln	238	2.5	3.0	1.5	0.75
Pinesburg Station Dolomite/ Rockdale Run Formations	Opr	305	3.2	6.0	3.0	1.5
Stonehenge Limestone	Os	152	1.6	3.0	1.5	0.75
Conococheague Formation	O-Ꞓco	24.4	0.25	0.8	0.4	0.2
Elbrook Formation	Ꞓe	30.5	0.3	3.0	1.5	0.75

[1] Transmissivity values summarized in this table were acquired from from single- and multi-well aquifer tests conducted as part of previous fracture-trace investigations in Jefferson and Berkeley Counties, West Virginia (McCoy and others 2005a, 2005b), a hydrogeologic assessment of Morgan County, West Virginia (Boughton and McCoy, 2006), and a statewide assessment of aquifer characteristics developed for West Virginia (Kozar and Mathes, 2001).

[2] Hydraulic-conductivity estimates were based on measured transmissivity, ratios of bedrock resistivity at specific depths, and average depth of wells.

[3] Hydraulic-conductivity values assigned to specific geologic formations and layers in the ground-water flow simulation

Table 4. (*A*) Current withdrawals from large-capacity production wells and (*B*) return flows from wastewater-treatment plants in the Opequon Creek watershed area, Virginia and West Virginia.

[Data in this table are public records available from the West Virginia Department of Environmental Protection, West Virginia Public Service Commission, and the Virginia Department of Environmental Quality. Withdrawals and return flows are based on 2002-03 averages; m, meters; m^3/d, cubic meters per day; UTM, Universal Transverse Mercator Projection]

A Site identification number in figure 3b	UTM Zone 18 Northing	UTM Zone 18 Easting	Well depth (m)	Current production (m^3/d)
W-1	249,476	4,365,335	122	0.0
W-2	233,821	4,360,756	111	11.4
W-3	234,245	4,360,525	46	11.4
W-4	244,391	4,372,420	146	3,785
W-5	243,327	4,367,733	153	4,731
W-6	249,810	4,366,842	54	217
W-7	249,692	4,366,907	91	217
W-8	250,018	4,367,360	72	217
W-9	251,701	4,361,565	117	454
W-10	248,718	4,371,569	125	394
W-11	227,984	4,338,339	125	96
W-12	227,882	4,338,189	125	1.9
W-13	225,605	4,339,071	125	1,018

B Site identification number in figure 3b	UTM Zone 18 Northing	UTM Zone 18 Easting	Return flow (m^3/d)
O-1	247,414	4,372,681	118.8
O-2	245,829	4,371,035	417.1
O-3	247,544	4,367,120	89.7
O-4	244,250	4,360,159	69.6
O-5	241,890	4,354,742	61.7
O-6	234,392	4,340,886	1012.9
O-7	227,309	4,333,443	207.4

than 1,000 gal/min). The locations of the springs then were assessed in relation to discharge and proximity to known faults or the contact between carbonate bedrock and the shale bedrock of the Martinsburg Formation (table 5). Faults and the Martinsburg Formation were found to be strong controls on ground-water flow in the Hopewell Run watershed area. The locations of springs were found to correlate with distance to known major faults and the contact with the Martinsburg Formation (table 5). Mean spring discharge and location information for the known springs in the Opequon Creek watershed area are presented in appendix 2. Sixty-one percent of all known springs and 80 percent of large springs with flow in excess of 1,000 gal/min were found within 300 m of either a known fault or the contact with the Martinsburg Formation.

Simulation of Ground-Water Flow

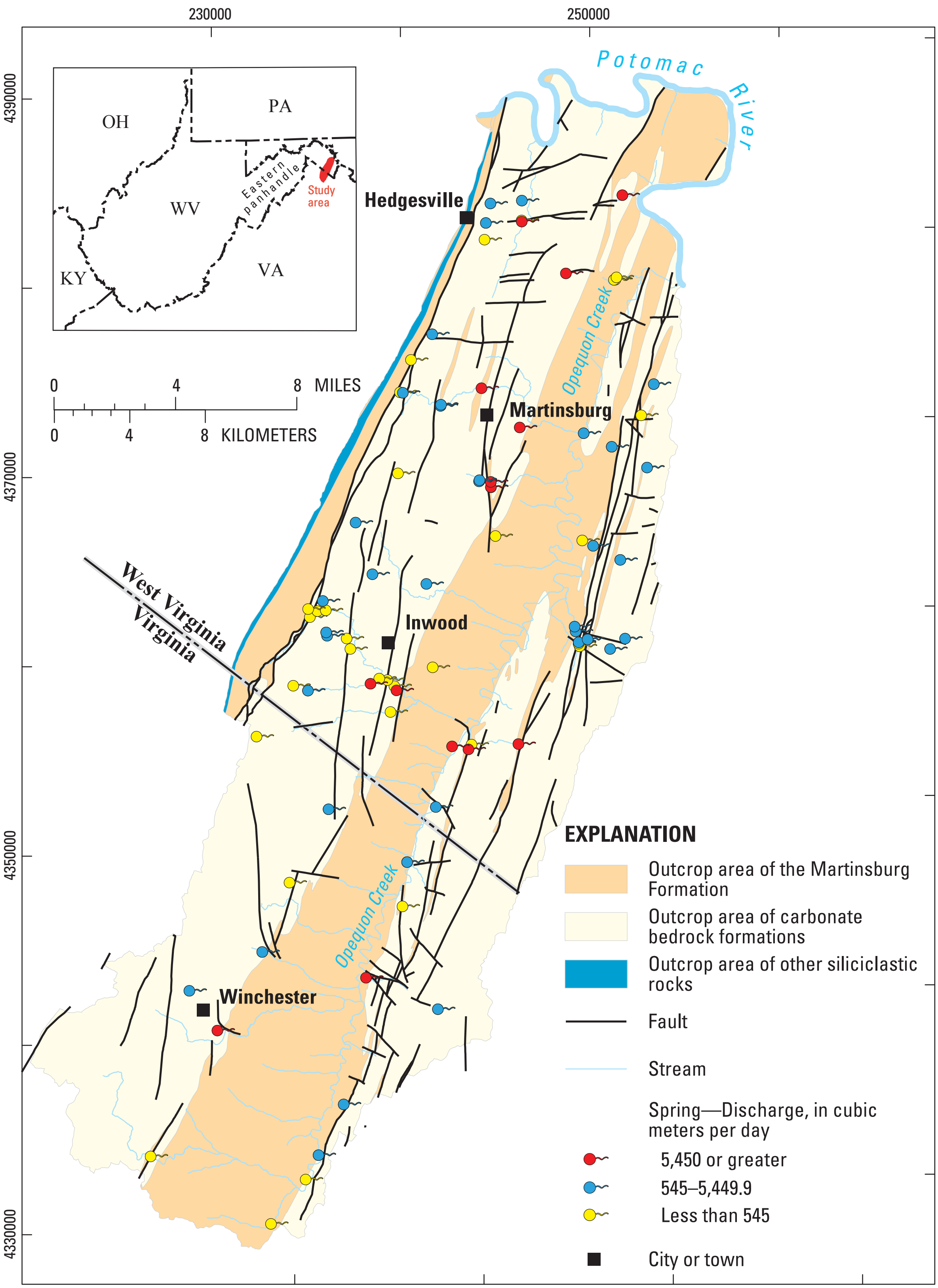
A calibrated steady-state ground-water flow model was developed and analyzed to (1) develop a water budget for the study area and assess the effects of ground-water withdrawals on long-term water availability, (2) evaluate hydraulic heads simulated by the model to better understand ground-water flow in the watershed and to assess potential structural controls on ground-water flow, (3) assess effects of drought on water availability by reducing the recharge to the model and comparing simulated water levels for average hydrologic periods to those simulated for drought periods, and (4) assess ground-water yields for subwatersheds in the model to evaluate potential availability of ground water during average and drought conditions in various parts of the watershed.

The suitability of using a three-dimensional numerical model such as MODFLOW for simulating ground-water flow in a karst setting is subject to debate. Because an equivalent porous medium is assumed in MODFLOW, its use in simulating ground-water flow may be inappropriate for some karst aquifers. This is especially true for cavernous and large-conduit-dominated karst systems such as that found in the Mammoth Cave area of Kentucky. MODFLOW has been effectively used to simulate ground-water flow in many karst aquifer systems, however. Although the aquifer does exhibit some karst features, sinkhole development is sparse, and caverns, where encountered, are limited in length and width. The majority of the rock mass in the region, especially in upland areas, is drained by an interconnected network of bedrock fractures with little solution development. The conduits that develop, predominantly in low-lying areas, act as drains for the interconnected fracture network in the more areally extensive fractured-rock mass. In the model, the conduits were simulated as a network of interconnected drains by assigning higher hydraulic conductivities to these more permeable features and the fractured-rock portion of the aquifer was effectively simulated by using an equivalent-porous-medium approach. Models that do not account for conduit drains or aquifer anisotropy do not effectively simulate ground-water flow in fracture-dominated karst aquifers drained by solution conduits.

Table 5. Results of geographic information system analyses of the location and discharge of springs with respect to faults, geologic formations, and the contact between carbonate bedrock and the adjacent shale bedrock of the Martinsburg Formation, Opequon Creek watershed area, Virginia and West Virginia.

[m, meters; m^3/d, cubic meters per day; <, less than; ≥, greater than or equal to; %, percent]

Spring location	Number and percentage of springs in relation to spring discharge				
	Springs <545 m^3/d	Springs ≥545 but < 5,450 m^3/d	Springs ≥545 m^3/d	Springs ≥5,450 m^3/d	All springs
Within 300 m of faults	19 of 33 (58%)	16 of 36 (44%)	25 of 51 (49%)	9 of 15 (60%)	45 of 84 (53%)
Near the geologic contact with the Martinsburg Formation	11 of 33 (33%)	12 of 36 (33%)	22 of 51 (43%)	10 of 15 (67%)	33 of 84 (39%)
Within 300 m of faults or near the geologic contact with the Martinsburg Formation	22 of 33 (67%)	18 of 36 (50%)	30 of 51 (59%)	12 of 15 (80%)	52 of 84 (61%)
Within the Martinsburg Formation	5 of 33 (15%)	6 of 36 (17%)	6 of 51 (12%)	0 of 15 (0%)	11 of 84 (13%)
Within Middle Ordovician limestone formations	5 of 33 (15%)	4 of 36 (11%)	12 of 51(24%)	8 of 15 (53%)	17 of 84 (20%)
Within the Pinesburg Station/ Rockdale Run Formations	9 of 33 (27%)	6 of 36 (17%)	11 of 51 (22%)	5 of 15 (33%)	20 of 84 (24%)
Within the Stonehenge Limestone	1 of 33 (3%)	3 of 36 (8%)	3 of 51 (6%)	0 of 15 (0%)	4 of 84 (5%)
Within the Conococheague Formation	0 of 33 (0%)	5 of 36 (14%)	6 of 51 (12%)	1 of 15 (7%)	6 of 84 (7%)
Within the Elbrook Formation	13 of 33 (39%)	12 of 36 (33%)	13 of 51 (25%)	1 of 15 (7%)	26 of 84 (31%)



Base from U.S. Geological Survey digital data, Universal Transverse Mercator Projection, Zone 18, NAD 83.

Figure 5. Distribution of disharge from selected springs and location of known faults and the contact between the Martinsburg Formation and other carbonate bedrock units in the Opequon Creek watershed area, Virginia and West Virginia.

Previous simulations of ground-water flow have been effectively developed in karst hydrogeologic settings similar to that of the Hopewell Run and Opequon Creek watershed areas using an equivalent-porous-medium approach and the MODFLOW software. White (2002) discussed the problems of simulating ground-water flow in karst settings but also indicated that the equivalent-porous-medium approach can work well when the locations of the major conduit drains are known or can be accurately estimated. A few examples of other equivalent-porous-media modeling of karst systems using MODFLOW include models developed for the Madison aquifer in South Dakota (Putnam and Long, 2005), the Edwards aquifer in Texas (Lindgren and others, 2005), the Burlington-Keokuk Limestone aquifer in Missouri (Quinn and others, 2005a), the Malm Formation aquifer in Germany (Quinn and others, 2005b), and the Boone-St. Joe Limestone aquifer in Arkansas (Unger and others, 2003).

The methods described were tested and evaluated in a steady-state ground-water flow model developed for the Hopewell Run watershed area in Jefferson County, West Virginia, and were found to work well for simulating ground-water flow in the complex, fracture-dominated karst aquifer in that area (Kozar and others, 2007, 2008). Geologic mapping, surface-geophysical surveys, and analysis of Light Detection and Ranging (LiDAR) imagery were employed in a hydrogeologic assessment of the Hopewell Run watershed area (Kozar and others, 2007, 2008) to accurately map the location of conduit drains within the aquifer. Hopewell Run is a tributary to the Opequon Creek, the hydrogeologic settings of the two watersheds are similar, and both watersheds are composed of the same bedrock formations. Because it was not practical to collect as intensive a data set of aquifer properties, water levels, and surface-geophysical and fracture-occurrence data for the Opequon Creek watershed area as was collected and analyzed for the Hopewell Run watershed area, the conceptual model of ground-water flow developed for the smaller Hopewell Run watershed area was extrapolated to the larger Opequon Creek watershed area.

Conceptual Model of Ground-Water Flow

A previously developed conceptual model of ground-water flow (Kozar and others, 1991; Shultz and others, 1995) in the Jefferson and Berkeley County areas of West Virginia was modified on the basis of additional borehole- and surface-geophysical data and geologic mapping conducted as part of an intensive investigation of the hydrogeology and ground-water flow in the Hopewell Run watershed area, West Virginia (Kozar and others, 2007, 2008). As Hopewell Run is part of the Opequon Creek watershed area and the geology and hydrology of the areas are similar, the conceptual model of ground-water flow developed for the Hopewell Run watershed area was applied to the larger Opequon Creek watershed area. Major findings of the studies were that although recharge to sinkholes can occur, it is not a dominant process, and ground-water recharge is distributed over a broad area. Recharge to sinkholes can be a dominant process only when surface runoff occurs, typically as a result of intense rainfall, and for sinkholes with large drainage areas. Areal recharge occurs as precipitation falls on the surface, quickly infiltrates the soil and regolith, and percolates into the epikarst, a zone of intense weathering from land surface to a depth of approximately 20 m. Hydrogeologic settings of carbonate bedrock bounded by low-permeability bedrock such as the Conococheague Limestone and Martinsburg Formation are conducive to conduit development and may provide good locations for development of ground-water supplies. Large quantities of ground water are funneled through these areas, but water availability is limited by periods of low streamflow and low ground-water levels. In addition to the Hopewell Run watershed area, there are other areas where low-permeability bedrock forces ground water to flow along strike-parallel thrust faults, resulting in large springs; these include areas near Inwood (Bunker Hill), Middleway, Winchester, and Martinsburg, along the margins of the Martinsburg Formation.

The epikarst is characterized by solutionally enlarged bedding planes and high-angle joints that allow rapid infiltration of water to the deeper bedrock aquifer. Below the epikarst, an intermediate zone of less weathered bedrock is present. This intermediate zone of moderately fractured bedrock typically does not exhibit the high density of solutionally enlarged conduits that is evident in the epikarst. Hydraulic conductivity is less in the intermediate zone than in the epikarst. Below a depth of about 75 m, the aperture of bedrock fractures decreases substantially, and the estimated hydraulic conductivity, based on aquifer-test data, is approximately half that in the intermediate zone. Vertical hydraulic conductivity is poorly understood and was simulated in both the Hopewell Run and Opequon Creek models as approximately one-tenth of the horizontal hydraulic conductivity. Sensitivity tests were used to evaluate the importance of variations in vertical hydraulic conductivity in the model.

The ground-water flow system is a triple-porosity system with negligible intergranular primary porosity. Microfractures (matrix porosity) provide some storage of water, a dominant set of diffuse fractures provides most of the storage in the aquifer, and a system of solutionally enlarged fractures (conduits) acts as drains for the intricate network of secondary-porosity features. Flow of ground water in the epikarst can be rapid, on the order of weeks, as indicated by results of tracer tests conducted in the area (Jones, 1997; Jones and Deike, 1981). This is especially true if flow is concentrated in solutionally enlarged conduits. Ground water in the intermediate zone is much older; estimates of ground-water age in the Great Valley carbonate rocks are on the order of 15 to 50 years (McCoy and Kozar, 2007a). There are few data from which to estimate the age of ground water in the deeper parts of the aquifer. It is likely that ground water flows slowly at depths greater than about 100 m. A chlorofluorocarbon (CFC) analysis of water from a 145-m-deep well at the USGS Leetown Science Center in the Hopewell Run watershed area indicated an apparent ground-water age of approximately 50 years. Water from greater depths is likely much older (Kozar and others, 2008).

Topography also has a major effect on ground-water flow. Depth to water typically is greater on hilltops than in valley or hillside settings. Upland areas are commonly formed from more resistant rock. These rock units typically have lower hydraulic conductivities than the more permeable formations in lowland areas. The Conococheague Limestone and Elbrook and Martinsburg Formations (fig. 2) are the principal lower permeability units and act as barriers to downgradient flow of ground water. Regional ground-water flow in the study area is primarily from the topographically higher areas in the east and west toward Opequon Creek, which drains the watershed near the center of the north-northeast-trending valley. The low-permeability Martinsburg Formation and Conococheague Limestone provide dominant controls on ground-water flow, impeding flow toward Opequon Creek. Water is forced to flow parallel to bedrock strike along solutionally enlarged thrust faults. Cross-strike faults, oblique faults, and associated fracture zones provide avenues along which ground water can flow either across or through the less permeable units.

The ground-water flow model developed for this investigation is a steady-state model of the Opequon Creek watershed area, including areas that drain directly to the Potomac River in the northern part of the study area (fig. 1). A 30-m USGS digital elevation model (DEM) of the Opequon Creek watershed area (fig. 6) provided the elevation from which the upper surface of the ground-water flow model was derived. Elevations in the watershed are highest in the southwestern part of the study area and along North Mountain in the west; the lowest are in the northern part of the watershed along the Potomac River. Topography, structural features such as thrust faults and cross-strike faults, and low-permeability bedrock such as the Conococheague Limestone and Elbrook and Martinsburg Formations are the principal factors governing rates and directions of ground-water flow in the watershed.

Design and Assumptions

The ground-water flow model is based on the conceptual model of ground-water flow previously discussed and derived primarily from investigations conducted for the Hopewell Run watershed area near Leetown, West Virginia (Kozar and others, 2007, 2008) The model consists of three layers that are used to simulate (1) the epikarst zone; (2) the primary intermediate zone in which most wells are completed; and (3) the less fractured, deeper part of the bedrock aquifer (fig. 7).

Assumptions were made for areas where data were limited or unavailable and for the overall depth of ground-water flow simulated by the model. Geologic maps developed as part of this investigation provided the locations of the major thrust and cross-strike faults, which were the basis for the simulation of conduits in the model. Aquifer tests conducted in the region (McCoy and others, 2005a, 2005 b) indicate that the faults in the area tend to have higher hydraulic conductivity than the bedrock formations (table 3). Therefore, as in the ground-water flow model for the Hopewell Run watershed area (Kozar and others, 2007, 2008), faults were simulated as areas of high conductivity throughout the model. Because few data were available to characterize the peripheral areas of the model, especially along the North Mountain fault, some simplifying assumptions were made. The simulation along North Mountain is less accurate than in other areas of the model; however, this area is not an emphasis of the study.

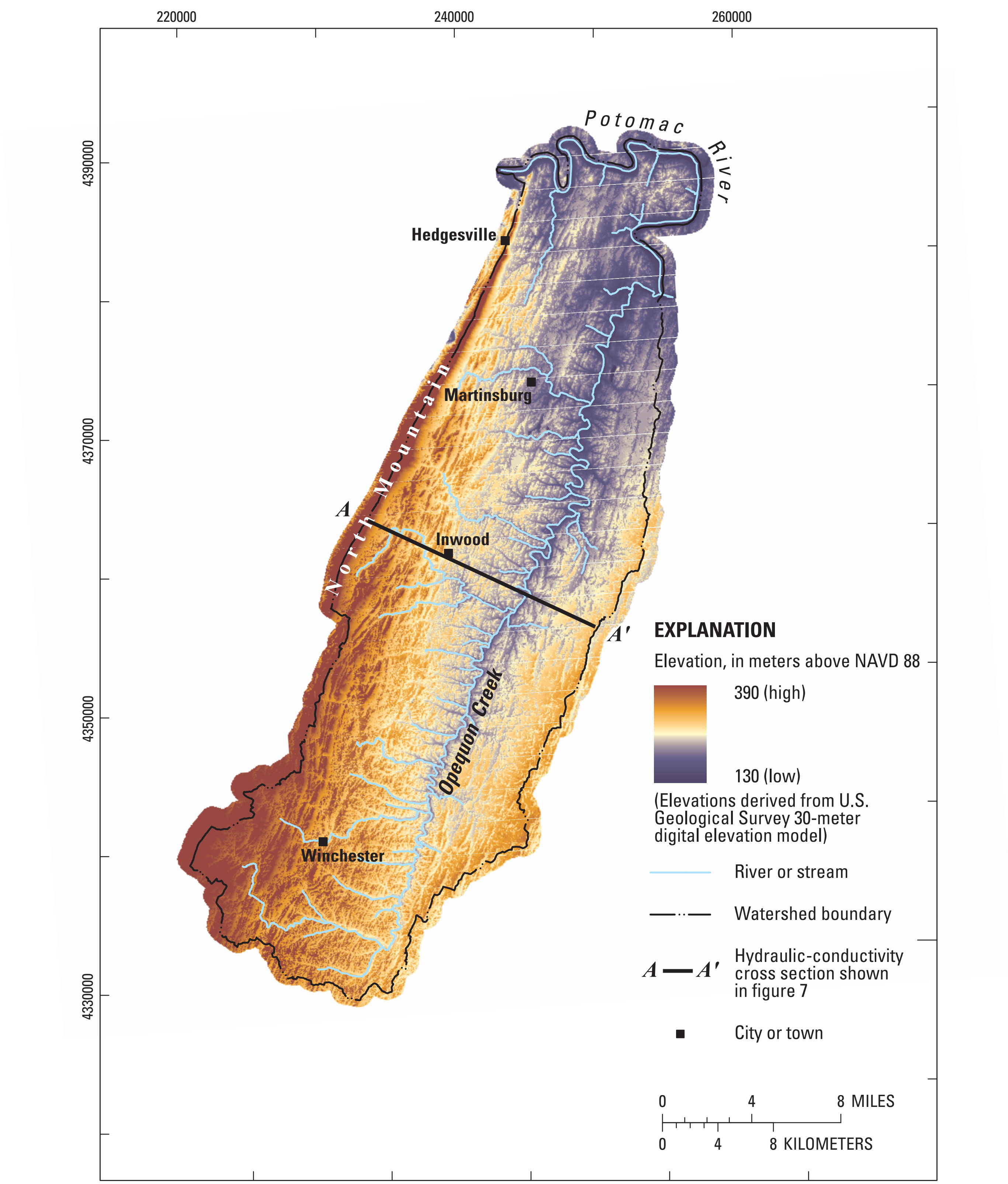
The base elevation of the study area near the Potomac River is approximately 130 m. Because the Potomac River is the primary surface- and ground-water discharge zone in the region, it is assumed that substantial ground-water flow does not occur at depths much greater than the base level of the Potomac River. However, the ground-water flow model was extended to a depth of approximately 30 m below NAVD 88 to account for the small amount of deeper ground-water flow that may occur. The maximum depth of ground-water flow simulated was approximately 185 m below land surface. Land-surface elevations simulated in the model range from a maximum of 390 m above NAVD 88 in the southwestern part of the model and along North Mountain to 130 m above NAVD 88 along the Potomac River in the northeastern part.

Grid, Layers, and Boundary Conditions

The model grid (fig. 4) extends from the Potomac River in the north to Winchester, Virginia, to the south, and is bounded by North Mountain to the west and by bedrock ridges to the east. The variably spaced grid consists of 170 rows and 73 columns, includes 37,230 individual nodes, and encompasses an area of 1,010 km^2. The larger nodes in the model each represent a surface area of approximately 472 m by 409 m and the smaller nodes each represent a surface area of approximately 236 m by 409 m. Approximately one-third of the nodes in the model are inactive. Opequon Creek and the Potomac River are the major streams simulated in the model.

The model consists of three layers that represent the layers previously discussed in “Conceptual Model of Ground-Water Flow.” Hydraulic conductivity is greatest in the upper layer (fig. 8 and table 3), which represents the epikarst and extends from land surface to a depth of 35 m. The middle layer represents the fracture-dominated bedrock part of the aquifer in which most wells are completed (fig. 9); it is 65 m thick and was assigned hydraulic conductivities approximately 2.0 to 2.5 times lower than those assigned to layer 1. The lower layer (fig. 10) represents mostly fractured rock with low permeability and little or no conduit development. This layer represents approximately 85 m of bedrock, and was assigned hydraulic conductivities approximately half that of the middle layer. The lower layer of the model extends to near or below NAVD 88 in most areas.

Two different boundary conditions were simulated in the model (fig. 11). No-flow cells were assigned to the bedrock ridges on the eastern, western, and southern margins of the model. The Opequon Creek and its tributaries were simulated with stream cells (fig. 11). Use of stream cells provided a more realistic simulation of spring and streamflow than was possible with either the river or the drain packages within



Base from U.S. Geological Survey digital data, Universal Transverse Mercator Projection, Zone 18, NAD 83.

Figure 6. Digital elevation map of the Opequon Creek watershed area, Virginia and West Virginia.

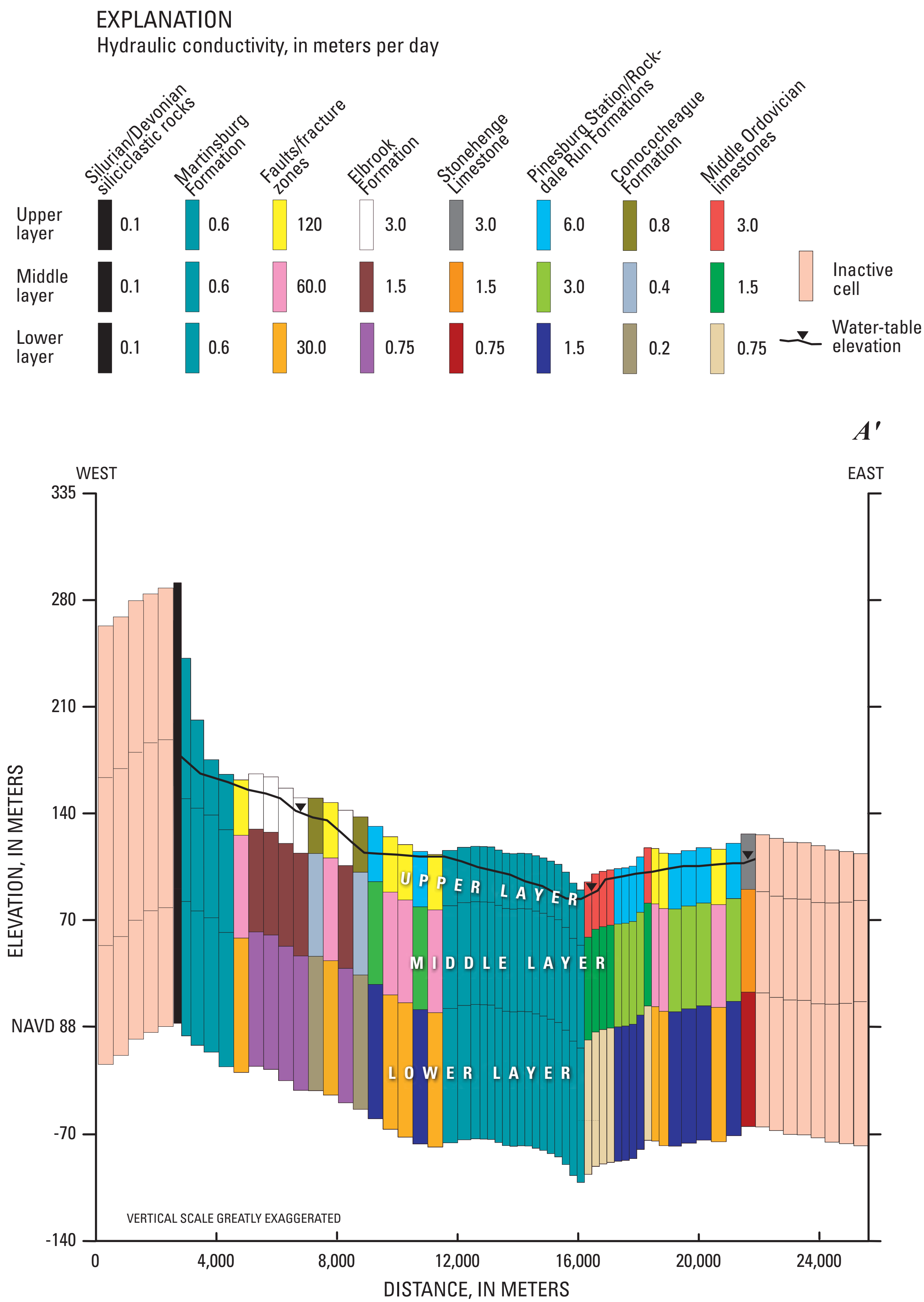


Figure 7. Cross section (as shown in figure 6) of the model-layer configuration, hydraulic conductivity, inactive cells, and water-table elevation simulated in the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.

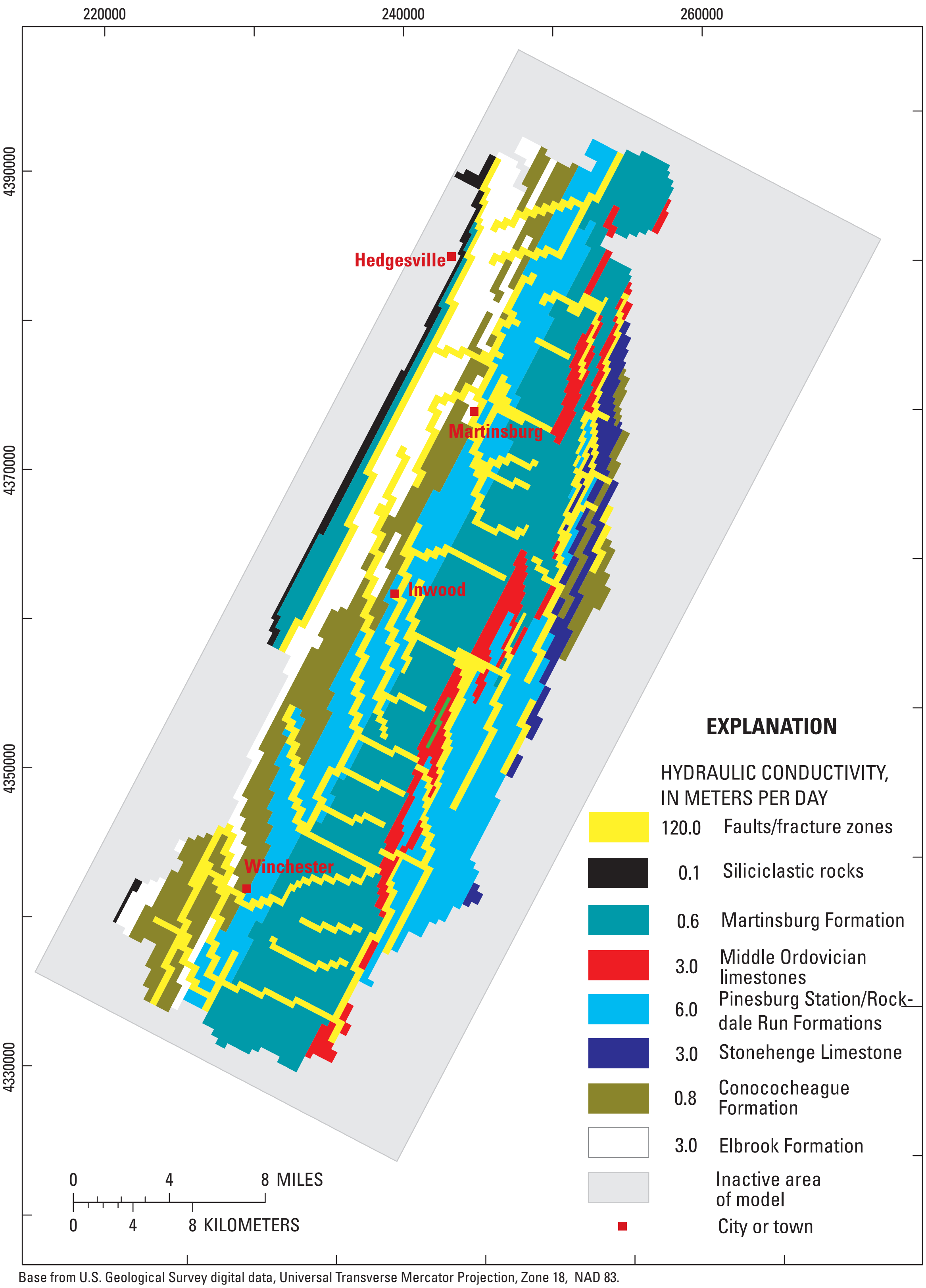


Figure 8. Hydraulic conductivities assigned to the upper layer of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.

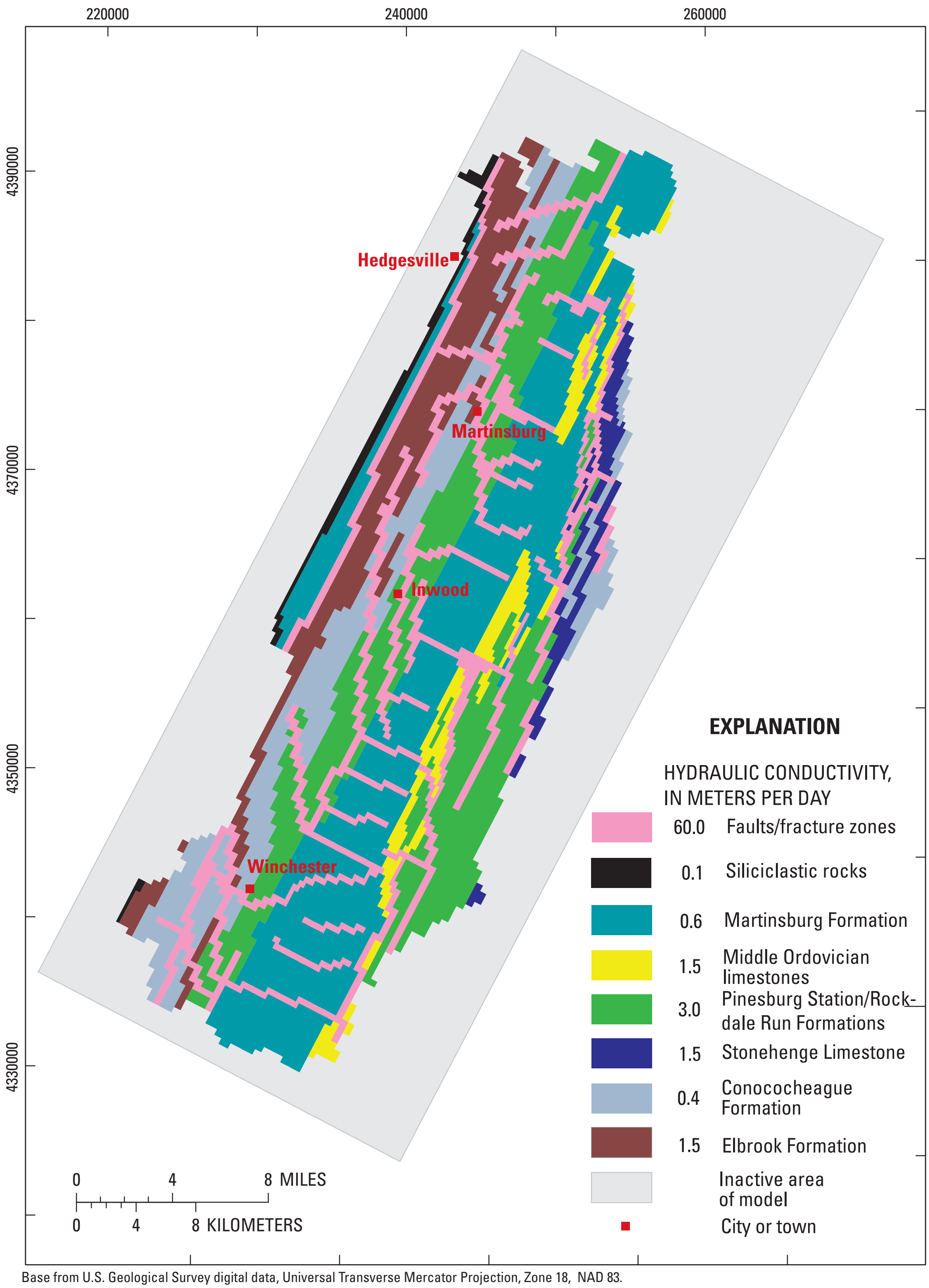


Figure 9. Hydraulic conductivities assigned to the middle layer of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.

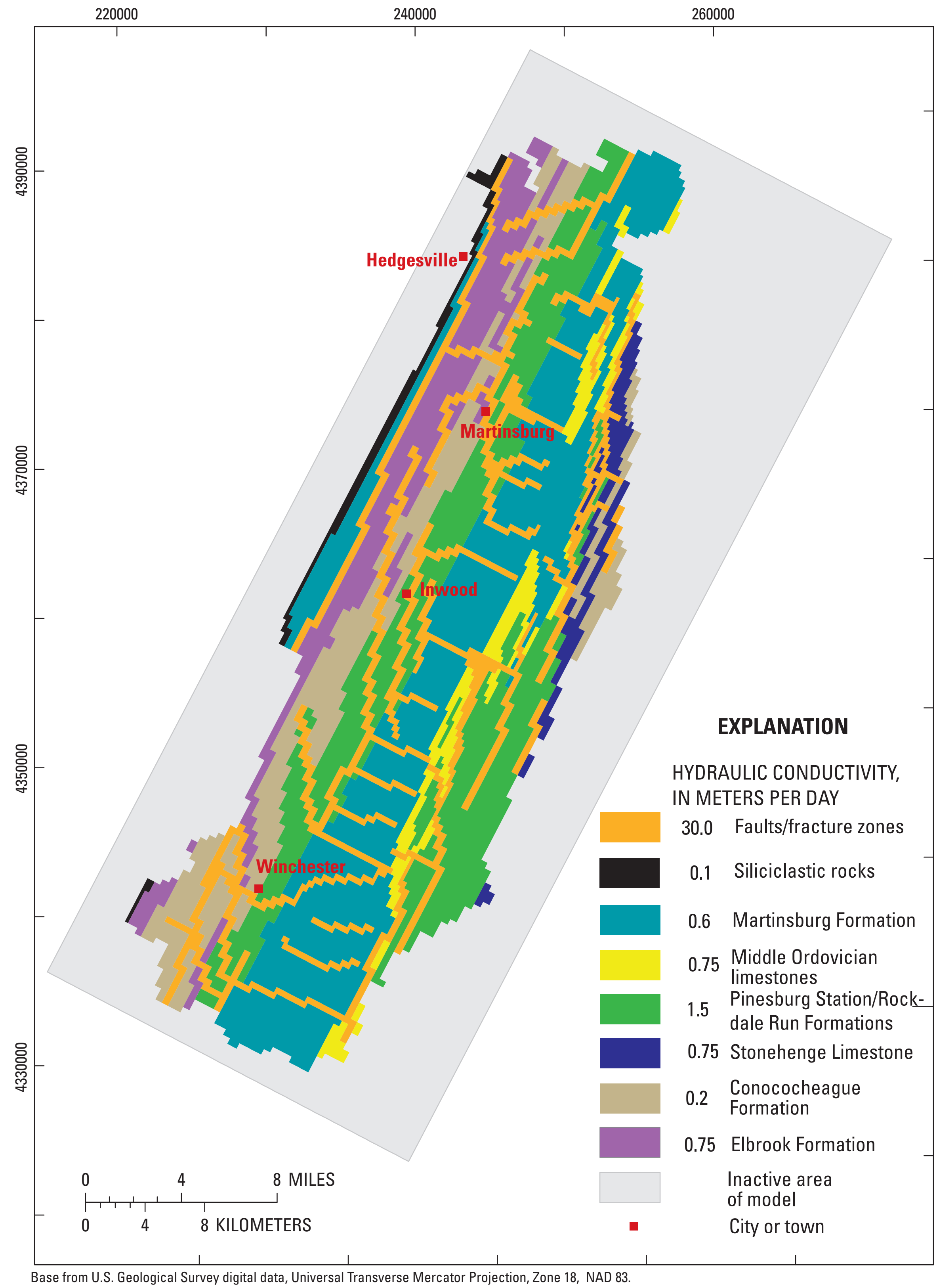


Figure 10. Hydraulic conductivities assigned to the lower layer of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.

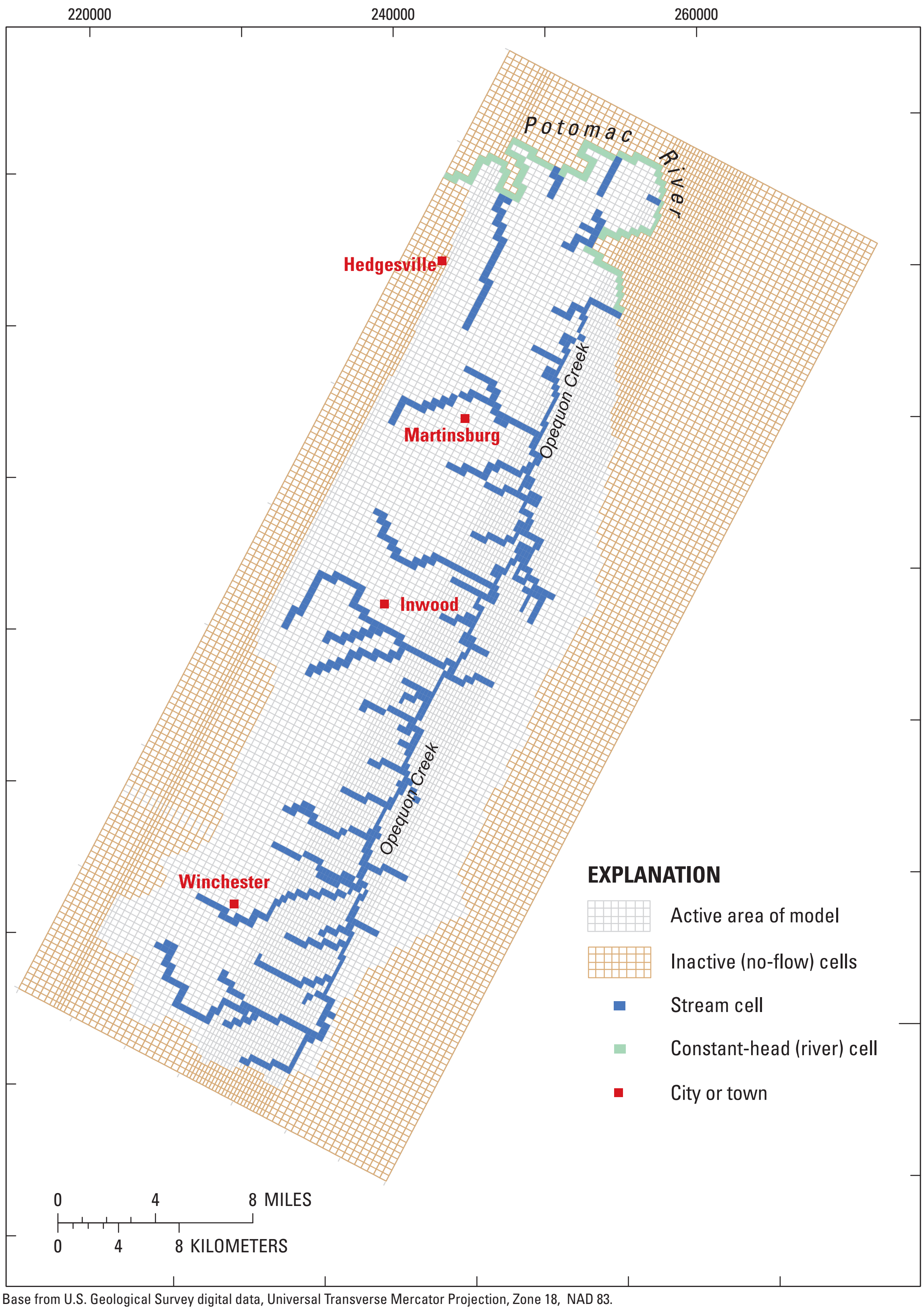


Figure 11. Boundary conditions and the active and inactive cells of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.

Visual MODFLOW. A streambed conductance of 0.09 m/d and a streambed thickness of 2 m were applied to all stream cells in the model. There is likely substantial variability in both streambed conductance and streambed thickness across the Opequon Creek watershed area, but site-specific data were not available to assess the range in variability. The Potomac River was simulated as constant-head cells using the MODFLOW river package, as river and ground-water levels on the Potomac River are regulated by locks and dams along its length and are relatively constant during base flow. Stream stage for the Potomac River, Opequon Creek, and tributaries were estimated from DEM elevation data and measurements of streamflow available from base-flow surveys conducted in the watershed (Evaldi and Paybins, 2006a, 2006b)

Calibration

The ground-water flow model was calibrated to both stream base flow and hydraulic heads (ground-water levels). USGS streamflow-gaging stations in the watershed (fig. 3b and table 1) provided the base-flow data to which simulated flows of Opequon Creek were calibrated. Water levels measured in 470 wells provided the data for calibration of the hydraulic heads simulated with the ground-water flow model. Aquifer-test results available for more than 300 wells provided the data needed for assigning hydraulic conductivity in the model. Because such an abundant data set of base-flow, water-level, and aquifer hydraulic data were available for development and calibration of the model, parameter estimation was not conducted. The model was calibrated manually by varying input parameters through a reasonable range of values until model output reasonably replicated observed base-flow and water-level data.

The Zonebudget subroutine in Visual MODFLOW was used to calculate the water budgets for 34 subwatersheds in the model (fig. 12). Base-flow discharge simulated in the model was compared to long-term measured base flow for two streamflow-gaging stations, one in the headwaters of the basin near Berryville, Virginia, and another upstream from the mouth of Opequon Creek near Martinsburg, West Virginia. The comparisons were made to assess the predictive capability of the model in simulating flow. A well-calibrated model provides the flux of water into and out of the aquifer and provides a baseline for managing water availability within the watershed. Results of the Zonebudget analyses are presented for simulated average and drought hydrologic conditions (tables 6a, 6b).

Simulated stream base flow in the model for the streamgaging station on the Opequon Creek near Martinsburg was 5.01 m^3/s. The long-term median and mean streamflow recorded for this station are 4.05 m^3/s and 6.95 m^3/s, respectively (Ward and others, 2000, 2001). Simulated stream base flow in the model for the streamgaging station on the Opequon Creek near Berryville was 0.90 m^3/s. The long-term median and mean streamflow recorded for this station are 0.54 m^3/s and 1.33 m^3/s, respectively (U.S. Geological Survey, 2008). Simulated base flow for three additional stations was also within the range of measured base flows. Therefore, base flows simulated by the model, both at the headwaters and at the mouth of the watershed, are considered reasonable based on the calibration data available.

Simulated and measured water levels are strongly correlated (fig. 13), with a correlation coefficient of 0.94 and a normalized root mean squared error of 5.79 percent. Simulation of spring discharge in the model proved difficult as a result of the large potential fluctuations in water levels near springs. A relatively minor change in head near a spring can result in large-magnitude errors in simulated spring discharge. Because of the inherent inaccuracy in simulating spring discharge, no attempt was made to calibrate to specific spring discharges. However, a qualitative comparison to known spring discharges indicated that simulated spring discharges were reasonable.

Several factors limited the accuracy of simulated water levels with respect to measured water levels. First, existing water-level data collected over a 40-year period were used to develop and calibrate the model. Although the data worked well for developing the steady-state model, they varied widely over varying hydrologic conditions. Therefore, the model was calibrated to the average water levels to approximate an average base-flow condition. In addition, elevations for well measuring points were based on the elevations derived from the DEM, and there are potentially large errors associated with the land-surface elevations assigned to these wells. Finally, the average horizontal error for the well locations, based on data from the GWSI database, can be as much as ± 10 to 35 m, especially for the older water-level data that were collected prior to the common use of global positioning system (GPS) receivers for establishing location information for wells. An additional limiting factor is that MODFLOW calculates the water level for the center of a node; if the observation well is not located near the center of the node, the difference between the locations of the simulated and measured water levels can be substantial. This error is most pronounced in areas of steep terrain and is as much as ± 10 m at some locations. Fortunately, the areas where topographic effects are pronounced, mainly along the crest of North Mountain, are not areas of emphasis for this study. Given the limitations of assigning elevations to wells and the error associated with topographic effects, the calibration results for hydraulic heads are considered acceptable.

Sensitivity Analysis

The sensitivity of the model to variations in input parameters, including both horizontal and vertical hydraulic conductivity as well as recharge and anisotropy, was analyzed to provide a measure of the uncertainty of input-parameter values and model output. Estimates of hydraulic conductivity used in the model were based on aquifer-test data collected in the region. Sensitivity-analysis simulations were conducted by varying the input parameters and comparing the root mean squared error to that of the calibrated model. The analyses

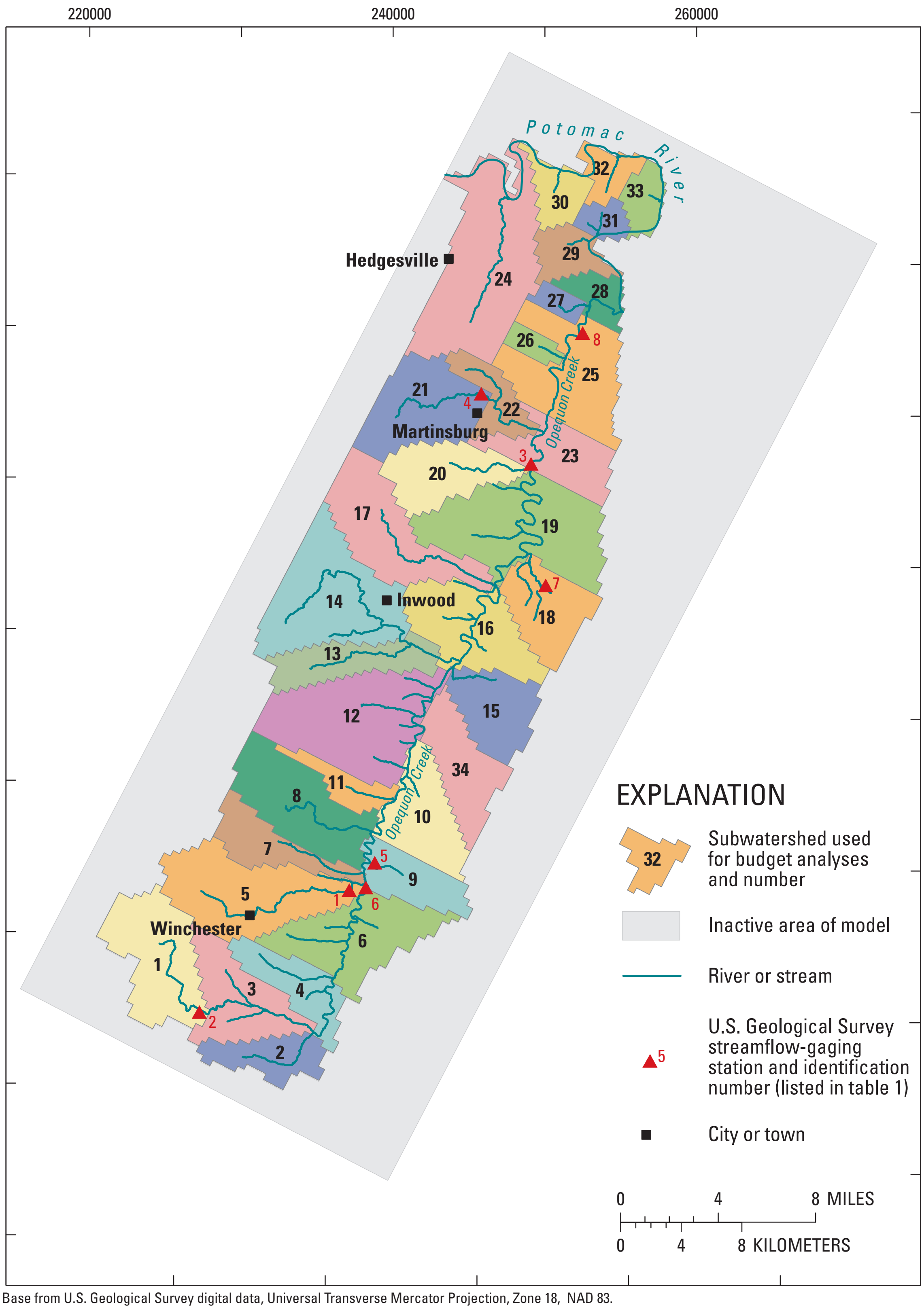


Figure 12. Subwatersheds for which water-budget analyses were conducted in the Opequon Creek watershed area, Virginia and West Virginia.

Table 6. Simulated water budgets for 34 subwatersheds and five streamflow-gaging stations (*A*) during average hydrologic conditions and (*B*) during a drought, derived as part of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.

[m³/d, cubic meters per day; km², square kilometers; budgets for subwatersheds A through E calculated by summation or difference and represent all discharge upstream from the gaging station]

A Subwatershed number in figure 12	Stream name	Recharge (m³/d)	Total water in/out of zone (m³/d)	Stream leakage to ground water (m³/d)	Base flow for normal conditions (m³/d)	Ground-water inflow to zone (m³/d)	Ground-water outflow from zone (m³/d)	Ground-water discharge to Potomac River (m³/d)	Ground-water withdrawals from wells (m³/d)	Subwatershed area (km²)	Recharge (m³/d/km²)	Base-flow yield (m³/d/km²)
1	Opequon Creek near Stephens City, VA	32,098	41,877	0	4,486	9,779	37,391	0	0	42.1	762	107
2	Wright's Run	8,766	10,280	0	3,889	1,514	6,391	0	0	18.3	480	213
3	Opequon Creek below Stephens City, VA	16,700	52,159	0	21,035	35,459	31,124	0	0	32.9	508	639
4	Opequon Creek mainstem and Buffalo Creek	10,404	33,674	0	18,136	23,270	15,538	0	0	22.3	467	814
5	Abrams Creek near Winchester, VA	32,490	45,286	0	16,345	12,796	27,923	0	1,018	51.3	633	319
6	Opequon Creek mainstem and tributaries	24,293	47,932	0	30,203	23,639	17,631	0	98	42.2	575	715
7	Redbud Run	13,866	33,742	0	9,825	19,876	23,917	0	0	21.0	662	469
8	Lick Run	27,221	48,920	0	5,794	21,699	43,126	0	0	42.3	644	137
9	Dry Marsh Run near Berryville, VA	15,501	53,253	0	32,628	37,752	20,625	0	0	21.2	733	1,542
10	Tributary stream to Opequon Creek	22,425	82,350	0	57,770	59,925	24,580	0	0	30.5	735	1,894
11	Unnamed tributary to Opequon Creek	5,986	35,619	0	5,393	29,634	30,226	0	0	11.3	531	478
12	Opequon Creek mainstem and tributaries	37,758	93,317	0	63,814	55,559	29,503	0	0	61.7	612	1,034
13	Swan Run	16,924	49,861	151	12,835	32,786	37,026	0	0	25.0	676	513
14	Tributaries to Swan Run	42,649	61,077	519	5,451	17,909	55,603	0	23	55.9	763	98
15	Unnamed tributary to Opequon Creek	20,014	46,937	0	4,215	26,923	42,722	0	0	26.3	762	160
16	Opequon Creek mainstem and tributaries	22,373	92,139	17	63,212	69,750	28,927	0	0	39.7	563	1,592
17	Middle Creek	30,869	65,249	484	8,834	33,896	56,415	0	0	43.3	712	204
18	Headwaters of Hopewell Run near Leetown, WV	18,805	30,922	0	10,791	12,117	20,131	0	0	27.9	674	386
19	Opequon Creek mainstem and tributaries	35,113	85,547	0	58,178	50,434	26,915	0	454	61.8	568	941
20	Unnamed tributary to Opequon Creek	21,225	58,721	0	2,975	37,496	51,015	0	4,731	29.1	729	102
21	Tuscarora Creek above Martinsburg, WV	29,458	93,493	0	4,180	64,035	85,528	0	3,785	38.4	767	109
22	Tuscarora Creek below Martinsburg, WV	10,302	55,044	31	9,498	44,711	45,546	0	0	15.5	665	614
23	Opequon Creek mainstem	16,129	58,400	0	33,679	42,271	24,070	0	651	26.9	600	1,252
24	Hogan Run	77,179	125,390	0	6,176	48,211	77,476	41,738	0	74.2	1,041	83
25	Opequon Creek mainstem	29,792	81,629	0	38,381	51,837	42,854	0	394	46.2	645	831
26	Unnamed tributary to Opequon Creek	3,871	19,539	0	1,685	15,668	17,854	0	0	6.0	643	280
27	Hoke Run	3,807	25,213	0	1,606	21,406	23,607	0	0	5.5	687	290
28	Opequon Creek mainstem	6,215	51,881	0	28,070	45,666	6,646	17,165	0	10.6	585	2,643
29	Unnamed tributary to Potomac River	12,721	36,628	0	2,516	23,907	25,097	9,015	0	13.9	917	181
30	Unnamed tributary to Potomac River	14,489	41,813	0	300	27,324	23,815	17,698	0	13.6	1,069	22
31	Unnamed tributary to Potomac River	4,544	7,890	0	1,549	3,346	1,567	4,774	0	7.3	620	211
32	Jordan Run	7,114	29,858	344	519	22,400	796	28,543	0	10.5	679	50
33	Unnamed tributary to Potomac River	5,504	6,384	0	208	880	730	5,446	0	10.6	519	20
34	Unnamed tributary to Opequon Creek	21,552	53,381	0	0	31,829	53,381	0	0	28.1	766	0
Totals for entire 1,013-km² model area		**698,156**	**1,755,405**	**1,546**	**564,176**	**1,055,703**	**1,055,697**	**124,379**	**11,154**	**1,013.3**	**689**	**557**
A	Opequon Creek at Myers Bridge, WV	566,583	1,430,348	1,202	523,232	862,564	895,963	0	11,154	867.2	653	603
B	Opequon Creek at Martinsburg, WV	455,806	1,063,522	1,171	432,834	606,545	629,096	0	1,593	707.1	645	612
C	Opequon Creek near Berryville, VA	92,261	185,922	0	77,749	93,661	108,075	0	98	157.8	585	493
D	Abram's Creek near Winchester, VA	32,490	45,286	0	16,345	12,796	27,923	0	1,018	51.3	633	319
E	Opequon Creek near Stephen's City, VA	32,098	41,877	0	4,486	9,779	37,391	0	0	42.1	762	107

Table 6. Simulated water budgets for 34 subwatersheds and five streamflow-gaging stations (*A*) during average hydrologic conditions and (*B*) during a drought, derived as part of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.—Continued

[m^3/d, cubic meters per day; km^2, square kilometers; budgets for subwatersheds A through E are calculated by summation or difference and represent all discharge upstream from the gaging station]

B Subwatershed number in figure 12	Stream name	Recharge (m^3/d)	Total water in/out of zone (m^3/d)	Stream leakage to ground water (m^3/d)	Base flow for normal conditions (m^3/d)	Ground-water inflow to zone (m^3/d)	Ground-water outflow from zone (m^3/d)	Ground-water discharge to Potomac River (m^3/d)	Ground-water withdrawals from wells (m^3/d)	Subwatershed area (km^2)	Recharge ($m^3/d/km^2$)	Base-flow yield ($m^3/d/km^2$)
1	Opequon Creek near Stephens City, VA	19,259	21,853	0	39	2,594	21,814	0	0	42.1	457	1
2	Wright's Run	5,259	6,378	42	634	1,077	5,744	0	0	18.3	288	35
3	Opequon Creek below Stephens City, VA	10,020	29,962	5	7,791	19,937	22,171	0	0	32.9	305	237
4	Opequon Creek mainstem and Buffalo Creek	6,243	26,797	0	10,465	20,555	16,332	0	0	22.3	280	470
5	Abrams Creek near Winchester, VA	19,494	29,379	0	6,548	9,885	21,814	0	1,018	51.3	380	128
6	Opequon Creek mainstem and tributaries	14,576	36,357	0	19,931	21,781	16,328	0	98	42.2	345	472
7	Redbud Run	8,320	24,583	0	5,986	16,263	18,597	0	0	21.0	397	286
8	Lick Run	16,333	32,201	0	2,431	15,868	29,770	0	0	42.3	386	57
9	Dry Marsh Run near Berryville, VA	9,301	40,738	0	22,336	31,437	18,402	0	0	21.2	440	1,056
10	Tributary stream to Opequon Creek	13,455	59,517	0	38,848	46,062	20,669	0	0	30.5	441	1,274
11	Unnamed tributary to Opequon Creek	3,591	23,987	0	2,217	20,396	21,770	0	0	11.3	318	197
12	Opequon Creek mainstem and tributaries	22,655	60,706	0	39,869	38,051	20,837	0	0	61.7	367	646
13	Swan Run	10,154	31,330	0	5,971	21,176	25,359	0	0	25.0	406	239
14	Tributaries to Swan Run	25,589	36,109	0	135	10,520	35,952	0	23	55.9	458	2
15	Unnamed tributary to Opequon Creek	12,009	32,994	62	1,728	20,923	31,266	0	0	26.3	457	66
16	Opequon Creek mainstem and tributaries	13,424	63,729	65	42,676	50,240	21,053	0	0	39.7	338	1,075
17	Middle Creek	18,522	42,580	0	3,346	24,058	39,234	0	0	43.3	427	77
18	Headwaters of Hopewell Run near Leetown, WV	11,283	20,726	15	4,019	9,428	16,707	0	0	27.9	404	144
19	Opequon Creek mainstem and tributaries	21,068	59,949	1	37,386	38,880	22,109	0	454	61.8	341	605
20	Unnamed tributary to Opequon Creek	12,735	39,409	0	1,024	26,674	33,654	0	4,731	29.1	437	35
21	Tuscarora Creek above Martinsburg, WV	17,675	59,235	0	0	41,560	55,450	0	3,785	38.4	460	0
22	Tuscarora Creek below Martinsburg, WV	6,181	35,984	28	3,512	29,775	32,472	0	0	15.5	399	227
23	Opequon Creek mainstem	9,677	40,965	0	23,305	31,288	17,009	0	651	26.9	360	866
24	Hogan Run	46,307	78,117	2	1,061	31,809	52,339	24,717	0	74.2	624	14
25	Opequon Creek mainstem	17,875	55,509	0	26,061	37,634	29,054	0	394	46.2	387	564
26	Unnamed tributary to Opequon Creek	2,322	13,121	0	404	10,799	12,717	0	0	6.0	386	67
27	Hoke Run	2,285	16,879	24	440	14,571	16,439	0	0	5.5	412	79
28	Opequon Creek mainstem	3,729	35,205	0	19,813	31,476	4,329	11,063	0	10.6	351	1,865
29	Unnamed tributary to Potomac River	7,633	23,465	0	1,349	15,833	16,038	6,077	0	13.9	550	97
30	Unnamed tributary to Potomac River	8,693	26,406	0	136	17,713	15,727	10,543	0	13.6	641	10
31	Unnamed tributary to Potomac River	2,726	5,128	0	916	2,402	1,035	3,177	0	7.3	372	125
32	Jordan Run	4,268	20,273	1,250	424	14,754	476	19,373	0	10.5	407	40
33	Unnamed tributary to Potomac River	3,303	3,927	0	166	625	461	3,300	0	10.6	312	16
34	Unnamed tributary to Opequon Creek	12,931	38,540	0	0	25,609	38,540	0	0	28.1	460	0
Totals for entire 1,013-km² model area		**418,894**	**1,172,038**	**1,493**	**330,967**	**751,651**	**751,667**	**78,251**	**11,154**	**1013.3**	**413**	**327**
A	Opequon Creek at Myers Bridge, WV	339,951	962,638	218	306,662	622,469	644,822	0	11,154	867.2	392	354
B	Opequon Creek at Martinsburg, WV	273,486	718,415	190	252,356	444,740	464,467	0	1,593	705.1	388	358
C	Opequon Creek near Berryville, VA	55,357	121,347	47	38,860	65,943	82,389	0	98	157.8	351	246
D	Abram's Creek near Winchester, VA	19,494	29,379	0	6,548	9,885	21,814	0	1,018	51.3	380	128
E	Opequon Creek near Stephen's City, VA	19,259	21,853	0	39	2,594	21,814	0	0	42.1	457	1

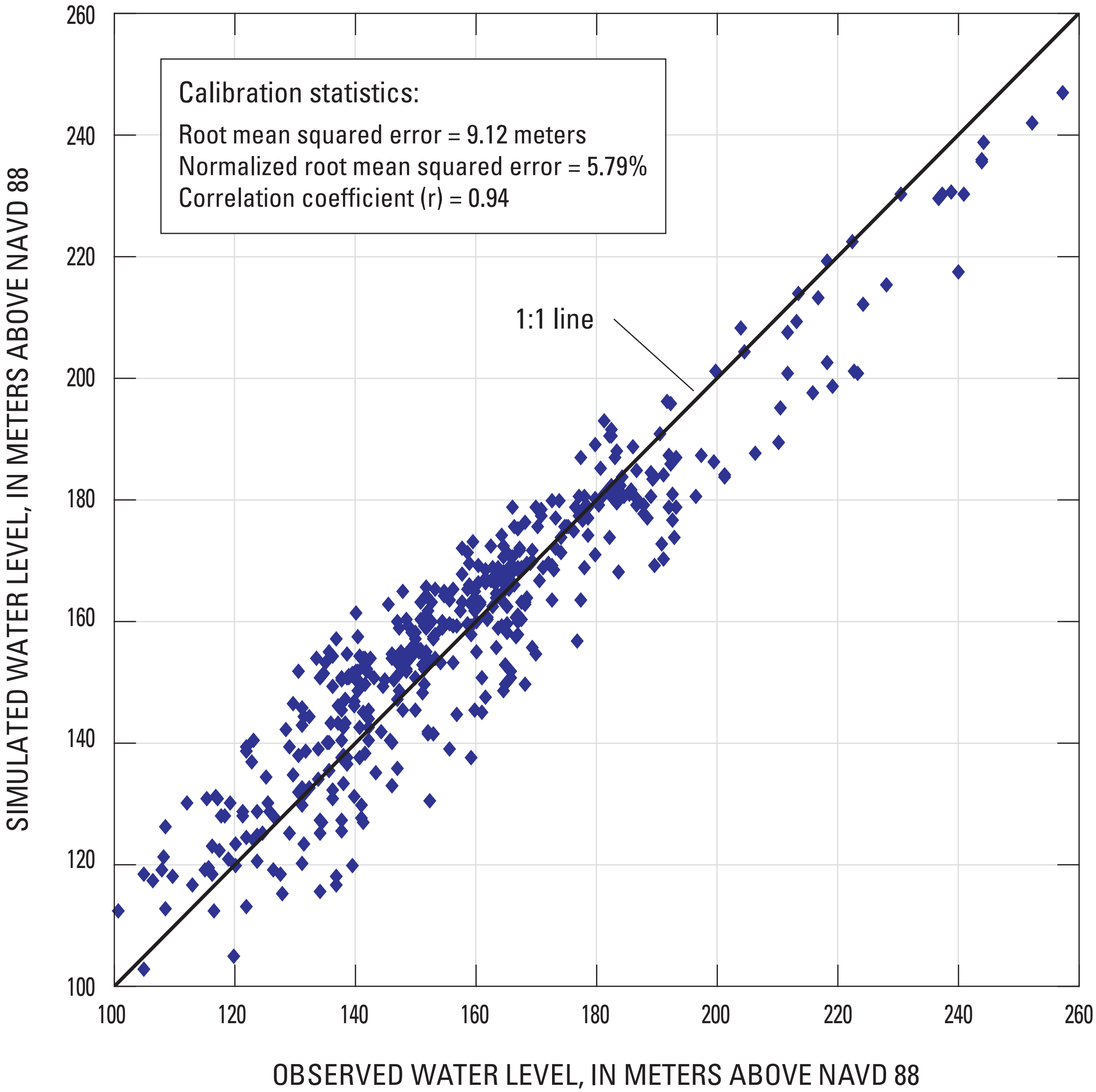


Figure 13. Relation between simulated and observed water levels in 470 observation wells in the Opequon Creek watershed area, Virginia and West Virginia.

were conducted by multiplying the calibrated parameters by a multiplier (from 0.2 to 2.4–4.0) and examining the resultant change in the root mean squared error of the model. Using a multiplier of 1 results in a value that is equivalent to the value of the calibrated model-input parameter. Changes in potentiometric surfaces and water budgets were also assessed to ensure that realistic values were generated.

Results of the sensitivity analyses (fig. 14) show that the ground-water flow model is most sensitive to recharge and to the values of hydraulic conductivity assigned to the simulated solution conduits, indicating that ground-water flow cannot be realistically simulated without taking into consideration the conduit flow component. Realistic estimates of recharge also are needed to accurately represent base flow and assess the flux of ground water within the model. Recharge for the model was based on analyses of streamflow hydrographs for several USGS streamflow-gaging stations in the watershed and was included in the sensitivity analysis to evaluate its importance for model calibration (table 1). Data from the gaging stations provided very reasonable estimates of recharge for the model and eliminated the need to assign a subjective recharge value. Even minor variations in recharge caused the model output to deviate from the 1:1 calibration line between simulated and observed water level. Therefore, recharge is considered to be the most important parameter for quantifying water budgets in the model.

The model was also somewhat sensitive to the values assigned for hydraulic conductivity of the less permeable geologic formations such as the Conococheague Limestone and Martinsburg and Elbrook Formations. Because the low-permeability geologic units are major controls on ground-water flow, it is not surprising that minor variations in the hydraulic conductivity of these formations would affect simulated heads and the calibration of the model. The model was not sensitive to variations in the hydraulic conductivity assigned to the Silurian and Devonian siliciclastic rocks along North Mountain.

Ratios of horizontal to vertical hydraulic conductivity ranging from 1:1 to 20:1 also were evaluated. Differences in calibration statistics for the various conductivity ratios were minimal, but the 5:1 ratio provided the best fit between simulated and measured water levels and was used for all simulations. The model was also somewhat sensitive to horizontal anisotropy, with an anisotropy of 3:1 in the direction of bedrock strike providing the best fit. In a similar ground-water modeling study of Fredrick County, Virginia, the optimal anisotropy in the direction of bedrock strike was also found to be 3:1 (Burbey, 2003)

Water Budgets

A water budget is a mass balance of inputs to and outputs from a watershed. The major input to the ground-water flow model was recharge derived from precipitation. One small wastewater-treatment plant return flow provides water initially derived from the Shenandoah River, but the quantity is negligible when compared to the total water balance for the watershed. No other inputs to the watershed were evident in the study area. Outputs from the model include base flow, consumptive use of water from wells, evaporation of water from land and water surfaces, and transpiration of water by trees, grasses, and other vegetation. Precipitation for the study area was based on records (National Oceanic and Atmospheric Administration, 2002a, 2002b) collected at five National Weather Service meteorological stations (table 2). Long-term mean precipitation for two stations, the Martinsburg Regional Airport, West Virginia, and the Winchester 3ESE, Virginia, weather stations, provided data for water-budget calculations. Mean precipitation for Martinsburg for the period 1926–2007 was 960 mm/yr and mean precipitation for Winchester for the period 1912–2007 was 957 mm/yr (National Oceanic and Atmospheric Administration, 2008). The major output, average streamflow of the Opequon Creek near Martinsburg, was available from existing data (U.S. Geological Survey, 2008b), and was approximately 311 mm/yr. The difference between the long-term average base flow and the long-term average recharge is attributable mostly to surface runoff and evapotranspiration. The water budget can be expressed by the equation

$$P = SRO + GWD + ET + \Delta S,$$

where

P	is	the total precipitation,
SRO	is	the component of streamflow that occurs as a result of surface runoff,
GWD	is	the ground-water discharge to the stream (stream base flow),
ET	is	evapotranspiration, and
ΔS	is	the change in ground-water storage.

As long-term streamflow and precipitation data were used to develop the water budget, change in storage (ΔS) was assumed to be negligible. Therefore, the only unmeasured quantity was ET, which was estimated by difference. Given an average long-term measured precipitation of 958 mm/yr (average of the values from the Martinsburg and Winchester meteorological stations), total streamflow of 311 mm/yr (surface runoff of 101 mm/yr and base flow (ground-water discharge) of 210 mm/yr), the water-budget equation was rearranged to solve for ET by filling in the known terms:

$$ET = P - (SRO + GWD + \Delta S)$$

$$ET = 958 - (101 + 210) = 647 \text{ mm/yr.}$$

Once ET has been estimated, the complete water budget equation can then be written as

$$P = SRO + GWD + ET + \Delta S,$$

$$958 = 101 + 210 + 647 - 0.0 \text{ mm/yr,}$$

with all terms expressed in millimeters per year.

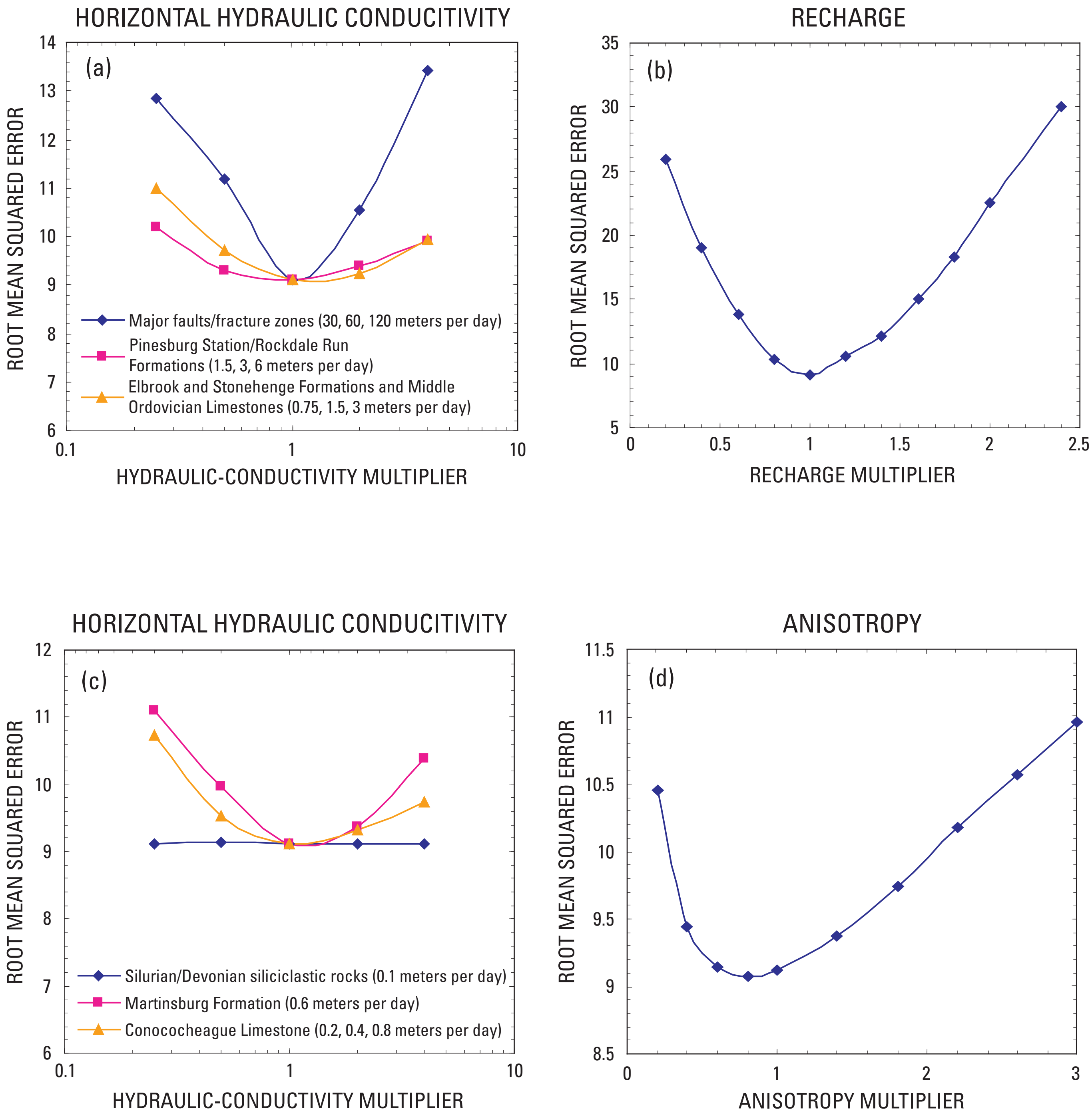


Figure 14. Results of sensitivity analyses of major input parameters for the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.

The water budget presented here is approximate and may have appreciable error as a result of variations in precipitation across the watershed (table 2). Therefore, the water-budget estimate of *ET* should be regarded as approximate only. The estimates for ground-water discharge and surface runoff are, however, well defined as they are based on historical streamflow data.

The effective mean recharge estimated by hydrograph separation of streamflow (Kozar and Mathes, 2001) for the Opequon Creek near Martinsburg streamflow-gaging station (table 1) was 241 mm/yr. This value compares favorably to the simulated ground-water recharge of 235 mm/yr over the 707-km^2 drainage area of the gaging station on the Opequon Creek near Martinsburg estimated by the ground-water flow model. The minor difference between recharge (235 mm/yr) and ground-water discharge (210 mm/yr) may be attributable to riparian evapotranspiration and (or) to subtle differences in mathematical analyses and computations used in the two methods.

Recharge was set to 150, 280, or 390 mm/yr on the basis of the proportion of carbonate bedrock and potential for deep weathering of the bedrock. Approximately 68 percent of precipitation is lost to evapotranspiration. Based on hydrograph separation of annual mean daily streamflow data for the Opequon Creek near Martinsburg streamflow-gaging station, approximately 68 percent of streamflow is derived from ground-water discharge and 32 percent is attributed to surface runoff. These estimates compare favorably with the water-budget estimates calculated for the Hopewell Run watershed area (Kozar and others, 2007, 2008), where *ET* was approximately 63 percent of total precipitation but base flow accounted for 93 percent of total streamflow and only 7 percent of surface runoff. The Hopewell Run is a tributary to the Opequon Creek and the two watersheds have similar hydrogeologic settings, with the Hopewell Run watershed consisting of a much larger percentage of highly permeable carbonate bedrock than the larger Opequon Creek watershed.

Analyses of the subwatershed water budgets for average hydrologic conditions are presented in table 6a. Areas composed solely of limestone bedrock, as would be expected, have higher recharge rates than areas dominated by shale bedrock. Areas where the bedrock is more evenly divided between carbonate and shale bedrock are intermediate with respect to recharge. Of five streamflow-gaging stations analyzed, Opequon Creek near Stephens City, Virginia, had the highest recharge rate (762 $m^3/d/km^2$), and Opequon Creek near Berryville, Virginia, had the lowest recharge rate (585 $m^3/d/km^2$). The drainage area for Opequon Creek near Stephens City is composed almost entirely of carbonate limestone and dolomite bedrock, whereas a substantial proportion of the drainage area of Opequon Creek near Berryville is non-carbonate shale of the Martinsburg Formation.

Recharge rates were highest (>1,000 $m^3/d/km^2$) in the northern portion of the basin in the Hogan Run watershed near Hedgesville, W.Va., and in a few of the tributaries that drain directly to the Potomac River (table 6). These areas (zones 24 and 30 in figure 12) are dominated by numerous cross-strike faults (fig. 2a). The subwatershed budgets also indicate that a substantial amount of ground water in the small subwatersheds in the northern portion of the basin discharges directly to the Potomac River. Base flow in these steams is typically very low, as the depth to ground water can exceed 50 m. Total recharge (698,156 m^3/d) distributed over the entire 1,013-km^2 watershed is 689 $m^3/d/km^2$ (table 6a). Because specific streamflow data for calibration of simulated streamflow in many of the subwatersheds were unavailable, estimates of recharge and base-flow yield for the individual subwatersheds should be regarded only as rough approximations.

Simulated base-flow yields ranged from 0 to approximately 2,643 $m^3/d/km^2$ for average conditions and from 0 to 1,865 $m^3/d/km^2$ for the simulated drought (table 6b). These values generally agree with the range of base-flow yields determined for the West Virginia portion of the Opequon Creek watershed in Berkeley County of -879 to 2,140 $m^3/d/km^2$ (Evaldi and Paybins, 2006a, 2006b). However, the Berkeley County, W.Va., base-flow-yield assessment was based on channel gains and losses and was conducted when hydrologic conditions were wetter than during the 1999 drought. Therefore, computed base-flow yields were negative where discharge decreased downstream but the values presented in table 6 cannot be less than zero. Simulated base-flow yields were expected to be slightly lower than those documented in the Berkeley County channel gains and losses study. Several stream reaches did show loss of streamflow to ground water (table 6) and several streams dried up completely in the drought simulation. Although the Opequon Creek at Stevens City streamflow-gaging station was not operational during the 1999 drought, annual low flows less than 1 m^3/s are common for that portion of the watershed (U.S. Geological Survey, 2008c).

Major production wells (both public supply and industrial) account for approximately 2 percent of ground-water recharge from the watershed upstream from the Opequon Creek near Martinsburg streamflow-gaging station during average flow conditions (table 6a). For a simulated drought, withdrawals as a percentage of overall ground-water recharge increase to approximately 3.2 percent (table 6b). Withdrawals from individual wells account for additional consumptive use, although quantification of the loss is difficult. A large portion of water withdrawn by individual residential wells is returned to the aquifer as septic-system return flows.

Ground-Water Flow Directions

Ground-water flow directions were analyzed by examining the hydraulic-head equipotentials in the upper layer of the model. Generally, ground water flows from topographically high areas toward Opequon Creek. The low hydraulic conductivity of the Martinsburg and Elbrook Formations and Conococheague Limestone (fig. 2) plays an integral role by retarding flow of ground water. Water is forced to travel roughly parallel to bedrock strike along a series of thrust faults (fig. 2) that parallel these lower permeability formations and act as drains, conveying water northward toward tributary streams that cross the thrust faults at roughly 90 degrees. Cross-strike faults allow water to cross the lower permeability bedrock and flow toward Opequon Creek. These complex geologic features are responsible for the large springs in the region. These processes are especially prominent where carbonate bedrock and thrust faults are in close proximity to the Martinsburg Formation, which is composed of low-permeability shale. Chemically aggressive water from the Martinsburg Formation enhances solution of carbonate rocks, forming conduits. There is an overall trend of flow not only toward Opequon Creek, but also from south to north in the Opequon Creek watershed area. Modeled directions of ground-water flow are outlined in figure 15. Thus, much of the ground water resident in the southern portion of the watershed is flowing toward Opequon Creek, but some ground water flows northward into West Virginia.

Simulated Flow for Average Conditions

The ground-water flow model for the Opequon Creek watershed area was developed and calibrated for average hydrologic conditions. Recharge applied in the model was apportioned with respect to the permeability of the various geologic formations. The resulting water-budget calculations (table 6a) and simulated potentiometric surface therefore reflect average conditions (fig. 15). For the model, recharge to the Opequon Creek watershed area upstream from the Martinsburg streamflow-gaging station was 455,806 m^3/d (646 $m^3/d/km^2$) and simulated base flow was 432,834 m^3/d (614 $m^3/d/km^2$). The difference between the recharge and the simulated base flow can be attributed to a number of factors, including evapotranspiration, transfer of ground water out of the watershed, or loss of streamflow to ground water. Simulated recharge over the entire 1,013-km^2 model area under average hydrologic conditions was 698,156 m^3/d (689 $m^3/d/km^2$). Mean and median measured streamflow for the Opequon Creek near Martinsburg streamflow-gaging station are 604,384 and 349,907 m^3/d, respectively (U.S. Geological Survey, 2008b). Therefore, the simulated base flow of 432,834 m^3/d for the watershed upstream from the Opequon Creek near Martinsburg station falls between the mean and median streamflow measured at this station.

Given the drainage areas of Opequon Creek and its tributaries (table 5), it is possible to calculate the average base-flow discharge rate from the Opequon Creek watershed area or its tributaries. This was done for the simulation using the Zonebudget calculations within the Visual MODFLOW software. Base-flow discharge estimates (table 6) provide a basis for management of long-term water availability. Water availability is limited not by average conditions but instead by periods of low flow; water-use planners need to take into consideration the quantity of water available during critical periods of low flow, such as those that occur in late summer or early fall.

Examination of simulated water budgets indicates that a substantial component of discharge to the Potomac River is through direct ground-water discharge. This phenomenon has long been suspected but now has been quantified. During average conditions, simulated base-flow discharge to the Potomac River was 564,176 m^3/d (6.53 m^3/s). An additional 124,379 m^3/d (1.44 m^3/s) of ground water is also estimated to discharge to the Potomac River and represents approximately 18 percent of the total discharge to the Potomac River. This additional ground water discharges along strike-parallel faults and fracture zones and as springs along the southern margin of the Potomac River. Direct ground-water discharge to the Potomac River is difficult to measure as a result of the locks and dams on the river, ground-water and spring discharges within the river, and tributary drainage from the Maryland side of the river. Although the simulation provides only an initial estimate of ground-water discharge to the Potomac River, it does at least indicate that this discharge is a mathematically reasonable hypothesis.

Simulated Flow for Drought Conditions

In order to provide an estimate of ground-water availability during critical low-flow periods, the ground-water model was used to simulate ground-water flow conditions for a drought period. Recharge was reduced to simulate the drought that affected the Shenandoah Valley from November 1998 through February 2000. This was the fourth most severe drought on record for the region with respect to precipitation deficits and was the longest drought on record, lasting 16 months (Cornell University, 2008). The base-flow estimates generated during the simulated drought can provide water planners with estimates of water availability for critical low-flow periods.

Recharge to the model was reduced 40 percent from average values to approximate recharge during the drought. The resulting water budgets (table 6b) and potentiometric surface (fig. 16) simulate severe drought conditions and provide a baseline for consideration in future water-management issues. The recharge applied to the model for the Opequon Creek watershed area upstream from the Martinsburg streamflow-gaging station was 273,486 m^3/d and simulated base flow for the Opequon Creek upstream from the station during the 1999 drought was approximately 252,356 m^3/d (2.95 m^3/s). Mean and median streamflow records for the Opequon Creek near Martinsburg station for the 16-month drought period were 341,098 (3.95 m^3/s) and 216,551 m^3/d (2.51 m^3/s), respectively (Ward and others, 2000, 2001). Therefore, the simulated drought base-flow discharge for the Opequon Creek near Martinsburg station falls between the mean and median streamflow measured during the 16-month drought. Recharge was 388 $m^3/d/km^2$ for the watershed upstream from the Opequon Creek near Martinsburg station, and 413 $m^3/d/km^2$ over the entire watershed. Once again the difference between the recharge and simulated base flow can be attributed to a number of factors, including evapotranspiration by riparian

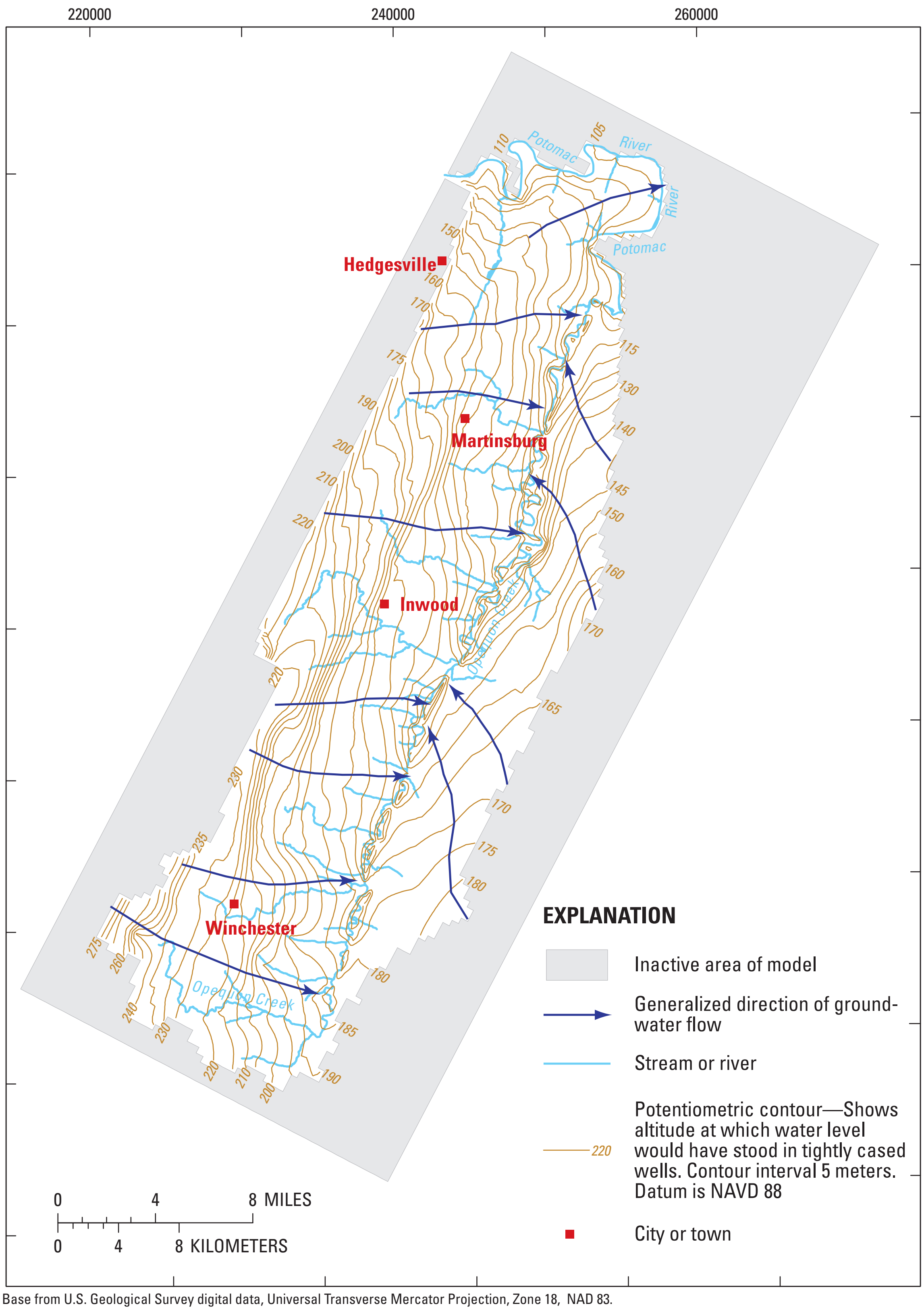


Figure 15. Simulated potentiometric surface and generalized directions of ground-water flow for average hydrologic conditions in the Opequon Creek watershed area, Virginia and West Virginia.

vegetation, transfer of ground water out of the watershed, or loss of streamflow to ground water. Table 6b provides recharge and base-flow estimates for Opequon Creek and its tributaries that can be used to obtain estimates of water availability in the Opequon Creek watershed area during critical low-flow periods. Because streamflow data for the 16-month drought were unavailable for calibration of simulated streamflow, estimates of recharge and base-flow yield for the individual subwatersheds should be regarded as rough approximations only.

Limitations of the Simulations

A major limitation of ground-water modeling in karst terranes is difficulty in accurately simulating potentiometric heads (ground-water levels). A 2- or 3-m difference between simulated and measured ground-water levels for a model of the scale described in this report is considered a very good calibration match; however, such a difference in water levels in the vicinity of springs is problematic. In addition, simulated potentiometric heads typically were slightly lower than water levels measured along North Mountain as a result of the pronounced topographic relief there.

Another major limitation of ground-water modeling in karst terranes is accurate simulation of spring discharge. It is extremely difficult to simulate spring discharge accurately in a karst aquifer such as that typified by the study area. Springs can be simulated either as withdrawal points (pumped wells), as drains, or as streams, but each approach has its limitations. If springs are simulated as withdrawals (pumped wells), a precise discharge can be specified but cones of depression are commonly observed in such an approach (Early, 2005), which is not realistic. Simulation of springs as drains does not allow a flux of water from streams back to ground water, as can occur in karst terranes. If springs are simulated as streams, then spring discharge is susceptible to small changes in nearby ground-water levels, making accurate estimation of spring discharge difficult. Because estimation of spring discharge was secondary to accurate estimation of base flow, springs were simulated as streams forming the headwaters of tributaries draining to Opequon Creek. However, water budgets resulting from a numerical simulation of ground-water flow are less affected by these limitations and provide estimates that accurately simulate the base flow measured at the various streamflow-gaging stations within the watershed.

The steady-state model of ground-water flow in the Opequon Creek watershed area was calibrated against 470 water levels retrieved from the GWSI database. These water-level data were collected under varying hydrologic conditions over a 40-year timeframe. In addition, the wells in this study were open to different depths within a given model layer, and potentially to multiple geologic formations. There is also a margin of error associated with the location and altitude of wells for which water-level measurements were available that could skew the distribution between simulated and observed water levels. Obvious outlier data were removed from the data set and the model was calibrated to the centroid of the water-level data. Therefore, the model is considered calibrated to average water-level conditions. Because ground-water level data for the 16-month actual drought period were unavailable for calibration of water levels during the simulated drought period, the resultant potentiometric surface and subwatershed water budgets should be regarded as estimates only. The simulations presented here represent average hydrologic conditions and conditions during the November 1998 through February 2000 drought, and are based on the best available data, but actual ground-water levels may be greater (higher) or less (lower) than those simulated.

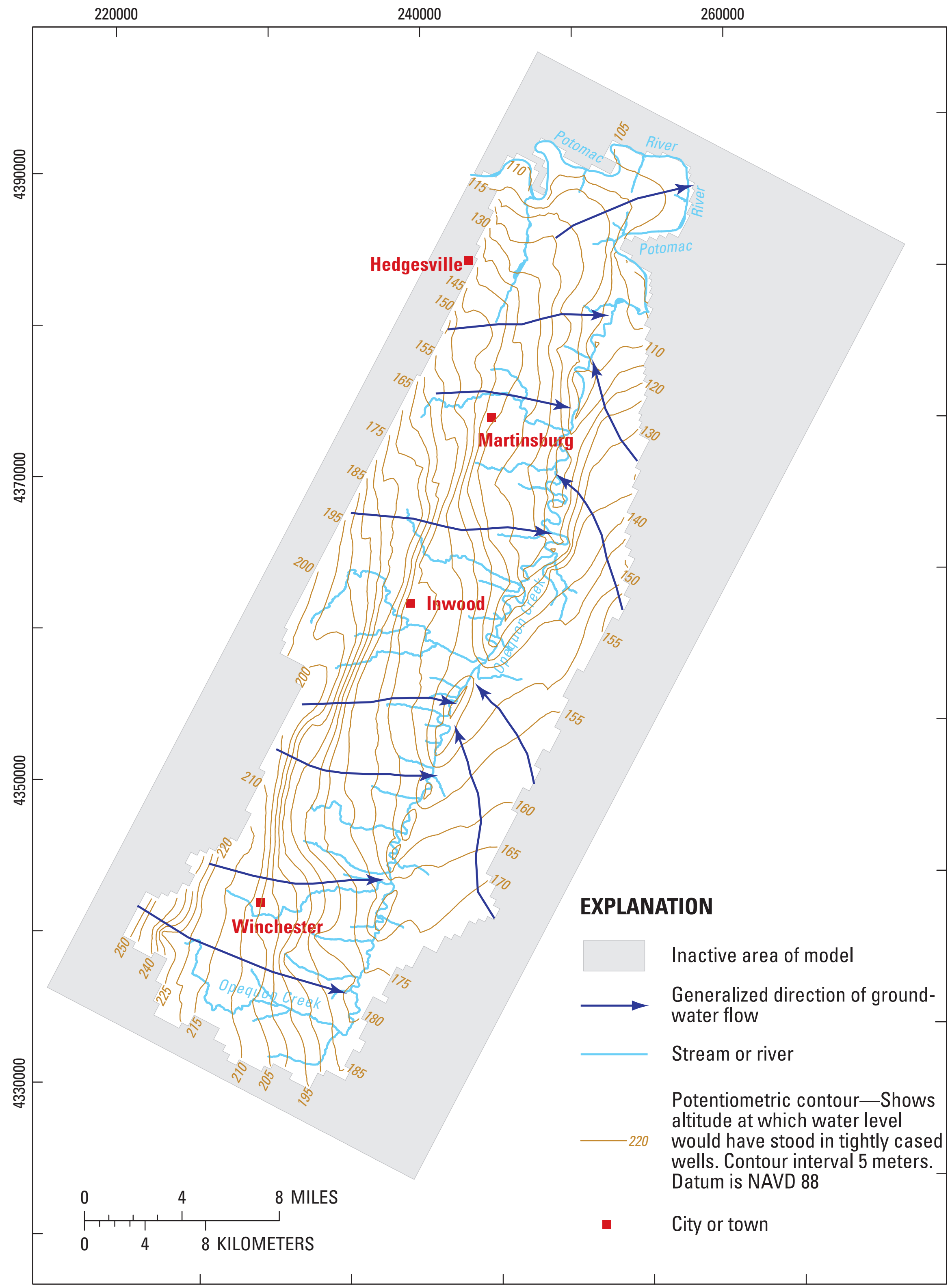
As stated above, the ground-water flow model was calibrated to steady-state conditions and represents long-term average conditions. However, short-term water budgets can vary substantially from long-term steady-state conditions. Although the water-budget estimates for the four gaging stations on Opequon Creek are reasonable, budget information for the subwatersheds should be regarded as estimates only because of the lack of data specific to the subwatersheds and the hydrologic conditions simulated. Differences between simulated and actual recharge, base-flow yields, and channel gains and losses are possible.

Summary and Conclusions

This report presents results of a steady-state simulation of ground-water flow developed in 2008 for the Opequon Creek watershed area in the northern Shenandoah Valley of Virginia and West Virginia. The resulting model was used to develop a budget of available ground-water resources and to assess the potential effects of drought on water availability within the watershed. The report describes the hydrogeology of the study area, documents the development of the ground-water flow model, presents the results of water-budget analyses, and quantifies simulated streamflow under both average and drought conditions. This report was prepared in cooperation with the West Virginia Department of Health and Human Services and the West Virginia Department of Environmental Protection.

Ground-water flow in the 1,013-km^2 Opequon Creek watershed area in Virginia and West Virginia was simulated using a three-dimensional finite-difference model. The steady-state ground-water flow model was developed by extrapolating the conceptual model of ground-water flow developed for the smaller watershed of Hopewell Run (52 km^2), which is a tributary to the much larger Opequon Creek. The model for the Opequon Creek watershed area was used to develop a water budget for the watershed and assess the potential effects of drought on water availability within the watershed.

The study area is dominated by karstic carbonate rocks of Cambrian and Ordovician age. Ground water flows through diffuse fractures and small, solutionally enlarged conduits, which serve as drains for the dominant diffuse system of interconnected fractures. Shallow ground-water flow occurs in



Base from U.S. Geological Survey digital data, Universal Transverse Mercator Projection, Zone 18, NAD 83.

Figure 16. Simulated potentiometric surface for drought conditions (November 1998–February 2000) in the Opequon Creek watershed area, Virginia and West Virginia.

an epikarstic zone that extends from land surface to a depth of 9 to 20 m. Most of the residential, production, and commercial wells in the study area are completed in the interval from about 25 to 100 m below land surface. Hydraulic conductivity decreases with depth in the bedrock aquifer, and ground-water flow occurs primarily in the upper 100 m of bedrock. Solutionally enlarged conduits are less pervasive at depths below about 50 m. Recharge is areally diffuse, occurring over a broad area with minimal focused recharge to sinkholes.

Geologic structure is a major control on ground-water flow. Strike-parallel thrust faults and cross-strike faults or fracture zones act as drains that funnel large quantities of water through the Opequon Creek watershed area. Poorly permeable bedrock such as the Conococheague Limestone and Martinsburg Formation, acts as a barrier to ground-water flow and retards its downgradient movement. This barrier effect causes ground water to flow laterally along bedding planes and thrust faults. Cross-strike faults and fracture zones allow ground water to flow through the less permeable units.

A three-layer steady-state numerical ground-water flow model was developed to represent the aquifer based on this conceptual understanding of ground-water flow. The epikarstic near-surface part of the aquifer was represented by the upper layer of the model, which extends from land surface to a depth of about 35 m. The intermediate zone, in which most wells are completed, was represented by the middle layer of the model, and extends from 35 to 100 m below land surface. The less fractured, deepest part of the bedrock aquifer was represented by the lower layer of the model, which extends from 100 to approximately 185 m below land surface. Areally diffuse recharge was applied to the entire model at rates (average 241 mm/yr) based on estimates of ground-water recharge provided by analyses of streamflow at three USGS streamflow-gaging stations, increasing proportionally with the percentage of carbonate rocks and (or) depth of bedrock weathering. Estimates of hydraulic conductivity were made based on results of aquifer tests conducted as part of recent fracture-trace and lineament analysis investigations in Jefferson and Berkeley Counties, West Virginia, and on results of single- and multi-well aquifer tests conducted as part of an intensive hydrogeologic investigation of the Hopewell Run watershed. Geologic mapping, conducted as part of recent and past investigations, provided the locations of faults and identified the geologic formations that crop out in the area.

Boundary conditions for the model included river (constant-head) cells along the Potomac River at the northern boundary of the model and no-flow cells representing bedrock ridges separating watersheds along the eastern and southern boundaries of the model and along North Mountain to the west. Hydraulic conductivities assigned to the model were based on geologic formations mapped in the area and on the results of aquifer tests. Faults were represented by zones of higher hydraulic conductivity to simulate conduit drains.

The model was calibrated based on recharge estimated from streamflow data collected at long-term USGS streamflow-gaging stations, results of aquifer tests, and water-level data collected over a 40-year timeframe. The model was developed as a steady-state three-dimensional simulation. Initially the model was calibrated to average hydrologic conditions based on long-term water-level and streamflow data available for the study area. Mean and median measured streamflow for the Opequon Creek near Martinsburg, W.Va., station are 604,384 and 349,907 m^3/d, respectively. The simulated base flow of 432,834 m^3/d for Opequon Creek near Martinsburg falls between the mean and median flow conditions measured for the watershed. Simulated subwatershed base-flow yield for average conditions ranged from 0 to 2,643 $m^3/d/km^2$, and was estimated to be 557 $m^3/d/km^2$ over the entire Opequon Creek watershed area.

The drought of November 1998 through February 2000 was simulated by reducing recharge in the initial model by 40 percent to values of 90, 168, and 234 mm/yr, rates that approximate the recharge during the prolonged 16-month drought. Mean and median measured streamflow for the Opequon Creek near Martinsburg streamflow-gaging station during the 16-month drought were 341,098 and 216,551 m^3/d, respectively. The simulated drought base-flow discharge for the Opequon Creek near Martinsburg station of 252,356 m^3/d falls between the mean and median streamflow measured during the 16-month drought. Recharge over the entire watershed during the simulated drought was 413 $m^3/d/km^2$, and was 388 $m^3/d/km^2$ at the Martinsburg station. Simulated subwatershed base-flow yield for drought conditions ranged from 0 to 1,865 $m^3/d/km^2$ and was 327 $m^3/d/km^2$ over the entire Opequon Creek watershed area.

Water budgets for the simulation indicate a substantial component of discharge to the Potomac River through direct ground-water discharge. This phenomenon has long been suspected but has now been quantified. During average conditions, approximately 564,176 m^3/d (6.53 m^3/s) of base flow discharges to the Potomac River. An additional 124,379 m^3/d (1.44 m^3/s) of ground water is also estimated to discharge directly to the Potomac River, and represents approximately 18 percent of the total discharge to the Potomac River.

Analyses of head equipotential lines with respect to geologic structures such as thrust and cross-strike faults illustrate that surface and ground water over a very broad area are funneled along the faults, especially where the faults are in close proximity to low-permeability bedrock such as the Conococheague Limestone and Martinsburg Formation. These structural and lithologic controls are responsible for many of the large springs in the Opequon Creek watershed area. Ground water discharges to the Potomac River through numerous strike-parallel faults or fracture zones. Although this process was suspected, it had not been fully documented. Although the simulation provides only an initial estimate of ground-water discharge to the Potomac River, it does at least indicate that this discharge is a mathematically reasonable hypothesis.

Although the water budget and potentiometric surfaces estimated by the model are reasonable, the accuracy of the model has some limitations. Therefore, water-budget information for the subwatersheds should be regarded as estimates only because of the lack of calibration data specific to the subwatersheds and the hydrologic conditions simulated. Differences between simulated and actual recharge, base-flow yields, and channel gains and losses are possible. In addition, it is difficult to accurately estimate spring discharge; therefore, the model was calibrated to base-flow stream discharge rather than spring flow.

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Appendixes

Appendix 1. Water levels and map coordinates for wells used in calibration of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.

[USGS, U.S. Geological Survey; UTM, Universal Transverse Mercator projection; m, meters; NAVD 88, North American Vertical Datum of 1988]

Report identification number	USGS local well number	UTM Easting (m)	UTM Northing (m)	Observed water level (m above NAVD 88)	Simulated water level (m above NAVD 88)
1	45W 15	224695	4332978	213.3	213.9
2	45X 2	224593	4335510	217.9	219.1
3	45X 3	219458	4339287	252.1	242.0
4	45X 6	221816	4343063	257.1	247.3
5	45X 7	224619	4343146	236.6	229.4
6	45X 8	225916	4342605	222.2	222.5
7	45X 12	221181	4336346	230.3	230.2
8	45X 13	219716	4336217	243.5	235.7
9	45X 14	220960	4339322	243.6	236.0
10	45X 15	220619	4339271	243.8	238.8
11	45X 18	223347	4342035	240.6	230.3
12	45X 19	223320	4342030	237.2	230.4
13	45X 20	223411	4342232	238.5	230.6
14	45Y 2	229466	4349961	211.5	200.4
15	45Y 3	229580	4350760	218.0	202.3
16	46W 33	230276	4329512	182.3	190.1
17	46W108	232627	4334216	184.0	183.5
18	46W178	231079	4331051	183.0	186.8
19	46W188	232038	4333216	186.6	184.4
20	46X 1	236386	4343011	164.6	171.8
21	46X 13	235636	4340011	173.0	176.6
22	46X 20	238930	4340085	177.1	180.3
23	46X 21	236139	4340673	168.2	176.0
24	46X 22	238653	4341144	177.7	177.8
25	46X 25	238724	4340370	173.7	179.5
26	46X 26	238831	4339996	184.4	180.2
27	46X 27	239647	4339969	182.9	181.6
28	46X 28	238061	4339250	179.8	180.0
29	46X 31	239984	4342149	170.7	178.2
30	46X 33	233855	4338527	192.9	173.2
31	46X 34	234088	4338303	192.6	176.3
32	46X 35	235573	4339581	170.7	177.1
33	46X 38	234242	4337897	192.0	178.4
34	46X 39	234386	4337892	186.5	178.6
35	46X 42	234086	4338242	188.4	176.5
36	46X 48	240055	4342116	169.8	178.4
37	46X 50	239955	4346318	161.5	168.1
38	46X 54	239414	4340193	181.3	181.1
39	46X 59	235176	4338483	166.1	178.3
40	46X 72	239368	4340966	186.5	179.7

Appendix 1. Water levels and map coordinates for wells used in calibration of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.—Continued

[USGS, U.S. Geological Survey; UTM, Universal Transverse Mercator projection; m, meters; NAVD 88, North American Vertical Datum of 1988]

Report identification number	USGS local well number	UTM Easting (m)	UTM Northing (m)	Observed water level (m above NAVD 88)	Simulated water level (m above NAVD 88)
41	46X 73	239318	4340906	182.6	179.7
42	46X 74	232448	4335334	182.4	182.1
43	46X 77	237295	4338627	172.4	179.5
44	46X 84	233788	4336999	196.2	180.2
45	46X 91	237449	4342481	164.3	173.7
46	46X 93	240738	4344594	174.0	173.5
47	46X 94	239081	4340296	177.8	180.3
48	46X 95	234685	4341031	157.6	171.5
49	46X 96	237839	4344104	164.9	170.4
50	46X100	240100	4342022	180.3	178.6
51	46X101	236846	4343829	166.2	170.1
52	46X103	238907	4347310	154.8	163.6
53	46X108	231491	4347699	184.0	182.0
54	46X110	230701	4347723	192.2	185.7
55	46X111	237910	4346471	155.3	163.8
56	46X112	240971	4347020	165.4	168.3
57	46X113	240978	4347006	162.7	168.3
58	46X114	234819	4341849	159.4	172.8
59	46X115	238057	4341806	170.1	175.3
60	46X118	239520	4340949	180.5	180.0
61	46X121	233477	4336833	192.4	180.4
62	46X124	240503	4338991	191.1	183.8
63	46X125	240422	4339209	189.4	183.3
64	46X126	240355	4339357	189.1	183.1
65	46X128	240870	4342900	187.6	177.2
66	46X129	240854	4344304	176.0	174.4
67	46X130	238880	4347702	150.9	162.7
68	46X132	238808	4347514	160.2	162.9
69	46X133	239665	4342877	177.5	176.2
70	46X134	236969	4338543	183.2	179.1
71	46X135	238584	4348760	146.9	159.5
72	46Y 1	230969	4353362	211.6	207.4
73	46Y 5	233390	4350082	177.0	176.9
74	Ber-0007	236829	4354726	165.8	165.4
75	Ber-0010	237837	4355464	168.2	162.7
76	Ber-0011	237454	4355477	168.5	163.5
77	Ber-0013	237292	4355668	163.4	163.4
78	Ber-0014	235593	4355756	174.0	171.0
79	Ber-0017	235678	4356155	167.3	171.4
80	Ber-0018	234003	4356273	184.1	180.5

Appendix 1. Water levels and map coordinates for wells used in calibration of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.—Continued

[USGS, U.S. Geological Survey; UTM, Universal Transverse Mercator projection; m, meters; NAVD 88, North American Vertical Datum of 1988]

Report identification number	USGS local well number	UTM Easting (m)	UTM Northing (m)	Observed water level (m above NAVD 88)	Simulated water level (m above NAVD 88)
81	Ber-0021	236367	4356656	165.8	167.9
82	Ber-0023	235243	4356756	178.6	176.7
83	Ber-0024	236178	4356755	166.1	168.6
84	Ber-0025	242194	4356677	129.2	138.5
85	Ber-0026	236408	4357180	172.8	168.1
86	Ber-0031	241141	4357453	164.9	149.2
87	Ber-0033	232783	4357735	213.0	209.3
88	Ber-0038	251504	4370931	138.0	137.0
89	Ber-0047	229814	4358548	228.0	215.4
90	Ber-0048	236809	4358401	157.6	167.4
91	Ber-0053	242560	4359783	152.1	141.1
92	Ber-0056	231262	4360227	216.7	213.0
93	Ber-0064	240996	4360298	163.4	155.1
94	Ber-0069	237633	4360781	170.4	166.1
95	Ber-0080	235092	4361484	190.5	190.5
96	Ber-0091	234181	4362164	199.6	201.1
97	Ber-0099	240020	4363386	165.2	159.0
98	Ber-0102	240200	4363751	163.7	158.4
99	Ber-0104	240083	4363817	164.3	158.9
100	Ber-0116	247580	4364526	152.4	129.7
101	Ber-0127	238563	4365627	166.4	175.3
102	Ber-0145	244112	4366862	159.1	137.0
103	Ber-0155	250057	4367070	131.7	143.8
104	Ber-0162	250206	4367250	132.3	143.7
105	Ber-0165	238154	4367709	201.2	183.4
106	Ber-0205	243228	4369824	140.8	141.8
107	Ber-0209	243305	4369976	138.1	141.9
108	Ber-0239	241214	4372577	159.4	162.1
109	Ber-0322	245133	4378960	147.2	148.0
110	Ber-0327	245134	4378991	140.5	148.1
111	Ber-0340	247169	4379820	135.6	139.3
112	Ber-0346	245659	4380425	131.4	144.9
113	Ber-0348	247382	4380492	137.8	139.6
114	Ber-0357	250347	4381260	141.4	126.2
115	Ber-0410	247205	4385313	134.1	126.5
116	Ber-0412	246968	4385352	108.5	125.5
117	Ber-0445	244200	4371706	128.7	141.7
118	Ber-0470	246970	4377387	133.9	138.2
119	Ber-0471	246853	4377484	135.3	139.3
120	Ber-0485	251505	4370950	137.9	137.0

Appendix 1. Water levels and map coordinates for wells used in calibration of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.—Continued

[USGS, U.S. Geological Survey; UTM, Universal Transverse Mercator projection; m, meters; NAVD 88, North American Vertical Datum of 1988]

Report identification number	USGS local well number	UTM Easting (m)	UTM Northing (m)	Observed water level (m above NAVD 88)	Simulated water level (m above NAVD 88)
121	Ber-0506	232079	4363749	239.9	217.6
122	Ber-0510	236224	4369411	210.1	189.0
123	Ber-0518	248089	4382382	134.0	133.4
124	Ber-0521	246386	4385834	108.3	120.2
125	Ber-0523	241966	4359926	161.7	147.0
126	Ber-0524	235236	4361480	179.6	188.9
127	Ber-0527	238483	4368254	188.9	180.3
128	Ber-0528	238903	4369351	193.2	178.3
129	Ber-0529	237375	4369464	191.9	187.0
130	Ber-0532	241164	4372517	157.6	162.5
131	Ber-0536	251883	4374018	124.8	124.5
132	Ber-0537	242028	4374772	140.2	160.7
133	Ber-0540	248965	4376983	137.8	124.8
134	Ber-0543	244205	4379114	138.7	153.9
135	Ber-0549	245325	4367347	138.0	132.5
136	Ber-0550	237794	4368401	197.4	187.0
137	Ber-0551	250740	4368221	138.3	142.6
138	Ber-0552	248697	4369460	126.8	126.9
139	Ber-0553	236510	4370080	206.2	187.5
140	Ber-0555	243937	4375937	130.7	151.1
141	Ber-0561	249716	4386867	118.9	120.2
142	Ber-0562	237702	4360717	163.2	166.0
143	Ber-0563	249070	4365435	137.9	144.7
144	Ber-0564	236996	4353270	166.7	160.0
145	Ber-0565	236996	4353270	167.6	159.9
146	Ber-0566	237587	4355164	172.7	163.1
147	Ber-0568	242269	4356767	130.8	137.4
148	Ber-0571	235313	4359532	188.8	184.0
149	Ber-0572	232515	4361110	203.8	208.1
150	Ber-0574	243920	4361775	140.9	136.9
151	Ber-0579	237237	4365394	185.9	188.5
152	Ber-0581	239028	4366661	174.7	175.3
153	Ber-0583	241125	4367764	151.2	152.4
154	Ber-0589	251747	4370765	138.1	137.3
155	Ber-0590	239765	4371483	164.5	170.1
156	Ber-0591	242133	4371435	146.2	153.4
157	Ber-0592	237842	4371949	185.4	180.6
158	Ber-0593	247047	4371705	146.0	132.3
159	Ber-0595	242646	4373208	146.5	153.7
160	Ber-0596	239087	4373389	175.2	175.1

Appendix 1. Water levels and map coordinates for wells used in calibration of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.—Continued

[USGS, U.S. Geological Survey; UTM, Universal Transverse Mercator projection; m, meters; NAVD 88, North American Vertical Datum of 1988]

Report identification number	USGS local well number	UTM Easting (m)	UTM Northing (m)	Observed water level (m above NAVD 88)	Simulated water level (m above NAVD 88)
161	Ber-0599	239834	4374969	179.7	170.4
162	Ber-0606	249662	4380047	134.6	126.0
163	Ber-0607	242487	4380653	176.6	156.3
164	Ber-0608	249755	4383656	121.4	127.1
165	Ber-0609	245963	4384582	115.4	130.0
166	Ber-0614	256195	4387863	105.2	101.8
167	Ber-0615	250163	4385186	123.9	123.9
168	Ber-0616	235440	4358324	176.5	178.4
169	Ber-0617	236163	4359843	175.0	175.0
170	Ber-0618	237429	4357577	147.9	164.6
171	Ber-0620	234704	4359954	182.0	190.1
172	Ber-0621	234660	4361468	192.2	195.6
173	Ber-0622	239218	4361592	168.0	162.1
174	Ber-0623	240496	4361858	165.2	157.7
175	Ber-0624	235327	4362742	181.2	192.6
176	Ber-0625	238727	4362689	167.5	162.8
177	Ber-0627	235611	4366159	210.5	194.9
178	Ber-0628	237635	4366523	183.2	187.8
179	Ber-0629	241275	4371556	151.8	165.1
180	Ber-0630	239534	4371738	167.1	171.7
181	Ber-0631	239534	4371738	173.2	171.7
182	Ber-0634	241886	4372647	147.2	158.4
183	Ber-0639	247807	4382515	146.9	135.1
184	Ber-0651	240363	4369187	169.4	171.1
185	Ber-0652	252754	4375615	127.6	117.4
186	Ber-0653	237285	4356967	159.8	164.4
187	Ber-0654	242402	4375297	154.5	158.5
188	Ber-0656	249833	4387373	113.0	115.7
189	Ber-0657	241926	4369701	140.3	151.0
190	Ber-0658	237310	4365001	193.0	186.7
191	Ber-0661	250155	4381566	141.1	126.9
192	Ber-0662	245796	4385860	123.1	123.4
193	Ber-0663	237366	4356819	151.6	163.7
194	Ber-0664	237115	4356986	166.4	165.5
195	Ber-0665	248310	4386186	117.6	121.5
196	Ber-0666	248283	4386058	120.1	122.7
197	Ber-0667	242617	4375284	149.3	157.6
198	Ber-0669	250713	4386464	126.5	118.3
199	Ber-0670	249804	4387138	115.1	118.1
200	Ber-0671	242158	4374146	161.7	160.0

Appendix 1. Water levels and map coordinates for wells used in calibration of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.—Continued

[USGS, U.S. Geological Survey; UTM, Universal Transverse Mercator projection; m, meters; NAVD 88, North American Vertical Datum of 1988]

Report identification number	USGS local well number	UTM Easting (m)	UTM Northing (m)	Observed water level (m above NAVD 88)	Simulated water level (m above NAVD 88)
201	Ber-0674	251985	4386275	136.8	115.9
202	Ber-0676	249585	4387161	116.4	117.5
203	Ber-0681	251016	4386435	104.9	117.6
204	Ber-0684	251731	4372978	125.7	129.4
205	Ber-0685	252002	4375325	139.6	118.8
206	Ber-0686	242528	4372748	140.9	153.8
207	Ber-0687	247574	4378471	129.8	133.9
208	Ber-0688	244296	4382356	141.4	144.2
209	Ber-0689	239649	4372211	165.3	170.5
210	Ber-0690	247614	4378467	125.2	133.5
211	Ber-0691	242650	4373003	141.4	153.3
212	Ber-0692	242628	4372973	142.4	153.4
213	Ber-0693	248390	4379812	117.1	130.4
214	Ber-0696	241952	4372384	158.9	158.6
215	Ber-0698	248711	4387461	127.9	114.2
216	Ber-0699	248696	4386804	115.8	118.5
217	Ber-0700	249732	4387179	109.9	117.3
218	Ber-0702	251348	4375800	134.1	114.5
219	Ber-0703	240203	4367101	162.7	161.9
220	Ber-0704	250982	4386643	106.6	116.3
221	Ber-0705	236322	4358956	190.9	169.9
222	Ber-0707	242497	4372535	148.4	153.7
223	Ber-0709	250318	4386941	99.6	117.1
224	Ber-0710	248539	4379811	112.3	129.4
225	Ber-0711	245906	4385970	116.2	122.0
226	Ber-0712	251488	4370953	138.5	136.9
227	Ber-0713	245735	4385939	122.0	123.5
228	Ber-0714	245528	4385964	129.3	124.4
229	Ber-0715	246409	4385852	123.7	119.8
230	Ber-0716	246323	4386077	108.1	118.4
231	Ber-0718	251728	4370285	146.0	139.2
232	Ber-0719	249279	4374046	100.2	111.6
233	Ber-0720	243228	4377755	166.9	159.4
234	Ber-0721	249301	4373993	108.7	111.6
235	Ber-0722	246158	4382146	131.7	137.8
236	Ber-0729	251466	4370929	138.7	137.0
237	Ber-0730	238532	4357509	145.6	162.2
238	Ber-0732	237472	4364901	180.5	184.8
239	Ber-0733	233456	4356885	182.4	191.3
240	Ber-0735	239997	4372124	167.1	167.5

Appendix 1. Water levels and map coordinates for wells used in calibration of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.—Continued

[USGS, U.S. Geological Survey; UTM, Universal Transverse Mercator projection; m, meters; NAVD 88, North American Vertical Datum of 1988]

Report identification number	USGS local well number	UTM Easting (m)	UTM Northing (m)	Observed water level (m above NAVD 88)	Simulated water level (m above NAVD 88)
241	Ber-0737	238152	4367882	201.0	183.7
242	Ber-0738	237982	4369361	199.5	186.0
243	Ber-0739	239463	4370190	178.6	173.9
244	Ber-0740	238478	4372206	178.0	178.5
245	Ber-0741	238377	4372400	178.5	178.5
246	Ber-0743	245024	4380075	141.6	149.0
247	Ber-0744	245561	4380712	131.3	145.0
248	Ber-0745	247247	4379129	141.5	137.7
249	Ber-0746	247458	4374102	146.2	132.2
250	Ber-0747	244815	4377736	151.0	147.7
251	Ber-0748	238953	4366191	182.2	173.5
252	Ber-0749	235093	4365924	215.8	197.5
253	Ber-0750	247367	4380542	142.3	139.6
254	Ber-0751	246808	4380776	152.8	140.7
255	Ber-0752	241841	4362443	165.7	150.0
256	Ber-0753	232430	4358300	224.0	212.0
257	Ber-0754	234561	4365078	223.2	200.7
258	Ber-0755	234232	4364928	222.6	201.0
259	Ber-0756	237947	4365123	185.6	181.2
260	Ber-0757	240360	4374241	178.0	168.5
261	Ber-0758	239458	4374457	190.6	172.5
262	Ber-0759	233479	4359162	204.4	204.3
263	Ber-0760	247946	4386771	116.7	111.3
264	Ber-0761	248032	4387231	122.1	112.1
265	Ber-0762	239959	4368263	162.5	172.0
266	Ber-0764	240282	4369058	158.7	170.9
267	Ber-0766	250833	4385226	131.5	122.6
268	Ber-0767	249845	4382967	117.9	127.3
269	Ber-0768	249851	4383010	118.4	127.3
270	Ber-0769	245293	4384694	131.6	130.8
271	Ber-0770	245187	4384382	131.3	131.7
272	Ber-0771	245040	4384782	132.6	131.8
273	Ber-0772	242564	4372961	146.2	153.9
274	Ber-0773	241654	4369000	165.7	151.1
275	Ber-0774	248187	4380397	143.4	134.5
276	Ber-0775	248159	4380411	135.7	134.7
277	Ber-0778	252098	4375798	136.8	117.1
278	Ber-0779	246026	4368723	119.3	129.2
279	Ber-0781	247239	4380790	145.7	139.6
280	Ber-0782	251483	4370941	138.5	137.0

Appendix 1. Water levels and map coordinates for wells used in calibration of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.—Continued

[USGS, U.S. Geological Survey; UTM, Universal Transverse Mercator projection; m, meters; NAVD 88, North American Vertical Datum of 1988]

Report identification number	USGS local well number	UTM Easting (m)	UTM Northing (m)	Observed water level (m above NAVD 88)	Simulated water level (m above NAVD 88)
281	Ber-0788	245188	4384703	130.6	131.1
282	Ber-0792	251865	4371589	138.7	135.9
283	Ber-0793	251815	4372573	136.3	131.6
284	Ber-0794	251661	4372831	117.3	130.0
285	Ber-0795	251739	4373078	140.9	128.9
286	Ber-0796	250477	4368561	142.1	141.8
287	Ber-0797	251900	4374027	134.1	124.5
288	Ber-0798	253181	4379145	120.0	104.1
289	Ber-0799	249262	4383092	131.2	129.1
290	Ber-0801	250409	4368825	144.4	141.3
291	Ber-0802	251862	4368999	142.4	143.2
292	Ber-0803	253306	4375408	131.2	119.5
293	Ber-0804	251973	4372935	136.4	130.2
294	Ber-0805	242439	4374360	151.3	158.7
295	Ber-0807	251586	4367177	149.8	144.7
296	Ber-0808	251738	4367761	148.0	144.9
297	Ber-0812	252206	4372996	139.9	130.3
298	Ber-0813	252023	4373619	137.9	126.7
299	Ber-0814	247469	4385132	125.8	127.9
300	Ber-0817	234040	4355099	187.7	178.8
301	Ber-0818	241856	4371666	159.1	158.8
302	Ber-0827	235013	4365144	219.0	198.4
303	Ber-0833	243908	4361257	122.0	137.8
304	Ber-0834	241986	4371973	149.9	157.8
305	Ber-0835	246886	4380733	152.1	140.8
306	Ber-0836	234648	4361401	191.7	195.8
307	Ber-0837	247340	4385055	123.9	128.0
308	Ber-0840	236550	4356986	166.1	167.6
309	Ber-0841	237311	4365009	177.4	186.7
310	Ber-0843	249472	4365351	140.0	145.6
311	Ber-0846	247334	4385088	121.3	127.9
312	Jef-0075	242471	4347623	168.5	169.1
313	Jef-0091	243234	4348216	171.0	168.5
314	Jef-0122	244321	4349878	183.5	167.8
315	Jef-0138	243888	4350602	161.5	166.4
316	Jef-0145	239830	4351230	136.8	156.5
317	Jef-0154	243746	4351378	165.5	164.7
318	Jef-0155	242452	4351421	177.4	163.0
319	Jef-0161	241156	4352143	140.5	157.0
320	Jef-0176	242361	4353029	151.8	158.9

Appendix 1. Water levels and map coordinates for wells used in calibration of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.—Continued

[USGS, U.S. Geological Survey; UTM, Universal Transverse Mercator projection; m, meters; NAVD 88, North American Vertical Datum of 1988]

Report identification number	USGS local well number	UTM Easting (m)	UTM Northing (m)	Observed water level (m above NAVD 88)	Simulated water level (m above NAVD 88)
321	Jef-0186	245249	4353305	157.3	161.3
322	Jef-0206	240834	4354006	133.5	153.4
323	Jef-0211	246230	4353983	159.7	161.2
324	Jef-0226	243537	4354503	166.7	157.1
325	Jef-0237	243983	4354951	167.0	157.4
326	Jef-0238	243959	4354952	159.1	157.3
327	Jef-0246	246245	4355186	160.0	159.4
328	Jef-0251	245467	4355582	156.7	158.8
329	Jef-0259	248048	4356053	157.6	162.8
330	Jef-0279	245595	4357306	153.0	157.0
331	Jef-0281	248861	4357478	165.2	166.1
332	Jef-0290	249335	4358049	163.7	168.3
333	Jef-0291	248286	4358237	151.8	160.5
334	Jef-0293	246159	4358430	169.8	154.0
335	Jef-0298	250816	4358650	167.0	174.9
336	Jef-0299	247823	4358746	150.6	154.8
337	Jef-0304	244571	4358976	131.4	142.3
338	Jef-0307	246585	4359002	152.1	152.3
339	Jef-0320	247594	4359803	134.7	150.8
340	Jef-0321	245870	4359859	159.7	144.7
341	Jef-0322	247596	4359865	134.4	150.6
342	Jef-0323	247559	4360205	140.4	149.9
343	Jef-0326	245923	4360012	156.7	144.2
344	Jef-0336	251132	4360276	169.2	169.6
345	Jef-0340	249510	4360513	150.9	159.9
346	Jef-0360	247257	4361975	137.2	142.7
347	Jef-0368	249231	4362250	142.0	151.1
348	Jef-0378	250829	4362785	155.7	158.9
349	Jef-0380	247773	4363100	155.7	138.2
350	Jef-0391	250755	4364208	154.2	152.6
351	Jef-0393	250879	4364358	147.2	152.4
352	Jef-0397	249695	4364767	139.9	146.3
353	Jef-0401	250066	4365125	146.9	146.5
354	Jef-0403	251244	4365272	143.2	149.9
355	Jef-0526	247547	4359835	139.5	150.6
356	Jef-0564	252019	4375279	120.2	118.9
357	Jef-0579	246350	4355386	158.4	159.2
358	Jef-0581	247603	4360238	144.9	149.9
359	Jef-0582	243782	4347348	189.6	168.9
360	Jef-0584	247564	4359758	139.7	150.9

Appendix 1. Water levels and map coordinates for wells used in calibration of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.—Continued

[USGS, U.S. Geological Survey; UTM, Universal Transverse Mercator projection; m, meters; NAVD 88, North American Vertical Datum of 1988]

Report identification number	USGS local well number	UTM Easting (m)	UTM Northing (m)	Observed water level (m above NAVD 88)	Simulated water level (m above NAVD 88)
361	Jef-0585	248616	4360202	150.7	154.5
362	Jef-0586	247686	4360272	138.8	150.0
363	Jef-0587	248275	4360321	148.6	151.3
364	Jef-0588	249126	4360034	151.9	160.0
365	Jef-0589	248972	4360117	151.6	158.2
366	Jef-0590	247505	4359735	139.8	150.9
367	Jef-0591	247524	4359778	139.6	150.7
368	Jef-0592	248623	4360190	150.7	154.6
369	Jef-0593	248026	4359011	149.4	155.3
370	Jef-0594	247810	4359003	148.5	154.1
371	Jef-0595	247505	4359732	139.8	150.9
372	Jef-0596	248275	4360324	148.6	151.6
373	Jef-0597	248616	4360196	150.7	154.8
374	Jef-0598	248972	4360117	151.6	158.6
375	Jef-0599	247686	4360269	138.9	150.1
376	Jef-0600	249126	4360034	151.9	160.0
377	Jef-0601	248611	4360190	150.6	154.5
378	Jef-0602	249067	4359391	152.7	162.5
379	Jef-0603	247557	4360289	137.8	149.7
380	Jef-0604	251156	4360293	160.4	168.8
381	Jef-0606	248295	4358589	154.4	159.4
382	Jef-0612	244966	4354345	148.6	159.8
383	Jef-0614	242938	4347596	172.0	169.1
384	Jef-0622	249030	4358220	160.5	165.7
385	Jef-0623	248876	4360330	152.9	156.6
386	Jef-0626	247869	4360976	140.5	149.4
387	Jef-0627	248559	4360442	156.2	152.6
388	Jef-0629	246898	4359344	140.6	151.3
389	Jef-0630	249177	4358804	158.7	164.7
390	Jef-0632	242912	4347967	172.6	168.7
391	Jef-0635	250871	4362225	161.8	159.6
392	Jef-0637	246933	4359300	151.4	151.6
393	Jef-0638	250691	4363253	153.4	157.2
394	Jef-0639	248696	4360536	153.1	153.2
395	Jef-0641	240358	4354330	164.6	148.1
396	Jef-0643	247406	4359102	148.6	152.7
397	Jef-0644	248472	4358352	165.0	161.8
398	Jef-0645	248608	4360415	152.5	153.1
399	Jef-0650	249537	4360296	152.1	161.1
400	Jef-0651	247250	4359456	147.6	151.2

Appendix 1. Water levels and map coordinates for wells used in calibration of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.—Continued

[USGS, U.S. Geological Survey; UTM, Universal Transverse Mercator projection; m, meters; NAVD 88, North American Vertical Datum of 1988]

Report identification number	USGS local well number	UTM Easting (m)	UTM Northing (m)	Observed water level (m above NAVD 88)	Simulated water level (m above NAVD 88)
401	Jef-0652	248524	4360412	151.4	152.5
402	Jef-0655	244172	4359100	121.9	138.7
403	Jef-0656	247198	4360301	136.4	148.8
404	Jef-0657	248790	4359814	152.0	158.6
405	Jef-0658	248783	4359508	151.6	160.0
406	Jef-0660	249604	4359929	155.6	163.1
407	Jef-0665	249155	4358657	159.7	165.2
408	Jef-0666	249331	4358602	163.5	166.7
409	Jef-0667	249132	4358704	153.3	164.7
410	Jef-0669	249517	4358471	167.4	168.5
411	Jef-0670	249519	4358474	167.0	168.5
412	Jef-0671	249066	4358137	162.5	166.2
413	Jef-0673	249419	4358534	165.0	167.6
414	Jef-0674	249131	4358698	156.2	164.8
415	Jef-0675	249037	4358234	161.6	165.7
416	Jef-0679	248361	4358757	152.6	159.4
417	Jef-0681	249005	4358158	159.0	165.5
418	Jef-0683	247427	4360555	144.6	148.8
419	Jef-0684	248361	4360923	149.9	150.2
420	Jef-0690	248151	4360711	146.6	150.1
421	Jef-0691	247476	4358915	141.8	153.3
422	Jef-0692	248361	4359436	150.0	156.6
423	Jef-0694	249067	4358653	154.7	164.5
424	Jef-0695	243819	4356596	148.0	152.6
425	Jef-0696	248336	4361545	151.5	149.0
426	Jef-0697	247942	4360718	146.3	149.8
427	Jef-0700	249423	4358552	164.6	167.5
428	Jef-0701	249125	4358077	163.1	166.8
429	Jef-0702	249473	4358063	169.0	169.1
430	Jef-0703	249498	4358067	159.0	169.3
431	Jef-0738	241538	4351439	167.0	160.5
432	Jef-0739	241062	4351544	148.7	158.6
433	Jef-0741	242726	4350436	164.9	165.0
434	Jef-0744	247495	4359936	134.3	150.2
435	Jef-0746	243268	4350326	163.4	165.9
436	Jef-0747	244496	4352820	164.5	162.6
437	Jef-0749	244594	4352937	159.1	162.3
438	Jef-0755	247389	4359766	138.7	150.2
439	Jef-0756	247433	4359852	139.0	150.4
440	Jef-0763	245819	4359821	160.8	144.5

Appendix 1. Water levels and map coordinates for wells used in calibration of the ground-water flow model of the Opequon Creek watershed area, Virginia and West Virginia.—Continued

[USGS, U.S. Geological Survey; UTM, Universal Transverse Mercator projection; m, meters; NAVD 88, North American Vertical Datum of 1988]

Report identification number	USGS local well number	UTM Easting (m)	UTM Northing (m)	Observed water level (m above NAVD 88)	Simulated water level (m above NAVD 88)
441	Jef-0764	245238	4359210	142.1	144.6
442	Jef-0765	245258	4358573	168.1	149.2
443	Jef-0766	245062	4358889	129.7	145.9
444	Jef-0767	246340	4358909	164.8	152.3
445	Jef-0768	244517	4356758	169.3	155.1
446	Jef-0769	244315	4356653	160.0	154.5
447	Jef-0770	244046	4356480	149.3	153.8
448	Jef-0771	244197	4356556	151.7	154.3
449	Jef-0772	244243	4356579	147.7	154.4
450	Jef-0773	243735	4356139	136.2	153.7
451	Jef-0774	243216	4355974	135.0	152.6
452	Jef-0775	243231	4355467	135.7	154.4
453	Jef-0776	246816	4358640	147.0	153.5
454	Jef-0777	246960	4359179	141.3	151.9
455	Jef-0778	246889	4359338	141.8	151.4
456	Jef-0779	247769	4354930	163.8	163.7
457	Jef-0780	247863	4355158	163.3	163.9
458	Jef-0781	248741	4356963	164.6	165.7
459	Jef-0782	248288	4356965	159.2	162.7
460	Jef-0783	248130	4356751	159.2	162.2
461	Jef-0784	247988	4356194	160.6	162.4
462	Jef-0785	248043	4356050	160.6	162.8
463	Jef-0786	245751	4355758	156.1	158.6
464	Jef-0787	243279	4357453	137.2	145.3
465	Jef-0788	243517	4357544	138.2	146.5
466	Jef-0789	243435	4358034	135.9	142.7
467	Jef-0790	244005	4359257	122.9	136.3
468	Jef-0791	244306	4359077	123.2	139.7
469	Jef-0792	247580	4360050	161.0	150.1
470	Jef-0793	247540	4360002	137.7	150.1

Appendix 2. Data for springs in the Opequon Creek watershed area, Virginia and West Virginia.

[UTM, Universal Transverse Mercator projection; NGVD 29, National Geodetic Vertical Datum of 1929; m^3/d, cubic meters per day; na, no data available]

USGS local well number	UTM Zone 18 easting (meters)	UTM Zone 18 northing (meters)	Altitude of land surface (meters above NGVD 29)	Spring discharge[1] (m^3/d)	Spring name	Geologic formation
45WS 1	229114	4329777	198	na	unnamed spring	Martinsburg Formation
45WS 2	222994	4333801	213	327	Springdale Farm Spring	Middle Ordovician Limestones
45YS 1	230151	4355631	229	na	unnamed spring	Elbrook Formation
46WS 32	231893	4333238	178	768	unnamed spring	Middle Ordovician Limestones
46WS 40	231117	4331993	177	337	unnamed spring	Rockdale Run/Pinesburg Station
46XS 1	237673	4348431	140	2,152	Wadesville Spring	Middle Ordovician Limestones
46XS 6	237258	4346099	165	na	Louise Eden's Spring	Rockdale Run/Pinesburg Station
46XS 7	235062	4342453	154	8,807	Afflick Spring	Middle Ordovician Limestones
46XS 8	238753	4340523	177	2,709	Perry Spring	Rockdale Run/Pinesburg Station
46XS 9	233410	4335838	180	1,673	unnamed spring	Rockdale Run/Pinesburg Station
46XS 10	231358	4347776	186	232	O. L. Payne Spring	Rockdale Run/Pinesburg Station
46YS 1	233704	4351520	186	4,960	Branson Spring	Rockdale Run/Pinesburg Station
Ber-0019S	237342	4356438	149	5	Crim Spring	Middle Ordovician Limestones
Ber-0032S	237740	4357567	143	12,808	Boiling Spring (Dove Spring)	Chambersburg Limestone
Ber-0036S	233051	4357881	210	2,861	Porter Farm Spring	Conocheague Formation
Ber-0037S	237651	4357786	148	na	Lemon spring	Middle Ordovician Limestones
Ber-0039S	236389	4358014	169	12,012	Lefevre Spring	Rockdale Run/Pinesburg Station
Ber-0042S	232295	4358184	226	291	Cool Spring	Conocheague Formation
Ber-0043S	237304	4358137	162	436	unnamed spring at Bunker Hill	Rockdale Run/Pinesburg Station
Ber-0045S	236876	4358244	171	436	Gum Spring	Rockdale Run/Pinesburg Station
Ber-0050S	239742	4358642	155	3	Boyer Farm Spring	Martinsburg Formation
Ber-0055S	235298	4360490	186	109	Lee Whitacre Farm Spring	Elbrook Formation
Ber-0065S	234275	4360710	194	1,199	Springvale Farm Spring	Elbrook Formation
Ber-0083S	233424	4361758	207	218	unnamed spring at Gerardstown	Elbrook Formation
Ber-0084S	234297	4362067	195	327	Peerless Orchard Farm Spring	Elbrook Formation
Ber-0085S	233841	4362052	195	436	Douglas Miller Farm Spring	Elbrook Formation
Ber-0089S	234171	4362566	212	2,916	Carter Spring	Elbrook Formation
Ber-0092S	233367	4362192	207	436	Grey Spring	Elbrook Formation
Ber-0114S	248704	4364490	128	4,998	Shaw Spring	Martinsburg Formation
Ber-0118S	248140	4364817	122	109	Van Metre Spring	Martinsburg Formation Formation
Ber-0125S	243560	4365368	158	16	Shade Spring	Martinsburg Formation
Ber-0175S	243502	4367963	163	10,900	unnamed spring	Middle Ordovician Limestones
Ber-0177S	242916	4368353	146	5,450	Big Spring and Snodgras Spring	Rockdale Run/Pinesburg Station
Ber-0181S	243511	4368240	143	5,450	unnamed spring	Middle Ordovician Limestones
Ber-0185S	251848	4368432	146	709	Dailey Spring	Stonehenge Limestone
Ber-0187S	238630	4369052	195	327	Griffith Spring	Elbrook Formation
Ber-0202S	250044	4369663	136	2,316	Couchman Spring	Martinsburg Formation
Ber-0216S	248611	4370481	116	1,722	Blairton Spring	Middle Ordovician Limestones
Ber-0221S	245254	4371023	122	7,467	Martinsburg Spring	Middle Ordovician Limestones
Ber-0246S	239180	4373293	174	1,384	D. T. Burkhart Spring	Elbrook Formation
Ber-0251S	243365	4373246	146	15,805	Kilmer Springs	Conococheague
Ber-0252S	252515	4372825	140	545	Swan Pond Spring	Stonehenge Limestone

Appendix 2. Data for springs in the Opequon Creek watershed area, Virginia and West Virginia.—Continued

[UTM, Universal Transverse Mercator projection; NGVD 29, National Geodetic Vertical Datum of 1929; m^3/d, cubic meters per day; na, no data available]

USGS local well number	UTM Zone 18 easting (meters)	UTM Zone 18 northing (meters)	Altitude of land surface (meters above NGVD 29)	Spring discharge[1] (m^3/d)	Spring name	Geologic formation
Ber-0329S	248266	4379012	122	12,966	Dennis Farm Spring	Rockdale Run/Pinesburg Station
Ber-0354S	244080	4381094	152	55	Fort Hill Spring	Elbrook Formation
Ber-0359S	246115	4381922	133	17,440	Harlan Spring	Conococheague
Ber-0362S	246117	4381984	131	na	G. Taylor Spring	Conococheague
Ber-0363S	244205	4381985	143	2,262	Speck Spring	Elbrook Formation
Ber-0376S	246199	4383031	126	1,717	Spring Mills Spring	Elbrook Formation
Ber-0384S	244525	4382993	143	545	Will Ellis Farm spring	Elbrook Formation
Ber-0386S	251548	4382950	113	10,900	Falling Waters Spring	Middle Ordovician Limestones
Ber-0461S	239723	4363088	158	545	McDonald Spring	Rockdale Run/Pinesburg Station
Ber-0482S	234233	4360896	194	948	Isherwood Spring	Elbrook Formation
Ber-0509S	236201	4366602	198	2,725	Arqua Spring	Elbrook Formation
Ber-0512S	251722	4371214	125	na	Dunn Spring	Stonehenge Limestone
Ber-0533S	241164	4372517	158	818	Olean Spring at Old Schoolhouse	Elbrook Formation
Ber-0542S	250931	4378617	104	540	unnamed spring at Bedington	Middle Ordovician Limestones
Ber-0586S	242891	4368323	146	1,499	Snodgras Spring	Rockdale Run/Pinesburg Station
Ber-0600S	239740	4375003	186	397	Kushwa Spring	Elbrook Formation
Ber-0601S	240955	4376290	177	545	Butler Brothers Spring	Elbrook Formation
Ber-0626S	236896	4363800	181	818	Pitzer Spring	Conocheague Formation
Ber-0632S	241138	4372456	158	1,090	Olean Spring along Tuscarora Creek	Elbrook Formation
Ber-0633S	239037	4373329	177	na	unnamed spring near Nollville	Rockdale Run/Pinesburg Station
Ber-0635S	235447	4359929	183	na	Ignatious Spring	Elbrook Formation
Ber-0636S	242917	4368384	146	1,499	Big Spring	Rockdale Run/Pinesburg Station
Ber-0637S	250855	4378496	104	3	Porterfield Sulphur Spring	Martinsburg Formation
Ber-0638S	250784	4378498	104	3	Porterfield Limestone Spring	Chambersburg Limestone
01616075	229665	4344206	190	3,739	Fay Spring near Winchester	Middle Ordovician Limestones
Jef-0146S	239399	4351244	146	1,635	Russell Farm Spring	Rockdale Run/Pinesburg Station
Jef-0213S	241344	4354174	134	5,559	Capper Farm spring	Middle Ordovician Limestones
Jef-0218S	244009	4354271	152	24,525	Turkey Run Spring	Rockdale Run/Pinesburg Station
Jef-0219SS	240487	4354388	140	35,425	R. Goodsell (Priest Field Spring)	Middle Ordovician Limestones
Jef-0223S	241519	4354415	146	na	Schlack Farm Spring	Middle Ordovician Limestones
Jef-0306S	249218	4358967	158	4,142	Springdale Farm Spring (Bell Spring)	Stonehenge Limestone
Jef-0327S	247457	4360024	140	2,453	Balch Spring	Middle Ordovician Limestones
Jef-0333S	247417	4360272	140	3,706	unnamed spring	Middle Ordovician Limestones
Jef-0385S	250090	4363643	152	4,578	General Gates Farm Spring	Conococheague
Jef-0488S	247582	4359433	145	25	wet weather spring	Stonehenge Limestone
Jef-0521S	247613	4359207	146	3,913	Gray Spring at Leetown	Stonehenge Limestone
Jef-0659S	247563	4359363	146	1,363	Blue Spring	Stonehenge Limestone
Jef-0754S	250046	4359452	169	1,639	Link Spring	Conocheague Formation
Jef-0757S	248058	4359553	151	1,045	Tabb Spring	Stonehenge Limestone
01615515	225660	4342422	227	1,248	Old Town Spring at Winchester	Conococheague
01615522	226991	4340215	198	9,892	Rouss Spring at Winchester	Rockdale Run/Pinesburg Station

[1] Average (mean) discharge is presented for sites with more than one measured discharge.

For additional information, write to:
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