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Geohydrology of the French Creek Basin and Simulated Effects of Drought and Ground-Water Withdrawals, Chester County, Pennsylvania

by Ronald A. Sloto

Water-Resources Investigations Report 03-4263

In cooperation with the
DELAWARE RIVER BASIN COMMISSION

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CONVERSION FACTORS AND DATUMS

Multiply	By	To obtain
	Length	
inch (in)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
gallon (gal)	0.003785	cubic meter
million gallons (Mgal)	3,785	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer
gallon per minute (gal/min)	0.06309	liter per second
gallon per day (gal/d)	0.003785	cubic meter per day
gallon per day per square mile [$(gal/d)/mi^2$]	0.001461	cubic meter per day per square kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
million gallons per year (Mgal/yr)	15.991	cubic meter per year
million gallons per day per square mile [$(Mgal/d)/mi^2$]	1,461	cubic meter per day per square kilometer
inch per year (in/yr)	25.4	millimeter per year
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).
Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

GEOHYDROLOGY OF THE FRENCH CREEK BASIN AND SIMULATED EFFECTS OF DROUGHT AND GROUND-WATER WITHDRAWALS, CHESTER COUNTY, PENNSYLVANIA

by Ronald A. Sloto

ABSTRACT

This report describes the results of a study by the U.S. Geological Survey, in cooperation with the Delaware River Basin Commission, to develop a regional ground-water-flow model of the French Creek Basin in Chester County, Pa. The model was used to assist water-resource managers by illustrating the interconnection between ground-water and surface-water systems. The 70.7-mi^2 (square mile) French Creek Basin is in the Piedmont Physiographic Province and is underlain by crystalline and sedimentary fractured-rock aquifers. Annual water budgets were calculated for 1969-2001 for the French Creek Basin upstream of streamflow-measurement station French Creek near Phoenixville (01472157). Average annual precipitation was 46.28 in. (inches), average annual streamflow was 20.29 in., average annual base flow determined by hydrograph separation was 12.42 in., and estimated average annual ET (evapotranspiration) was 26.10 in. Estimated average annual recharge was 14.32 in. and is equal to 31 percent of the average annual precipitation. Base flow made up an average of 61 percent of streamflow.

Ground-water flow in the French Creek Basin was simulated using the finite-difference MODFLOW-96 computer program. The model structure is based on a simplified two-dimensional conceptualization of the ground-water-flow system. The modeled area was extended outside the French Creek Basin to natural hydrologic boundaries; the modeled area includes 40 mi^2 of adjacent areas outside the basin. The hydraulic conductivity for each geologic unit was calculated from reported specific-capacity data determined from aquifer tests and was adjusted during model calibration. The model was calibrated for above-average conditions by simulating base-flow and water-level measurements made on May 1, 2001, using a recharge rate of 20 in/yr (inches per year). The model was calibrated for below-average conditions by simulating base-flow and water-level measurements made on September 11 and 17, 2001, using a recharge rate of 6.2 in/yr. Average conditions were simulated by adjusting the recharge rate until simulated streamflow at streamflow-measurement station 01472157 matched the long-term (1968-2001) average base flow of 54.1 cubic feet per second. The recharge rate used for average conditions was 15.7 in/yr.

The effect of drought in the French Creek Basin was simulated using a drought year recharge rate of 8 in/yr for 3 months. After 3 months of drought, the simulated streamflow of French Creek at streamflow-measurement station 01472157 decreased 34 percent. The simulations show that after 6 months of average recharge (15.7 in/yr) following drought, streamflow and water levels recovered almost to pre-drought conditions.

The effect of increased ground-water withdrawals on stream base flow in the South Branch French Creek Subbasin was simulated under average and drought conditions with pumping rates equal to 50, 75, and 100 percent of the Delaware River Basin Commission Ground Water Protected Area (GWPA) withdrawal limit (1,393 million gallons per year) with all pumped water removed from the basin. For average recharge conditions, the simulated streamflow of South Branch French Creek at the mouth decreased 18, 28, and 37 percent at a withdrawal rate equal to 50, 75, and 100 percent of the GWPA limit, respectively. After 3 months of drought recharge conditions, the simulated streamflow of South Branch French Creek at the mouth decreased 27, 40, and 52 percent at a withdrawal rate equal to 50, 75, and 100 percent of the GWPA limit, respectively.

The effect of well location on base flow, water levels, and the sources of water to the well was simulated by locating a hypothetical well pumping 200 gallons per minute in different places in the Beaver Run Subbasin with all pumped water removed from the basin. The smallest reduction in the base flow of Beaver Run was from a well on the drainage divide between the French Creek Basin and the Marsh Creek Basin to the south; the simulated base flow of Beaver Run at the mouth was

reduced 1 percent. The greatest reduction in the base flow of Beaver Creek was from a well close to Beaver Run; the simulated base flow of Beaver Run at the mouth was reduced 8 percent. The simulations showed that (1) if the contributing area of a well is in a basin, pumping will affect stream base flow and water levels in that basin whether the well is inside or outside that basin; (2) wells in different areas of a basin away from a divide produce a similar reduction in base flow; (3) a well within a basin will derive more water from diverted base flow and less water from storage than a well on or near a basin divide; and (4) the reduction in base flow at the mouth of the stream is the same for a well in the headwaters and a well downstream near the confluence.

Model simulations illustrate some of the typical analyses and results that can be produced. The model was calibrated using annual values for recharge and ground-water ET and then was run using the annual values in a seasonally independent transient mode to show changes with time. The timing and relative magnitude of some of the changes simulated with the model when viewed in terms of a normal climatic year may be subject to considerable uncertainty because of the variability in seasonal recharge and ground-water ET rates. Transient model simulations for short-term periods are indicative of possible hydrologic system response and are considered an approximation.

INTRODUCTION

The Delaware River Basin is a 13,500-mi^2 watershed in Delaware, New Jersey, New York, and Pennsylvania. The Delaware River Basin Commission (DRBC) is a Federal/interstate agency with regulatory authority over water resources in the basin. The DRBC reviews water-resource projects and issues permits for withdrawals of surface and ground water. In response to concerns over increasing use of ground water in an area with a limited ground-water resource, the DRBC in 1980 established the Southeastern Pennsylvania Ground Water Protected Area (GWPA), which covers about 1,250 mi^2. Special regulations were issued by the DRBC for the GWPA to provide for the effective management of ground-water resources, to protect the rights of present and future water users, and to acquire additional information to more accurately plan and manage water resources (Delaware River Basin Commission, 1999). As demand for use of limited water resources increases in the future, water allocations may be subject to conjunctive use and conservation requirements established in the GWPA. The permitting process will become more involved at that point, requiring analyses of the combined effects of withdrawals on surface and ground water.

The effects of pumping ground water on ground-water availability and streamflow during low-flow (drought) conditions in the GWPA have not been quantified; hence, management decisions can be based only on simple comparisons between pumping rates and estimated base flow. Questions such as the effect of ground-water pumping and drought on the hydrologic system cannot be adequately addressed. Furthermore, the effect of expected increases in ground-water pumping cannot be determined using available information.

The objective of this study was to develop a regional numerical model of ground-water flow for the French Creek Basin in Chester County, Pa., to use as a tool to evaluate interactions between the ground-water and surface-water system. The model was used to illustrate ground-water/surface-water interactions by simulating stress on the ground-water system. The French Creek Basin, located in the GWPA (fig. 1), is typical of many rural areas of southeastern Pennsylvania that are undergoing a rapid population increase. New development and an expanding population increase consumptive ground-water use and have the potential to reduce ground-water levels and stream base flow.

This study was done by the U.S. Geological Survey (USGS) in cooperation with the DRBC. This study provides information that will allow water-resource-management decisions to be based on an objective quantitative understanding of the ground-water-flow system and simulated effects of drought and current and potential future pumping on the ground-water and surface-water systems.

Purpose and Scope

This report describes the geology and ground-water-flow system of the French Creek Basin in Chester and Berks Counties, Pa. Water budgets and recharge estimates for the French Creek Basin for calendar years 1969-2001 are presented. This report presents the results of numerical simulation of ground-water flow in the French Creek Basin. The model domain includes areas outside the French Creek Basin. Model calibration and sensitivity are described. The model was used to evaluate the effects of drought on stream base flow and

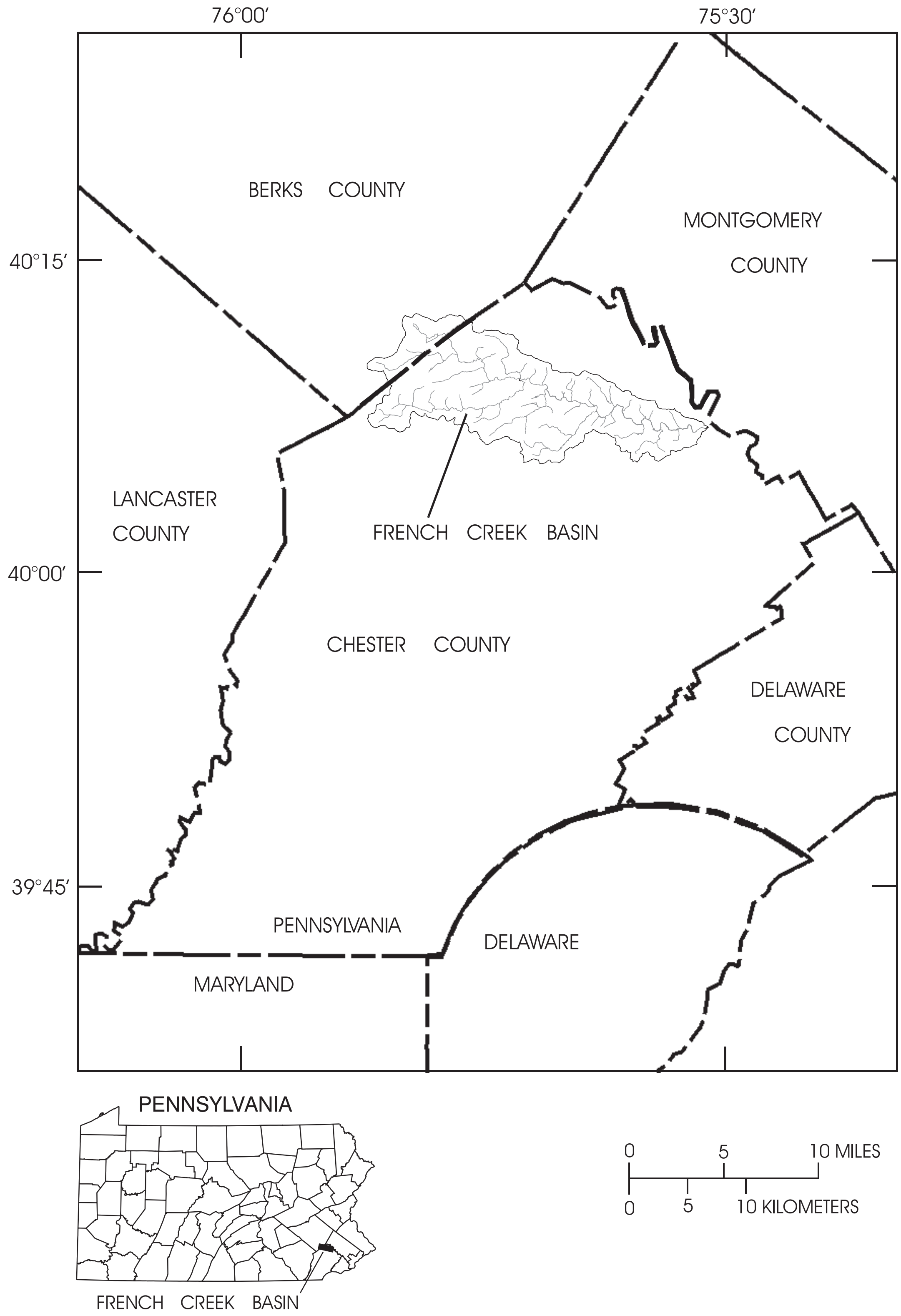


Figure 1. Location of the French Creek Basin and surrounding area, Chester and Berks Counties, Pennsylvania.

water levels in the basin; to simulate the effects of ground-water withdrawals at 50, 75, and 100 percent of the GWPA withdrawal limit in the South Branch French Creek Subbasin on stream base flow and water levels; and to simulate the effects of pumping a hypothetical well in various locations in the Beaver Run Subbasin on stream base flow and water levels.

Physiographic Province and Topography

French Creek is a tributary to the Schuylkill River, which is a major tributary to the Delaware River. The 70.7- mi^2 French Creek Basin mainly lies in northern Chester County, Pa., but has its headwaters in both Berks and Chester Counties. The mouth of French Creek is at Phoenixville in Chester County. The French Creek Basin is in the Piedmont Physiographic Province and is underlain by crystalline and sedimentary rocks. Some of the rocks have been intruded by diabase. The topography generally is rolling uplands, common to the Piedmont Physiographic Province. Some of the terrain in the northwestern part of the basin is relatively steep compared to the eastern part of the basin. Elevations in the basin range from 1,002 ft above NGVD 29 on the northwestern drainage divide to about 80 ft at the confluence. The basin has well-developed dendritic drainage patterns and is moderately incised.

Previous Investigations

The geology of the French Creek Basin was described by Bascom and Stose (1938), Huntsman (1975), and Demmon (1977) and was summarized by Sloto (1994). The geology of the Hammer Creek Formation was described by Glaeser (1963, 1966) and adopted by Wood (1980).

The hydrology of the French Creek Basin was described by Sloto (1994). The geology and hydrology of the Stockton Formation in southeastern Pennsylvania was described by Rima and others (1962). Wood (1980) described the hydrology of the Hammer Creek Formation. Longwill and Wood (1965) described the hydrology of the Brunswick Group in southeastern Pennsylvania.

The potentiometric surface in the French Creek Basin was mapped by Aichele and Wood (1996), Eden (1998), McManus (1990, 1992), Rowland (2000), and Senior and Garges (1989).

Acknowledgments

The cooperation of the residents of the French Creek Basin who made their wells accessible for water-level measurements and their property accessible for streamflow measurements is greatly appreciated. Streamflow measurements were made by David Galeone, Kevin Housel, Abdul Mohammed, Leif Olson, Andrew Reif, and Curtis Schreffler of the USGS Pennsylvania District. Ground-water pumpage data were compiled by Elaine Gee. Model simulations were developed during discussions with Anthony Bonasera, Gregory Cavallo, and Hernan Quinodoz of the DRBC, who provided critical reviews of this report. Curtis Schreffler of the USGS Pennsylvania District and Leslie Desimone of the USGS Massachusetts District also provided critical reviews of this report.

GEOLOGY

Precambrian and Cambrian crystalline rocks in the southern part of the French Creek Basin underlie 53 percent of the basin, Triassic sedimentary rocks in the northern part underlie 40 percent of the basin, and Jurassic diabase in the western part underlies 7 percent of the basin. The major formations are the granulite-facies felsic and intermediate gneiss, which underlies 31 percent of the basin, and the Stockton Formation, which underlies 30 percent of the basin. The geology of the modeled area is shown on figure 2, and the stratigraphic column is shown in table 1.

Precambrian Crystalline Rocks

The Precambrian crystalline rocks of the Honey Brook massif (table 1, fig. 2) are described by Crawford and Hoersch (1984). These units represent a metamorphosed sequence of rocks of predominantly granitic composition overlain by a basalt-rhyolite sequence of calcic-alkaline volcanic rocks. The rocks of the Honey Brook massif have undergone two episodes of burial and metamorphism, one during the Grenville orogeny and one during the Taconic orogeny (Crawford and Crawford, 1980). The Honey Brook massif includes amphibolite-facies and granulite-facies gneiss.

Table 1. *Stratigraphic column for the French Creek Basin and the surrounding area, Pennsylvania*

Age	Map symbol on figure 2	Geologic unit	
Early Jurassic	Jrd	Diabase	
Late Triassic	Trb	Brunswick Group	NEWARK SUPERGROUP
	Trh	Hammer Creek Formation sandstone	NEWARK SUPERGROUP
	Trhc	Hammer Creek Formation quartz conglomerate	NEWARK SUPERGROUP
	Trl	Lockatong Formation	NEWARK SUPERGROUP
	Trs	Stockton Formation	NEWARK SUPERGROUP
Cambrian	Cv	Vintage Dolomite	CHESTER VALLEY SEQUENCE
Cambrian and late Precambrian	Zah	Antietam and Harpers Formations, undivided	CHESTER VALLEY SEQUENCE
	Zch	Chickies Quartzite	CHESTER VALLEY SEQUENCE
Precambrian	Yhfa	Felsic gneiss, amphibolite facies	HONEY BROOK MASSIF
	Yhmg	Felsic gneiss, granulite facies	HONEY BROOK MASSIF
	Yhfg	Felsic and intermediate gneiss, granulite facies	HONEY BROOK MASSIF
	Yhga	Graphitic felsic gneiss, amphibolite facies	HONEY BROOK MASSIF
	Yhgg	Graphitic felsic gneiss, granulite facies	HONEY BROOK MASSIF

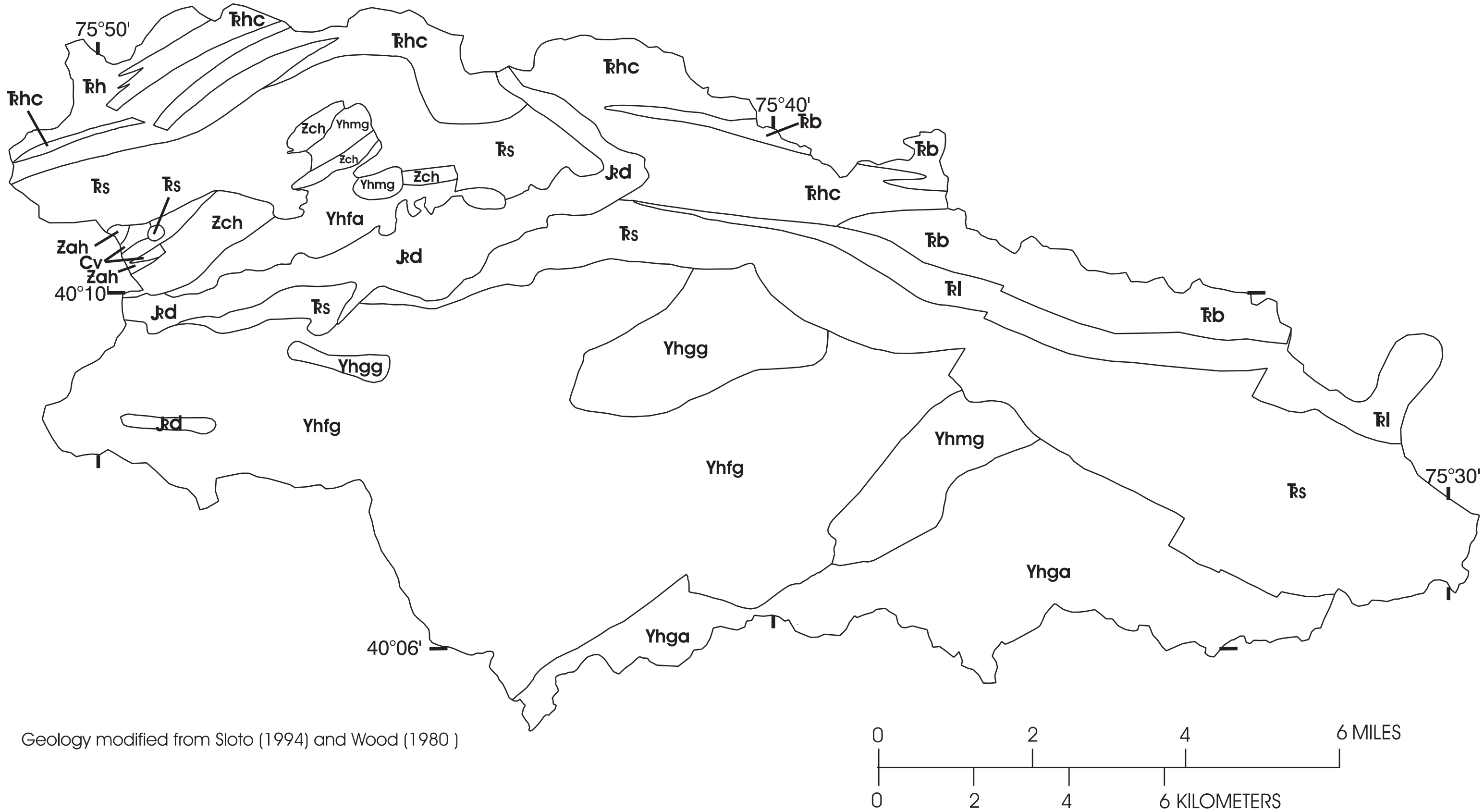
The amphibolite-facies gneiss includes felsic gneiss, graphitic felsic gneiss, and felsic and intermediate gneiss mapped as separate units. The amphibolite-facies gneisses are massive and slightly foliated with granular quartz-rich layers that alternate with and grade into quartz-plagioclase layers. Clots of muscovite flakes parallel scattered biotite layers. Retrograde chlorite partly replaces garnet, biotite, muscovite, and epidote. The amphibolite-facies felsic gneiss is a quartz-plagioclase-biotite-muscovite-epidote gneiss with trace hornblende and orthoclase. The amphibolite-facies graphitic felsic gneiss is a quartz-plagioclase-epidote-graphite gneiss with minor biotite and muscovite and trace orthoclase; it differs from the amphibolite-facies felsic gneiss solely by the presence of graphite. Graphite formation in the graphitic felsic gneiss and marble is related to metamorphism of organic-rich muds and carbonates accompanied by localized fluid flow (Crawford and Valley, 1990).

The granulite-facies felsic and intermediate gneiss is a medium- to coarse-grained, quartz-plagioclase-mesoperthite felsic gneiss with subordinate hornblende, augite, and hypersthene. Intermediate gneiss contains a higher proportion of mafic minerals than does the felsic gneiss. The felsic gneiss is extensively interlayered with subordinate amounts of the mafic and intermediate gneiss. Retrograde biotite and chlorite surround the mafic minerals. The granulite-facies graphitic felsic gneiss is a medium- to coarse-grained, quartz-plagioclase-mesoperthite-hypersthene-graphite felsic gneiss with subordinate microcline, hornblende, and augite with a faint foliation caused by alignment of mafic grains and elongation of quartzofeldspathic clusters. Graphite is present as medium-grained rods, irregular patches, stringers, and as distinct layers up to 2 in. thick. The granulite-facies graphitic felsic gneiss is interlayered extensively with subordinate mafic gneiss. Retrograde biotite and chlorite surround the mafic minerals.

Metamorphosed Sedimentary Rocks

Rocks of the Chester Valley Sequence are present west of the Honey Brook massif (table 1, fig. 2). The rocks that make up the Chester Valley sedimentary sequence were deposited by continental margin sedimentation when the Honey Brook massif became submerged during the late Precambrian, Cambrian, and Ordovician; during that time, this area was the eastern edge of the North American continent (Rodgers, 1968, p. 141-148).

The Chickies Quartzite is a resistant unit that forms prominent hills. Depositional environments include intertidal sand flat, subtidal channel, and tidal flat pond (Goodwin and Anderson, 1974). The Chickies Quartzite is a white to light gray, thin- to thick-bedded, cross-bedded, medium-grained quartzite with interbeds of quartzose schist and sandy mica schist. The basal unit is a coarse-grained, schorl-bearing quartzite and arkosic pebble conglomerate.



EXPLANATION

JTRd	Diabase	TRs	Stockton Formation	Yhga	Graphitic felsic gneiss, amphibolite facies
TRb	Brunswick Group	Cv	Vintage Dolomite	Yhfg	Felsic and intermediate gneiss, granulite facies
TRh	Hammer Creek Formation	Zch	Chickies Quartzite	Yhgg	Graphitic felsic gneiss, granulite facies
TRhc	Hammer Creek conglomeritic sandstone	Zah	Antietam and Harpers Formations, undivided	Yhmg	Felsic gneiss, granulite facies
TRl	Lockatong Formation	Yhfa	Felsic gneiss, amphibolite facies		

Figure 2. Generalized geology of the French Creek Basin and surrounding area, Pennsylvania.

The Antietam and Harpers Formations are not mapped as separate units in Chester County. In general, they consist of gray, thin- to thick-bedded, laminated quartzite, quartzose schist, and sandy micaceous schist. Kauffman and Frey (1979) interpret the Antietam Formation as a line of barrier islands fronting the early Cambrian continent. The Antietam Formation is a gray, laminated quartzite and quartzose schist that grades downward into the Harpers. Schwab (1970) interprets the Harpers Formation as a vertical repetition of nearshore and shallow marine platform sands and offshore, fine-grained, deep-water turbitite deposits. The Harpers Formation is a gray, sandy, micaceous schist with interbeds of quartz schist and thin-bedded quartzite.

The Vintage Dolomite crops out in small occurrences west of the Honey Brook massif. The Vintage is a dark gray, granular dolomite with a wavy texture. The lower part of the Vintage is a fine-grained, thin- to medium-bedded, argillaceous to sandy dolomite with abundant mica on the bedding planes. The upper part is a light gray, fine- to coarse-grained, thick-bedded dolomite. The Vintage Dolomite grades into the underlying Antietam Formation.

Triassic Sedimentary and Jurassic Igneous Rocks

Late Triassic sedimentary rocks of the Newark Supergroup crop out in northern Chester County along the Schuylkill River (table 1, fig. 2). They dip about 12°. The Triassic sedimentary rocks are predominantly lacustrine sediments deposited in the extensive, closed Newark Basin, which was occupied by a shallow, alkaline lake. The Newark Basin was formed by crustal downwarping. Subsidence kept pace with deposition, and sediment filled the basin from all sides. The sediments are laterally and vertically transitional between depositional environments. Following deposition, the basin was tilted toward the northwest by simultaneous faulting and folding (Faill, 1973, p. 725). Toward the end of deposition in the early Jurassic, diabase intruded the sediments. The sedimentary formations are the Stockton, Lockatong, and Hammer Creek Formations, and the Brunswick Group.

The depositional environments of the Stockton Formation include alluvial, marginal lacustrine, and nearshore lacustrine (Turner-Peterson, 1980). The Stockton consists of light to medium gray, thin- to thick-bedded, fine- to coarse-grained arkosic sandstone in the lower part and reddish brown to purplish gray, fine-grained sandstone, siltstone, shale, and mudstone in the upper part. The lower contact is unconformable with underlying Precambrian rocks. Where diabase intrudes the Stockton, the Stockton is an indurated, highly arkosic, fine-grained, gray conglomerate. Rima and others (1962, p. 9) estimated that the Stockton is 2,300 ft thick at Phoenixville.

The Lockatong Formation crops out in a narrow band in northern Chester County and has an average dip of 15°. Offshore lacustrine deposits formed the Lockatong (Turner-Peterson, 1980). The Lockatong is predominantly a medium to dark gray, thick- to very-thick-bedded argillite with thin beds of gray to black shale, siltstone, and marlstone. The depositional sequence is composed of alternating detrital and chemical-lacustrine cycles (Van Houten, 1964). The detrital cycles, averaging 14-20 ft thick, consist of laminated, medium-dark-gray to black, calcareous, pyritic siltstone and shale overlain by dark gray, platy to massive, calcareous siltstone and fine-grained sandstone. The chemical-lacustrine cycles, averaging 8-13 ft thick, consist of medium dark gray to black, platy, dolomitic siltstone and marlstone overlain by massive, gray or red, analcime- and carbonate-rich siltstone. The lower contact of the Lockatong grades into and laterally interfingers with the Stockton Formation. The Lockatong is about 1,500 ft thick at the Schuylkill River and thins westward (Bascom and Stose, 1938, p. 72).

The Hammer Creek Formation (Brunswick Formation quartz pebble conglomerate of Bascom and Stose, 1938, p. 74) sediments were deposited in an alluvial fan. Wood (1980, plate 1, part 3) mapped both a quartz conglomerate and a sandstone unit of the Hammer Creek Formation. The Hammer Creek quartz conglomerate is a fanglomerate composed of poorly sorted pebbles to boulders of white vein quartz and red siltstone in a red silty sandstone matrix. The Hammer Creek sandstone is a fine- to coarse-grained, red, brown, and gray sandstone containing pebbles and some cobbles of well-rounded pink to light gray vein quartz and quartzite and some clasts of red and brown siltstone and sandstone. The Hammer Creek Formation may be as much as 9,200 ft thick (Lyttle and Epstein, 1987).

The Brunswick Group (Brunswick Formation of Bascom and Stose, 1938, p. 73) is late Triassic in age in Chester County. Sediments of the Brunswick were deposited in a lacustrine-nearshore environment. The Brunswick Group consists of grayish-red to reddish-brown, evenly to irregularly bedded, thin- to medium-bedded shale, siltstone, and fine-grained sandstone containing some green and brown shale interbeds. Mudcracks, ripple marks, crossbeds, and burrows are common. The Brunswick contains detrital cycles of medium to dark gray and olive to greenish gray, thin-bedded shale and siltstone. Near the base are tongues of thick-bedded red argillite interbedded with dark gray argillite characteristic of the underlying Lockatong Formation. The lower contact is gradational with the Lockatong. The Brunswick laterally interfingers with the Lockatong and Hammer Formations. Bascom and Stose (1938, p. 76) estimated that the thickness of the Brunswick Group and Hammer Creek Formation together is about 8,000 ft.

Early Jurassic diabase intrudes the Triassic sedimentary rocks as dikes and sheets. It is a dark gray to black, fine- to medium-grained, intrusive igneous rock. In northwestern Chester County, a large intrusive body, the Morgantown diabase sheet, forms a prominent ridge. The shales and siltstones in contact with the sheet have been altered thermally.

HYDROLOGY

All the geologic units in the French Creek Basin are fractured-rock aquifers. Nearly all wells in fractured-rock aquifers have casing set into the upper few tens of feet of unweathered rock and are completed as open-hole wells. The ground-water-flow system in fractured rocks generally is local with streams acting as drains. Flow paths are short, and ground water flows from areas of higher elevation to adjacent streams. Ground-water and surface-water divides usually coincide.

Primary (intergranular) porosity below the weathered zone, except in a very few Triassic sedimentary beds, is nonexistent in most geologic units in the French Creek Basin. Ground water flows through a network of interconnected secondary openings that compose the water-bearing zones that provide water to wells. The vertical distribution of water-bearing openings is irregular and unpredictable. Adjacent wells may tap different systems of openings in the rock. The number and size of the water-bearing openings determines the secondary porosity of the rock; the number, size, and degree of interconnection of the openings determines the secondary permeability. The larger, more numerous, and more interconnected the openings, the greater the yield of a well drilled into that rock. Where a formation is extensively fractured, permeability may be high; elsewhere, where few fractures are present, the same unit may be nearly impermeable.

Ground water in the Triassic sedimentary rocks moves through the intergranular openings in the weathered zone and through a network of interconnecting secondary openings—fractures, bedding planes, and joints—in unweathered rock. In a few units, some water may move through intergranular openings in the bedrock where the cement has been removed and the permeability has increased. Triassic sedimentary beds form a series of alternating aquifers and semi-confining units feet to tens of feet thick; each bed generally has different hydraulic properties. In the Stockton Formation, the beds are lens-shaped, overlap, and pinch out. In the Brunswick Group and Lockatong Formation, the beds are more continuous, and single beds may extend downdip for a few hundred feet below land surface. Water-bearing zones generally are more continuous along strike than in the direction of dip; they tend to close downdip with depth because of compression.

In the crystalline rock units and diabase, ground water moves through intergranular openings in the saprolite (weathered zone) and through a network of interconnecting secondary openings—fractures and joints—in the underlying unweathered rock. Water-bearing and ground-water-flow characteristics of diabase are similar to that of crystalline rocks, but diabase is not as fractured and does not have the thick weathered zone usually associated with crystalline rocks.

Water levels measured in wells in an unconfined aquifer indicate the level of the water table. Static water levels in an aquifer that is not being pumped or stressed by other anthropogenic activities reflect natural conditions. Under natural conditions in an unconfined aquifer, water levels generally are closest to land surface in valleys near streams (discharge areas) and deepest below land surface on hilltops (recharge areas).

Water levels fluctuate in response to recharge to the ground-water system from precipitation and discharge from the ground-water system to pumping wells, to the atmosphere by ground-water evapotranspiration, and to streams. Water levels generally rise during the late fall, winter, and early spring when ground-water and soil-moisture evapotranspiration are at a minimum and recharge is at a maximum. Water levels generally decline during the late spring, summer, and early fall when ground-water evapotranspiration and soil-moisture evapotranspiration are at a maximum and recharge is at a minimum.

Water levels were measured monthly in wells CH-1571 and CH-2328 in the French Creek Basin from 1974 to 2001 (fig. 3). Water levels in the observation wells show similar patterns of response to seasonal changes in recharge and evapotranspiration (fig. 4). Water levels generally decline in the summer and fall despite precipitation because recharge is decreased by evapotranspiration. The range in fluctuation in these wells for 1974-2001 was up to 6.9 ft. Although the seasonal fluctuations in water levels are similar from year to year, changes in climatic conditions can affect the seasonal pattern.

Ground-Water/Surface-Water Relations

The ground-water and surface-water systems are well connected in the French Creek Basin. In most areas, streams act as drains for the ground-water system and gain water. Streamflow is composed of ground-water discharge (base flow) and surface (overland) runoff. The quantity of ground water discharged to streams is related directly to the altitude of the water table. Base flow generally declines when ground-water levels decline and increases when ground-water levels increase. The time of lowest base flow generally coincides with the lowest ground-water levels. Precipitation from June through October generally produces little recharge and little increase in ground-water levels; most of the infiltrated precipitation replenishes soil moisture. Streamflow was separated into base-flow and surface-runoff components (table 2) using the HYSEP computer program of Sloto and Crouse (1996). The local minimum hydrograph-separation technique was used here. On the basis of hydrograph separations, the annual base flow of French Creek measured at streamflow measurement station 01472157 (French Creek near Phoenixville) ranged from 5.50 in/yr in 1981 to 19.92 in/yr in 1996 (table 2). The average annual base flow of French Creek is 12.42 in/yr and is equal to 27 percent of the average annual precipitation. Base flow made up an average of 61 percent of streamflow.

Two sets of base-flow measurements were collected for this study for model calibration (table 3). Measurement sites are shown on figure 5. The first set of measurements was collected on May 1, 2001, during a period of higher than average base flow. Streamflow at the streamflow-measurement station on May 1 was 71.7 ft^3/s; average base flow at the streamflow-measurement station for 1968-2001 is 54.1 ft^3/s (fig. 6). The second set of base-flow measurements was collected during a period of much lower than average base flow on September 11 and 17, 2001. Field work on September 11 was interrupted, and additional measurements were made on September 17. Streamflow at the streamflow-measurement station was 17.1 ft^3/s on September 11 and 12.8 ft^3/s on September 17. The Q_{7-10} at the streamflow-measurement station is 10.5 ft^3/s (Schreffler, 1998, p. 15). The Q_{7-10} is defined as the lowest mean streamflow over 7 consecutive days, which, on average, has and probably will occur once every 10-year period.

All sites were measured on May 1, 2001. The base-flow measurements made on May 1 show that French Creek gained water between all sites measured except in the lower reach above site 31 (table 3, fig. 5). On May 1, 2001, the streamflow per square mile ranged from 0.43 to 1.8 $(ft^3/s)/mi^2$. The median streamflow per square mile, 1.3 $(ft^3/s)/mi^2$, was close to the 1.2 $(ft^3/s)/mi^2$ measured at the streamflow-measurement station.

Not all sites were measured on September 11, 2001. Field work was interrupted because of the attack on the World Trade Center. The base-flow measurements made on September 11 show that French Creek gained water between all sites measured except in the lower reach above site 28 (table 3, fig. 5). On September 11, the streamflow per square mile ranged from 0.02 to 1.2 $(ft^3/s)/mi^2$. The median streamflow per square mile, 0.22 $(ft^3/s)/mi^2$, was close to the 0.29 $(ft^3/s)/mi^2$ measured at the streamflow-measurement station.

Additional base-flow measurements were made on September 17, 2001. The base-flow measurements made on September 17 show that French Creek gained water between all sites measured except in the lower reach above site 28 (table 3, fig. 5). On September 17, the streamflow per square mile ranged from 0 to 0.42 $(ft^3/s)/mi^2$. The median streamflow per square mile, 0.26 $(ft^3/s)/mi^2$, was close to the 0.22 $(ft^3/s)/mi^2$ measured at the streamflow-measurement station.

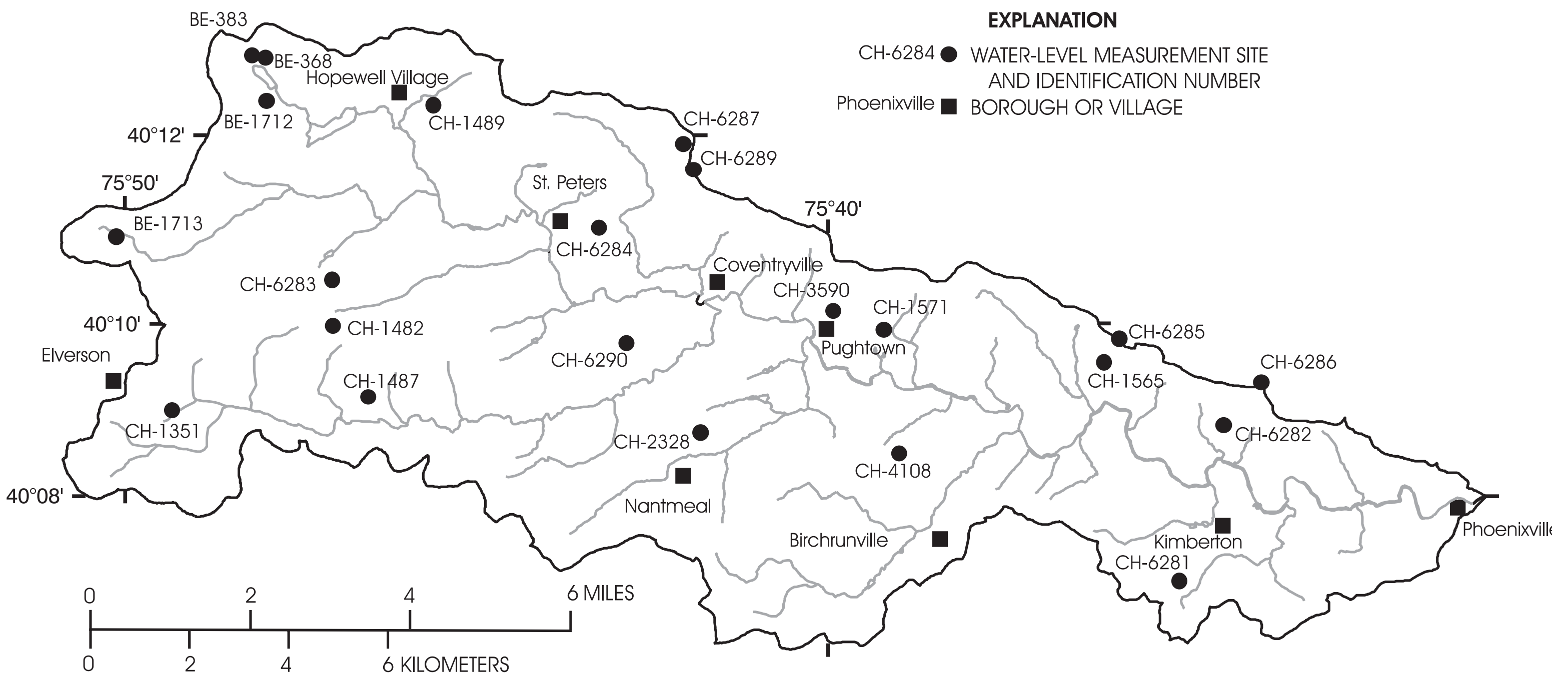


Figure 3. Location of observation wells in the French Creek Basin and surrounding area, Pennsylvania.

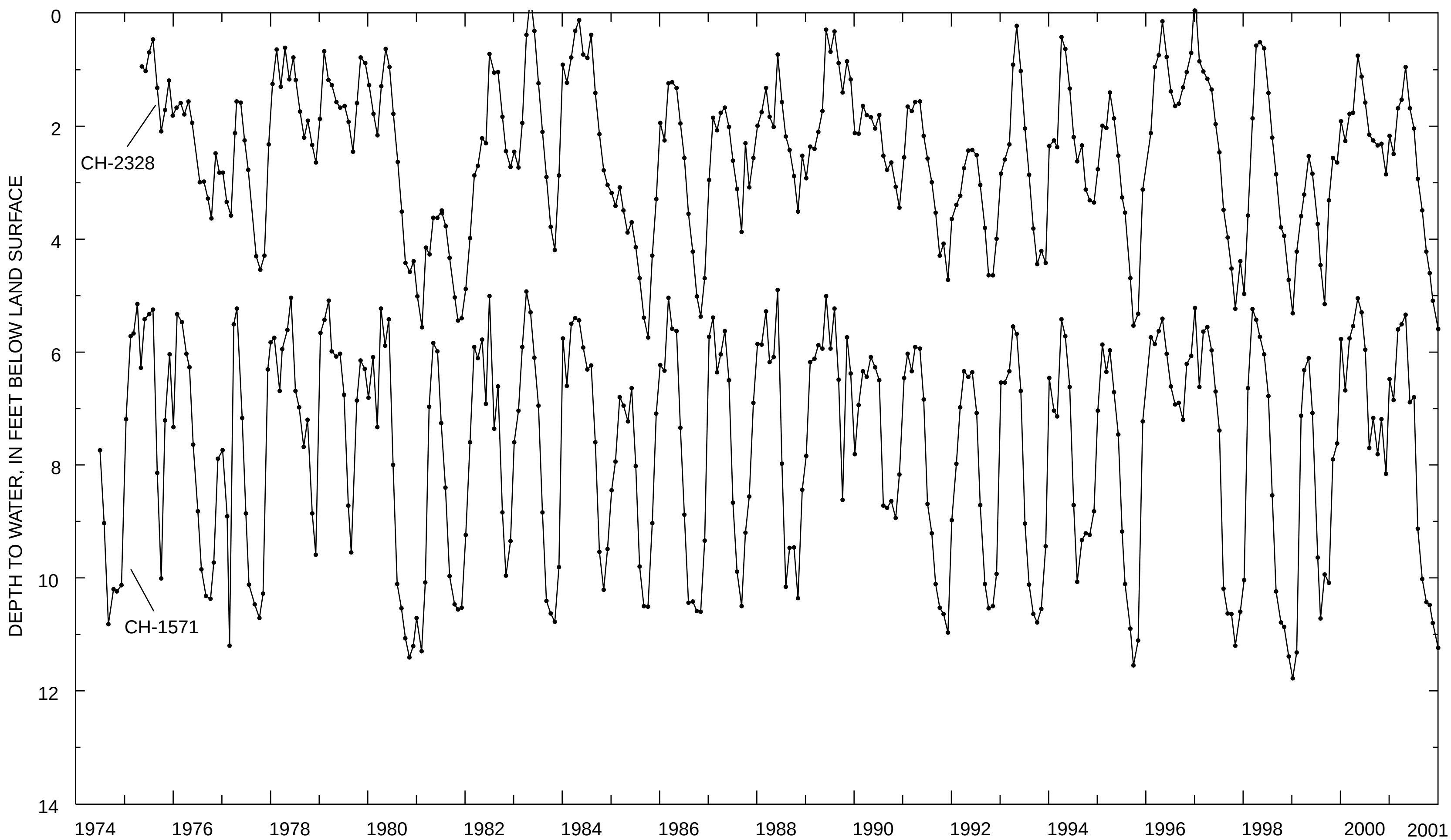


Figure 4. Hydrographs from wells CH-2328 and CH-1571, 1974-2001, French Creek Basin, Pennsylvania.

Table 2. *Annual base flow and surface runoff for the French Creek Basin, Pennsylvania, 1969-2001 (Inches can be converted to million gallons per day per square mile by multiplying by 0.048.)*

Year	Precipitation (inches)	Streamflow (inches)	Base flow (inches)	Surface runoff (inches)	Percentage of streamflow as base flow	Percentage of precipitation as base flow
1969	37.16	9.90	6.16	3.74	62	17
1970	41.68	17.70	11.01	6.69	62	26
1971	53.94	21.98	13.67	8.31	62	25
1972	57.36	28.97	18.02	10.95	62	31
1973	51.38	26.33	16.38	9.95	62	32
1974	44.93	19.90	12.38	7.52	62	28
1975	55.70	26.10	16.10	10.00	62	29
1976	41.60	17.10	11.10	6.00	65	27
1977	48.20	19.10	10.80	8.30	57	22
1978	47.90	29.00	17.60	11.40	61	37
1979	59.70	31.50	17.60	13.90	56	29
1980	33.70	15.60	11.30	4.30	72	34
1981	39.30	8.70	5.50	3.20	63	14
1982	48.20	17.80	10.30	7.50	58	21
1983	55.60	27.00	15.50	11.50	57	28
1984	50.30	30.50	18.30	12.20	60	36
1985	41.10	13.70	8.30	5.40	61	20
1986	43.10	16.60	10.20	6.40	61	24
1987	39.70	16.90	10.30	6.60	61	26
1988	40.80	19.80	12.00	7.80	61	29
1989	51.05	25.40	15.44	9.97	61	30
1990	47.82	18.25	11.98	6.28	66	25
1991	40.94	16.92	10.75	6.17	64	26
1992	39.71	11.36	8.19	3.17	72	21
1993	49.63	21.63	13.74	7.88	64	28
1994	45.65	25.54	14.89	10.65	58	33
1995	42.06	13.15	8.49	4.66	65	20
1996	66.80	33.52	19.92	13.60	59	30
1997	38.54	21.51	11.79	9.72	55	31
1998	43.72	16.07	11.78	4.28	73	27
1999	49.18	13.85	8.48	5.37	61	17
2000	48.16	22.93	12.06	10.87	53	25
2001	32.79	15.43	9.92	5.51	64	30
Average	46.28	20.29	12.42	7.87	61	27

Table 3. *Base-flow measurements in the French Creek Basin, Pennsylvania, May 1, September 11, and September 17, 2001 (Location of measurement sites are shown on figure 5.)*

[lat, latitude; long, longitude; mi^2, square miles; ft^3/s, cubic feet per second; [$(ft^3/s)/mi^2$], cubic feet per second per square mile; --, not measured; a negative number indicates a losing reach]

Site number	Station name and number	Location	Drainage area (mi^2)	Measurement		Discharge per square mile [$ft^3/s)/mi^2$]	
				Date	Discharge (ft^3/s)	Between measurement sites	Cumulative
1	French Creek upstream of State Route 345 at Hopewell Village, Pa. 014721252	Lat 40°11′56″, long 75°45′53″, 40 feet upstream of bridge on State Route 345	2.78	5-01-01	4.28	1.54	1.54
				9-17-01	.96	.35	.35
2	Unnamed tributary to French Creek at Hopewell Village, Pa. 014721256	Lat 40°12′26″, long 75°45′47″, 25 feet downstream of Hopewell Road	.69	5-01-01	1.01	1.46	1.46
				9-11-01	.15	.22	.22
				9-17-01	.11	.16	.16
3	Pine Creek at State Game Lands 43 near Pine Swamp, Pa. 01472127	Lat 40°11′00″, long 75°48′38″, 75 feet upstream of bridge on Harmonyville Road	1.95	5-01-01	2.02	1.04	1.04
				9-11-01	.27	.14	.14
4	Pine Creek downstream of Harmonyville Road at Pine Swamp, Pa. 01472128	Lat 40°11′15″, long 75°46′28″, 350 feet downstream of bridge on Harmonyville Road	4.52	5-01-01	4.59	1.0	1.02
				9-11-01	.63	.14	.14
				9-17-01	.30	--	.07
5	French Creek near Knauertown, Pa. 01472129	Lat 40°11′09″, long 75°46′28″, 30 feet downstream of dam	11.7	5-01-01	14.6	1.27	1.25
				9-17-01	2.5	.31	.21
6	Unnamed tributary to French Creek at Harmonyville, Pa. 01472131	Lat 40°11′23″, long 75°44′27″, 200 feet downstream of Harmonyville Road	.62	5-01-01	.94	1.52	1.52
				9-11-01	.25	.40	.40
				9-17-01	.26	.42	.42
7	French Creek at St. Peters, Pa. 01472132	Lat 40°11′02″, long 75°44′00″, 200 feet upstream of private driveway bridge	14.4	5-01-01	18.3	1.33	1.27
				9-17-01	2.84	.04	.20
8	Unnamed tributary to French Creek at St. Peters, Pa. 01472133	Lat 40°10′46″, long 75°43′57″, 20 feet upstream of confluence with French Creek	1.94	5-01-01	.92	.47	.47
				9-11-01	.04	.02	.02
9	French Creek upstream of State Route 23 at Knauertown, Pa. 01472134	Lat 40°10′21″, long 75°43′45″, 600 feet upstream of bridge on State Route 23	16.9	5-01-01	21.4	3.89	1.27
				9-11-01	4.2	--	.25
				9-17-01	3.05	--	.18
10	French Creek near Coventryville, Pa. 01472138	Lat 40°10′14″, long 75°41′50″, 25 feet upstream of bridge on Mount Pleasant Road	19.9	5-01-01	27.0	1.87	1.36
				9-17-01	4.38	.44	.22
11	Rock Run at Harmonyville, Pa. 01472136	Lat 40°11′30″, long 75°42′34″, 25 feet upstream of Harmonyville Road	1.25	5-01-01	1.69	1.35	1.35
				9-11-01	.43	.34	.34
12	Rock Run above confluence near Coventryville, Pa. 01472137	Lat 40°10′19″, long 75°41′48″, 100 feet upstream of confluence with French Creek	3.33	5-01-01	4.10	1.16	1.23
				9-11-01	.64	.10	.19
				9-17-01	.38	--	.12
13	South Branch French Creek upstream of State Route 401 near Elverson, Pa. 014721382	Lat 40°08′56″, long 75°48′37″, 75 feet upstream of bridge on State Route 401	1.95	5-01-01	2.96	1.52	1.52
				9-11-01	.65	.33	.33

Table 3. *Base-flow measurements in the French Creek Basin, Pennsylvania, May 1, September 11, and September 17, 2001—Continued*
(Location of measurement sites are shown on figure 5.)

[lat, latitude; long, longitude; mi^2, square miles; ft^3/s, cubic feet per second; [(ft^3/s)/mi^2], cubic feet per second per square mile; --, not measured; a negative number indicates a losing reach]

Site number	Station name and number	Location	Drainage area (mi^2)	Measurement		Discharge per square mile [ft^3/s)/mi^2]	
				Date	Discharge (ft^3/s)	Between measurement sites	Cumulative
14	South Branch French Creek downstream of State Routes 401 and 345 at Marsh. Pa. 014721387	Lat 40°08′51″, long 75°47′37″, 100 feet downstream of bridge on State Route 345	5.52	5-01-01	5.36	0.67	0.97
				9-11-01	1.22	.16	.22
15	South Branch French Creek near Knauertown, Pa. 014721395	Lat 40°08′55″, long 75°44′20″, 25 feet downstream of bridge on Valley Way Road	9.59	5-01-01	10.5	1.25	1.09
				9-11-01	3.35	.52	.35
16	South Branch French Creek at Coventryville, Pa. 01472140	Lat 40°09′18″, long 75°42′52″, 200 feet upstream of bridge on Warwick Furnace Road	12.4	5-01-01	16.4	2.11	1.32
				9-11-01	3.27	-.03	.26
17	South Branch French Creek along township road 424 at Coventryville, Pa. 01472145	Lat 40°09′49″, long 75°41′37″, 50 feet upstream of pond	13.1	5-01-01	17.1	1.10	1.30
				9-11-01	4.61	1.91	.35
				9-17-01	4.38	--	.33
18	Beaver Run at Prizer Road at Pughtown, Pa. 01472153	Lat 40°09′37″, long 75°40′18″, 30 feet downstream of bridge on Prizer Road	4.97	5-01-01	6.69	1.35	1.35
				9-11-01	1.63	.33	.33
				9-17-01	1.16	.23	.23
19	French Creek downstream of State Route 100 at Pughtown, Pa. 014721532	Lat 40°09′47″, long 75°40′13″, 150 feet downstream of bridge on State Route 100	44.3	5-01-01	58.8	1.31	1.33
				9-17-01	10.3	.01	.23
20	Unnamed tributary to French Creek downstream of Pughtown Road near Pughtown, Pa. 014721538	Lat 40°09′42", long 75°38′45″, 300 feet downstream of bridge on Pughtown Road	1.13	5-01-01	.68	.60	.60
				9-11-01	.14	.13	.13
				9-17-01	.10	.09	.09
21	French Creek near Pughtown, Pa. 01472154	Lat 40°09′17″, long 75°38′25″, 250 feet downstream of bridge on Sheeder Mill Road	46.1	5-01-01	61.0	2.27	1.32
				9-17-01	10.3	-.15	.22
22	Birch Run upstream of Horseshoe Trail near Birchrunville, Pa. 014721547	Lat 40°07′01″, long 75°39′33″, 60 feet upstream of bridge on Horseshoe Trail	2.62	5-01-01	2.92	1.11	1.11
				9-11-01	.68	.26	.26
				9-17-01	.61	.23	.23
23	Birch Run above confluence at Sheeder, Pa. 014721568	Lat 40°08′50″, long 75°37′20″, 100 feet downstream of bridge on Buttonwood Lane	6.55	5-01-01	9.02	1.55	1.38
				9-17-01	1.48	.22	.23
24	Unnamed tributary to French Creek at Sheeder, Pa. 01472156	Lat 40°09′05″, long 75°36′14″, 100 feet upstream of confluence with French Creek	1.68	5-01-01	1.2	.71	.71
				9-17-01	.13	.08	.08
25	Unnamed tributary to French Creek near Sheeder, Pa. 014721573	Lat 40°09′12″, long 75°36′02″, 30 feet upstream of confluence with French Creek	.39	5-01-01	.28	.73	.73
				9-17-01	0	0	0
26	French Creek near Phoenixville, Pa. 01472157	Lat 40°09′05″, long 75°36′06″, 70 feet downstream of bridge on French Creek Road	59.1	5-01-01	71.7	2.17	1.21
				9-11-01	17.1	--	.29
				9-17-01	12.8	.53	.22

Table 3. *Base-flow measurements in the French Creek Basin, Pennsylvania, May 1, September 11, and September 17, 2001*—*Continued*
(Location of measurement sites are shown on figure 5.)

[lat, latitude; long, longitude; mi^2, square miles; ft^3/s, cubic feet per second; [(ft^3/s)/mi^2], cubic feet per second per square mile; --, not measured; a negative number indicates a losing reach]

Site number	Station name and number	Location	Drainage area (mi^2)	Measurement		Discharge per square mile [ft^3/s)/mi^2]	
				Date	Discharge (ft^3/s)	Between measurement sites	Cumulative
27	Unnamed tributary to French Creek at Wilsons Corner, Pa. 014721575	Lat 40°09′02″, long 75°35’29″, 50 feet downstream of bridge on Lucas Road	0.39	5-01-01	0.19	0.48	0.48
				9-11-01	.02	.04	.04
28	Unnamed tributary to French Creek upstream of Seven Stars Road at Kimberton, Pa. 014721579	Lat 40°08′17″, long 75°34′32″, 100 feet upstream of confluence with French Creek	1.84	5-01-01	3.31	1.80	1.80
				9-11-01	2.11	1.15	1.15
29	French Creek upstream of Seven Stars Road at Kimberton, Pa. 01472158	Lat 40°08′26″, long 75°34′36″, 100 feet downstream of Kennedy Covered Bridge on Seven Stars Road	62.8	5-01-01	83.5	5.65	1.33
				9-11-01	20.4	.78	.32
30	Unnamed tributary to French Creek upstream of State Route 113 at Kimberton, Pa. 014721587	Lat 40°07′48″, long 75°33′33″, 30 feet downstream of bridge on State Route 113	1.94	5-01-01	2.09	1.08	1.08
				9-11-01	.67	.34	.34
31	French Creek upstream of Rapps Dam Road Bridge at Phoenixville, Pa. 01472159	Lat 40°08′17″, long 75°33′12″, 100 feet downstream of covered bridge on Rapps Dam Road	66.7	5-01-01	85.5	-.05	1.28
				9-11-01	19.8	-.63	.30
32	Unnamed tributary to French Creek upstream of State Route 23 at Phoenixville, Pa. 014721593	Lat 40°08′03″, long 75°32′28″, 50 feet upstream of confluence with French Creek	.70	5-01-01	.56	.8	.8
				9-11-01	.05	.07	.07
33	Unnamed tributary to French Creek at Township Line Road at Phoenixville, Pa. 014721595	Lat 40°08′11″, long 75°32′23″, 30 feet downstream of Township Line Road	.53	5-01-01	.30	.56	.56
				9-11-01	.02	.04	.04
34	French Creek at Railroad Bridge at Phoenixville, Pa. 014721612	Lat 40°08′10″, long 75°30′41″, 250 feet upstream of railroad bridge	70.7	5-01-01	89	.95	1.26
				9-11-01	20.2	.12	.29

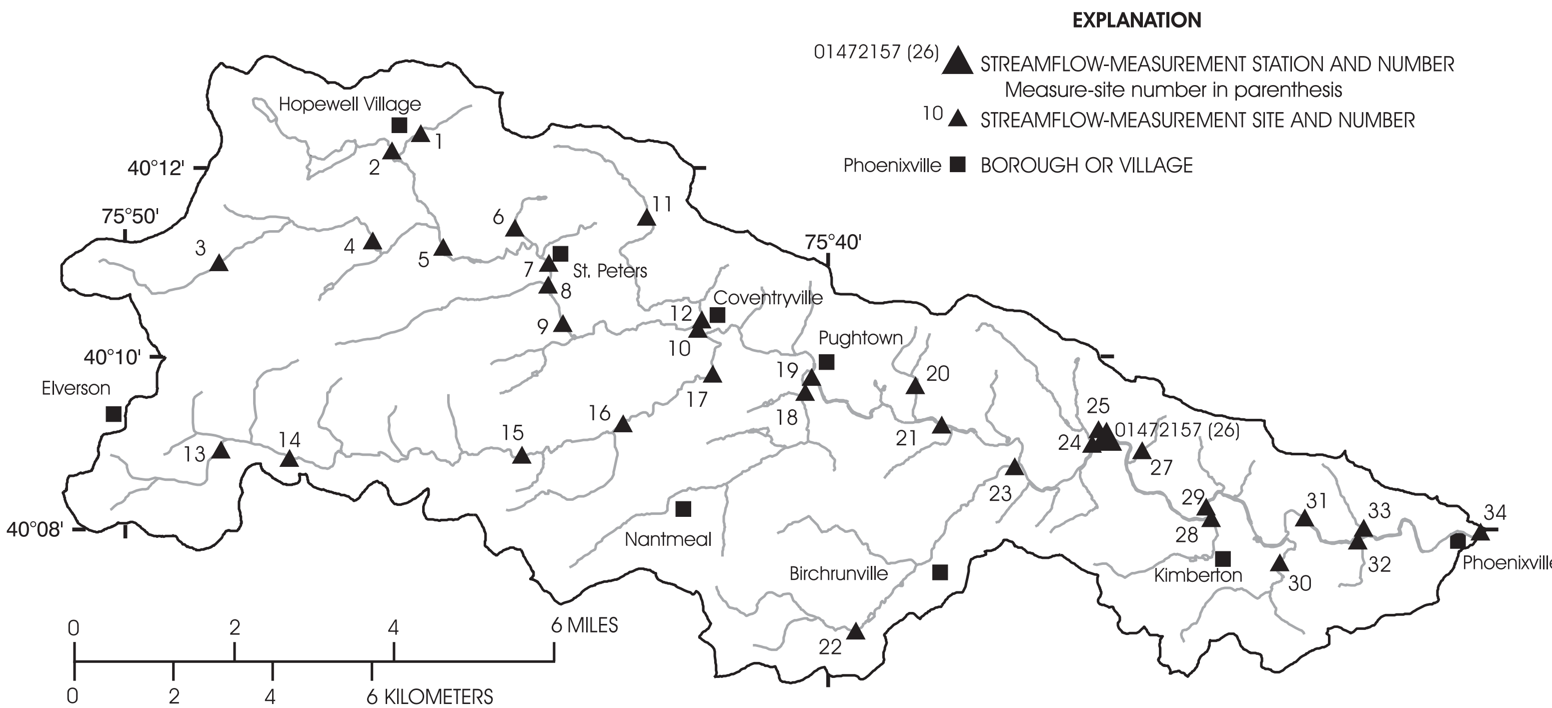


Figure 5. Location of streamflow-measurement sites in the French Creek Basin, Pennsylvania.

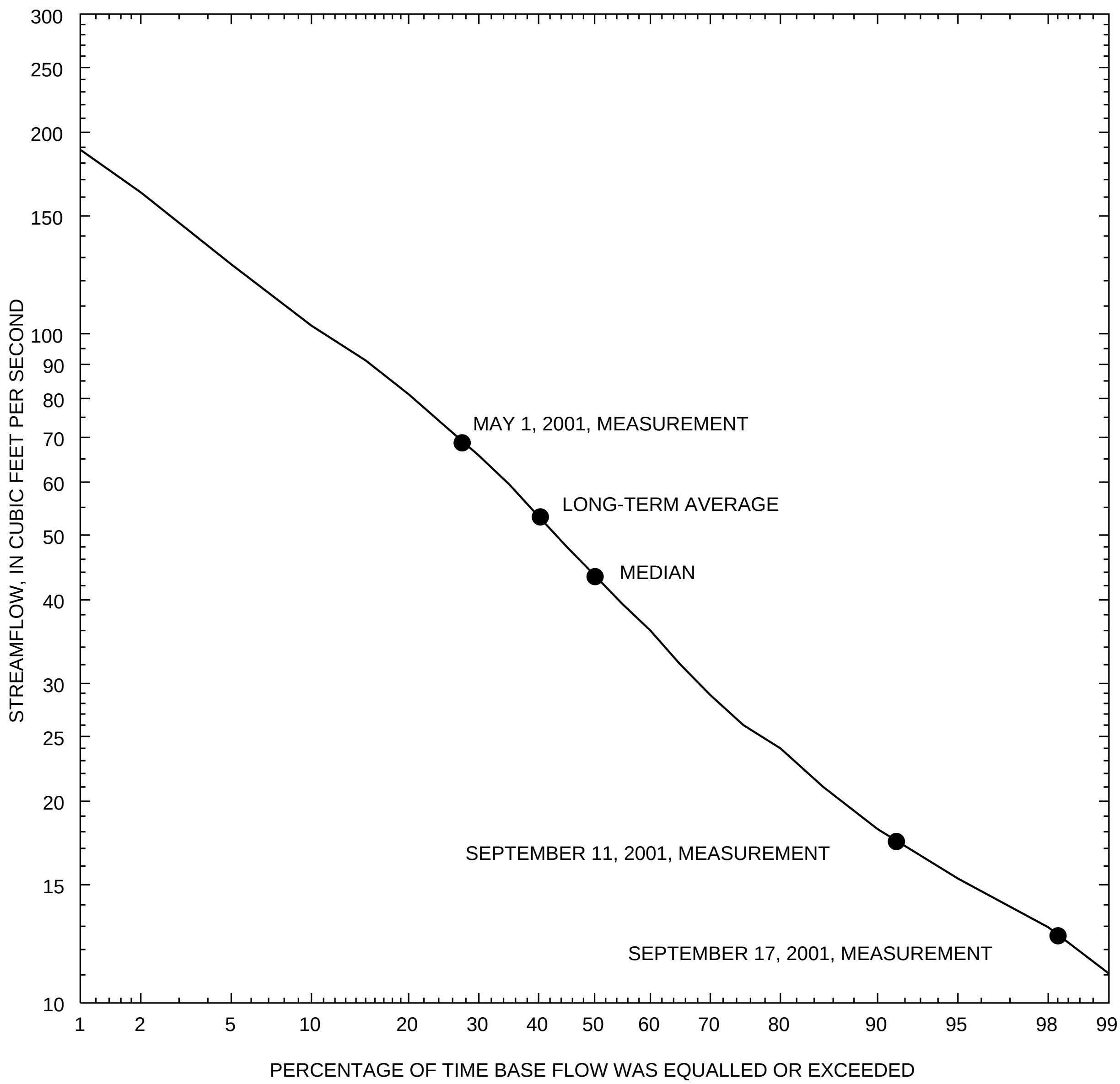


Figure 6. Duration of daily base flow at streamflow-measurement station French Creek near Phoenixville, Pennsylvania (01472157), 1969-2001.

Water Budget

A water budget is an estimate of water entering and leaving a basin plus or minus changes in storage for a given time period. For a basin where ground-water and surface-water divides coincide, water enters as precipitation and imported water (if any) and leaves as streamflow, evapotranspiration, and diversions, such as exported ground-water pumpage (if any). Water also is taken into or released from ground-water and soil-moisture storage.

Because the water budgets described in this report begin and end in winter when soil moisture usually is at field capacity, the change in soil moisture is equal to zero, and a soil-moisture term is not included in the water-budget equation. No water is exported from or imported into the French Creek Basin, and, therefore, an export/import term is not included in the equation. An annual water budget for basins where ground-water and surface-water divides coincide, such as the French Creek Basin, can be expressed as

$$P = SF + \Delta GWS + ET, \qquad (1)$$

where

P is precipitation,

SF is streamflow leaving basin,

ΔGWS is change in ground-water storage, and

ET is evapotranspiration.

All terms in the water-budget equation are known or can be estimated except evapotranspiration (ET); equation 1 is solved for ET.

Equation 1 was used to calculate the annual water budgets presented in this report. Data-collection sites necessary to calculate a water budget include one or more rain gages to measure precipitation (P), a streamflow-measurement station to measure streamflow (SF), and one or more observation wells to estimate the change in ground-water storage (ΔGWS).

Annual precipitation data are from the National Oceanic and Atmospheric Administration (NOAA) precipitation stations in and around the French Creek Basin. Annual precipitation data from the Glenmoore and Phoenixville stations were averaged for each year for 1969-88. Annual precipitation data from the Glenmoore, Hopewell, and Phoenixville stations were averaged for each year for 1989-97 and 2001. Because of missing record, annual precipitation data from the Glenmoore and Phoenixville stations were averaged for 1998, data from the Glenmoore station were used for 1999, and data from the Glenmoore and Hopewell stations were averaged for 2000.

Streamflow data are from the USGS streamflow-measurement station French Creek near Phoenixville (station number 01472157), which has a period of record beginning on October 1, 1968. The station measures streamflow from the upper 59.1 mi^2 of the basin.

Water-level data from USGS observation wells CH-1571 and CH-2328 (fig. 2) in the basin were used to calculate the change in ground-water storage. Water-level measurements made in January of each year were used to calculate the annual change in water level. The annual change in water level was multiplied by 0.08, the specific yield of the zone of water-level fluctuation (McGreevy and Sloto, 1980, p. 18), to calculate the annual change in ground-water storage. Basin specific-yield calculations made for the nearby Valley Creek Basin by Sloto (1990, p. 26) ranged from 0.04 to 0.12 and averaged about 0.08. Monthly water-level measurements at CH-1571 began in June 1974 and at CH-2328 began in April 1975. Water levels prior to the start of record were estimated for January of each year using a technique described by Sloto (1991, p. 439-440). Regression equations were developed using USGS observation well CH-10 as the long-term index well, and water levels for well CH-1571 for 1969-74 and well CH-2328 for 1969-75 were estimated from the regression equations.

Water budgets are calculated for 1969-2001 for the French Creek Basin above streamflow-measurement station 01472157 (table 4). Water budgets for 1975-88 are from Sloto (1994, p. 40). Quantities in table 4 are given in inches. Inches can be converted to millions of gallons per day per square mile by multiplying by 0.048.

Annual precipitation ranged from 33.70 in. in 1980 to 66.80 in. in 1996. The average annual precipitation for 1969-2001 is 46.28 in. Annual streamflow ranged from 8.7 in. in 1981 to 33.52 in. in 1996; average annual streamflow is 20.29 in. and is equal to 44 percent of the average annual precipitation. The annual change in ground-water storage ranged from an increase of 4.52 in. in 1999 to a decrease of 4.87 in. in 1997; the average annual change in ground-water storage for 1969-2001 was a decrease of 0.11 in. Estimated annual ET ranged from 18.80 in. in 1978 to 31.42 in. in 1971; the estimated average annual ET is 26.10 in. and is equal to 56 percent of the average annual precipitation.

Table 4. *Water budgets and estimated recharge for the French Creek Basin, Pennsylvania, 1969-2001 (Inches can be converted to million gallons per day per square mile by multiplying by 0.048.)*

Year	Precipitation (inches)	Streamflow (inches)	Change in ground-water storage (inches)	Evapo-transpiration (inches)	Recharge (inches)
1969	37.16	9.90	-0.21	27.47	7.95
1970	41.68	17.70	1.06	22.92	14.07
1971	53.94	21.98	.53	31.42	16.20
1972	57.36	28.97	1.30	27.09	21.32
1973	51.38	26.33	-.33	25.37	18.05
1974	44.93	19.90	-1.57	26.59	12.81
1975	55.70	26.10	.40	29.20	18.50
1976	41.60	17.10	-2.50	27.00	10.60
1977	48.20	19.10	2.80	26.30	15.60
1978	47.90	29.00	.10	18.80	19.70
1979	59.70	31.50	-.80	29.00	18.80
1980	33.70	15.60	-4.30	22.40	9.00
1981	39.30	8.70	2.50	28.10	10.00
1982	48.20	17.80	.90	29.50	13.20
1983	55.60	27.00	.90	27.70	18.40
1984	50.30	30.50	-1.70	21.50	18.60
1985	41.10	13.70	1.30	26.10	11.60
1986	43.10	16.60	.60	25.90	12.80
1987	39.70	16.90	-.20	23.00	12.10
1988	40.80	19.80	-1.40	22.40	12.60
1989	51.05	25.40	.40	25.25	17.84
1990	47.82	18.25	.44	29.12	14.42
1991	40.94	16.92	-1.73	25.76	11.02
1992	39.71	11.36	1.56	26.80	11.74
1993	49.63	21.63	.27	27.73	16.02
1994	45.65	25.54	-.48	20.58	16.42
1995	42.06	13.15	-.26	29.17	10.22
1996	66.80	33.52	2.64	30.65	24.55
1997	38.54	21.51	-4.87	21.90	8.91
1998	43.72	16.07	-1.00	28.65	12.79
1999	49.18	13.85	4.52	30.82	15.00
2000	48.16	22.93	-.47	25.70	13.59
2001	32.79	15.43	-3.93	21.29	7.99
Average	46.28	20.29	-.11	26.10	14.32

Recharge

Precipitation that infiltrates to the water table recharges the ground-water system. Recharge to the ground-water system depends on many factors, including the duration and intensity of precipitation, antecedent soil-moisture conditions, slope, degree of urbanization, and soil and bedrock characteristics. Generally, recharge occurs on hilltops and hillsides; topographically low areas commonly are discharge areas.

Recharge was estimated for the French Creek Basin using the following equation:

$$R = BF + \Delta GWS + GWET, \qquad (2)$$

where

R is estimated recharge,

BF is base flow,

ΔGWS is change in ground-water storage, and

$GWET$ is estimated ground-water evapotranspiration.

No water is exported from or imported into the French Creek Basin; therefore, a term for exported/imported water is not included in equation 2. Recharge estimates for 1975-88 are from Sloto (1994, p. 40). Ground-water ET is ET directly from the saturated zone. It is estimated to be about 2 in/yr (Sloto, 1990).

Average annual estimated recharge for the French Creek Basin (table 4) ranged from 7.95 in. [0.38 (Mgal/d)/mi^2] in 1969 to 24.55 in. [1.2 (Mgal/d)/mi^2] in 1996. The estimated average annual recharge for 1969-2001 is 14.32 in. [0.69 (Mgal/d)/mi^2] and is equal to 31 percent of the average annual precipitation.

SIMULATED EFFECTS OF DROUGHT AND GROUND-WATER WITHDRAWALS

A ground-water-flow model was developed for the French Creek Basin and surrounding area to assess the potential effects of drought, increased ground-water withdrawals, and well location. A flow model provides the ability to determine both short- and long-term responses to changes in the hydrologic system.

Ground-water flow in the French Creek Basin was simulated using the finite-difference MODFLOW-96 computer program (McDonald and Harbaugh,1988 and Harbaugh and McDonald, 1996). The preconditioned conjugate gradient method of Hill (1990) was used to solve the model equations. The stream-aquifer package of Prudic (1989) was used to simulate stream-aquifer relations. The Groundwater Modeling System (GMS) was used as the interface to the MODFLOW-96 program (Environmental Modeling Systems, Inc., 2001).

Model Description and Assumptions

The model structure is based on a simplified conceptualization of the ground-water-flow system. Initially, a three-dimensional model was developed but drainage of water from the upper layer representing the weathered zone in areas of steeper topography produced dry cells that dropped out of model computations. In addition, hydraulic data are not available in the z direction. Therefore, a two-dimensional approach was used. The fractured-rock formations in the French Creek Basin were modeled as equivalent porous media, such as unconsolidated granular deposits. Thus, it is assumed that ground-water flow can be described by a flow equation based on Darcy’s law. In this approach, the hydraulic conductivities used in the model represent the bulk properties of the fractured-rock formations. Water flux, which may pass through only a small fraction of the rock mass occupied by fractures, is simulated as distributed throughout the formations. The model cannot simulate ground-water flow controlled by a few discrete permeable fractures or fracture zones. The model is assumed to approximately represent regional flow conditions that are controlled by a large number of fractures or fracture zones distributed throughout the basin.

The model grid is aligned parallel to the regional strike of the sedimentary rocks and corresponds to the major axis of anisotropy of hydraulic conductivity, which also is aligned parallel to French Creek. An anisotropy of 0.2 for crystalline rocks, taken from Sloto (1990, p. 39), was applied to all rocks in the basin.

Model Domain and Boundary Conditions

The modeled area is 111 mi^2, which includes 70.7 mi^2 of the French Creek Basin and 40.3 mi^2 of adjacent areas (fig. 7). The modeled area was extended outside the French Creek Basin to natural hydrologic boundaries. To the east, the model boundary is the Schuylkill River. To the north, the model boundary includes Pigeon Creek, Stony Run, an unnamed tributary to the Schuylkill River, and the surface-water divides between those streams. To the west, the model boundary includes unnamed tributaries to Hay Creek, a short reach of Hay Creek, and the surface-water divide between French Creek and the Conestoga River. To the south, the model boundary includes Marsh Creek, Black Horse Creek, Pickering Creek, and the surface-water divide between Black Horse Creek and Pickering Creek.

Lateral boundaries of the model are defined as zero flux (no flow) cells at topographic divides that are assumed to be no-flow boundaries and as head-dependant cells at boundary streams using the MODFLOW-96 general-head boundary package. Head-dependent cells were used for boundary streams (McDonald and Harbaugh, 1988, p. 11-1) because ground-water discharge to these streams is both from within and outside the modeled area, and heads (water levels) in these cells can be affected by areas both within and outside the modeled area. The boundary head was set to the stream elevation. Streams outside the French Creek Basin draining to boundary streams are simulated using the MODFLOW-96 river package. The

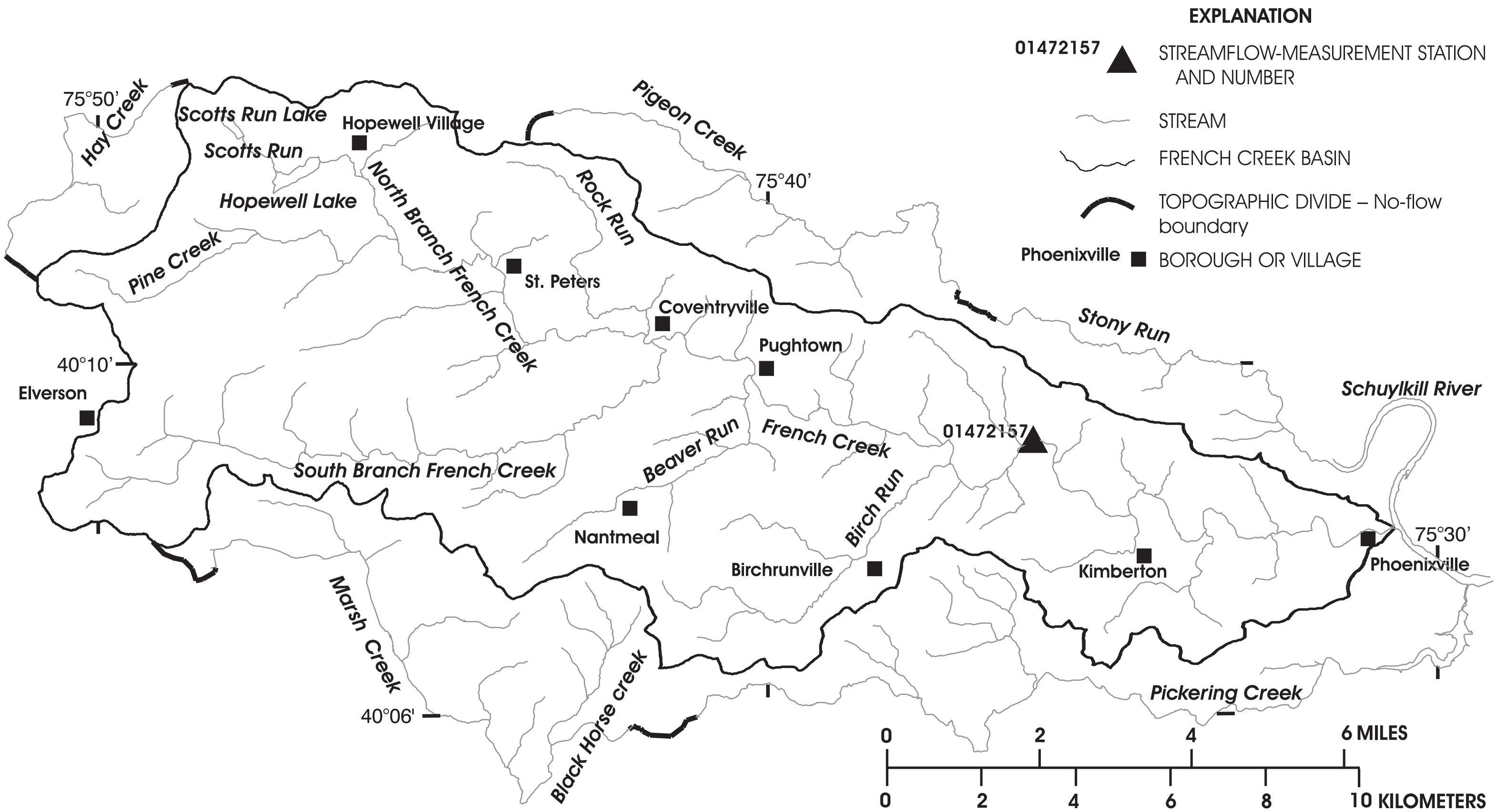


Figure 7. Model domain and streams in the French Creek Basin and surrounding area, Pennsylvania. The domain boundary is the outer streams and topographic divides.

bottom of the model was defined as a no-flow boundary, and the top was defined as a constant-flux boundary, where the flux equals the recharge rate. Constant-head cells are used to define Scotts Run Lake and Hopewell Lake at the upstream end of the North Branch French Creek. River cells are used to define the short reach of Scotts Run that connects Scotts Run Lake and Hopewell Lake.

Model Discretization

The modeled area is divided into a 232 by 127 cell grid totaling 29,464 cells (fig. 8). Within this grid are 18,096 active cells defining the modeled area. Cell size ranges from 142 by 180 ft to 532 by 540 ft. A finer grid was used around pumping wells. Land-surface elevations are from USGS digital elevation models (DEMs), which were converted from meters to feet and resampled on a 300-ft grid.

Locations of stream and river cells are from a geographic information system (GIS) spatial data set. 1,859 cells are defined as stream cells, and 410 cells are defined as river cells. The elevation of the stream and river cell bottoms were set at 1 ft below the cell land-surface elevation. The conductance for each stream and river cell was calculated with GMS using hydraulic conductivity, the length of the stream segment in the cell determined from the spatial data set, and stream width, which was estimated from field measurements. Stream widths measured at base-flow-measurement sites ranged from 4 ft for headwaters streams to 80 ft at base-flow measurement site 29 (fig. 5). Calculated conductances for stream and river cells ranged over several orders of magnitude. Conductance values generally were higher than aquifer hydraulic conductivity, which allowed free movement of water between the aquifer and stream.

Hydraulic Conductivity

Hydraulic conductivity was determined from specific-capacity data in the USGS Ground Water Site Inventory (GWSI) database. Specific capacity was computed from short-term (usually less than 4 hours) aquifer tests. Median specific capacities range from 0.13 (gal/min)/ft for diabase to 1.2 (gal/min)/ft for the Stockton Formation (table 5). Because few specific-capacity data are available for some geologic units in the French Creek Basin, data from the GWSI database for all wells in southeastern Pennsylvania for the geologic units present in the French Creek Basin were used (table 5).

The range of specific-capacity values is greater and the mean and median specific capacity is higher for wells in southeastern Pennsylvania than for wells in the French Creek Basin (table 5) because most wells in the French Creek Basin are domestic wells. Domestic wells include household wells and wells used by small business and commercial establishments. Nondomestic wells include public, industrial, and institutional supply wells. Generally, the specific capacity of nondomestic wells provides a better estimate of maximum aquifer productivity than does the specific capacity of domestic wells. Nondomestic wells are purposefully located and constructed for maximum yield. Domestic wells usually are located for convenience and are drilled only until an adequate yield for domestic use is obtained. The difference in specific capacity is attributed to nondomestic wells generally being deeper, penetrating more water-bearing zones, and having larger diameters than domestic wells.

Initial hydraulic conductivity for each geologic unit was calculated from reported specific-capacity data (table 5) using the method of Theis (1963, p. 332-341).

$$T' = 0.134\, Q/s\, (K - 264 \log_{10} 5S + 264 \log_{10} t) \qquad (3)$$

and

$$K = -66 - 264 \log_{10} (3.74\, r^2 \times 10^{-6}), \qquad (4)$$

where

T' is estimated transmissivity in feet squared per day,

Q/s is specific capacity in gallons per minute per foot,

K is a constant,

S is storage (dimensionless),

t is duration of pumping in days, and

r is well radius in feet.

Because the wells used for analysis have small diameters and tap consolidated rock, r was set equal to the well radius (Theis, 1963, p. 335). A storage value of 0.01 was used for crystalline rocks, and a storage value of 0.001 was used for Triassic sedimentary rocks. A monograph (Theis, 1963, p. 334) is used in the Theis method to

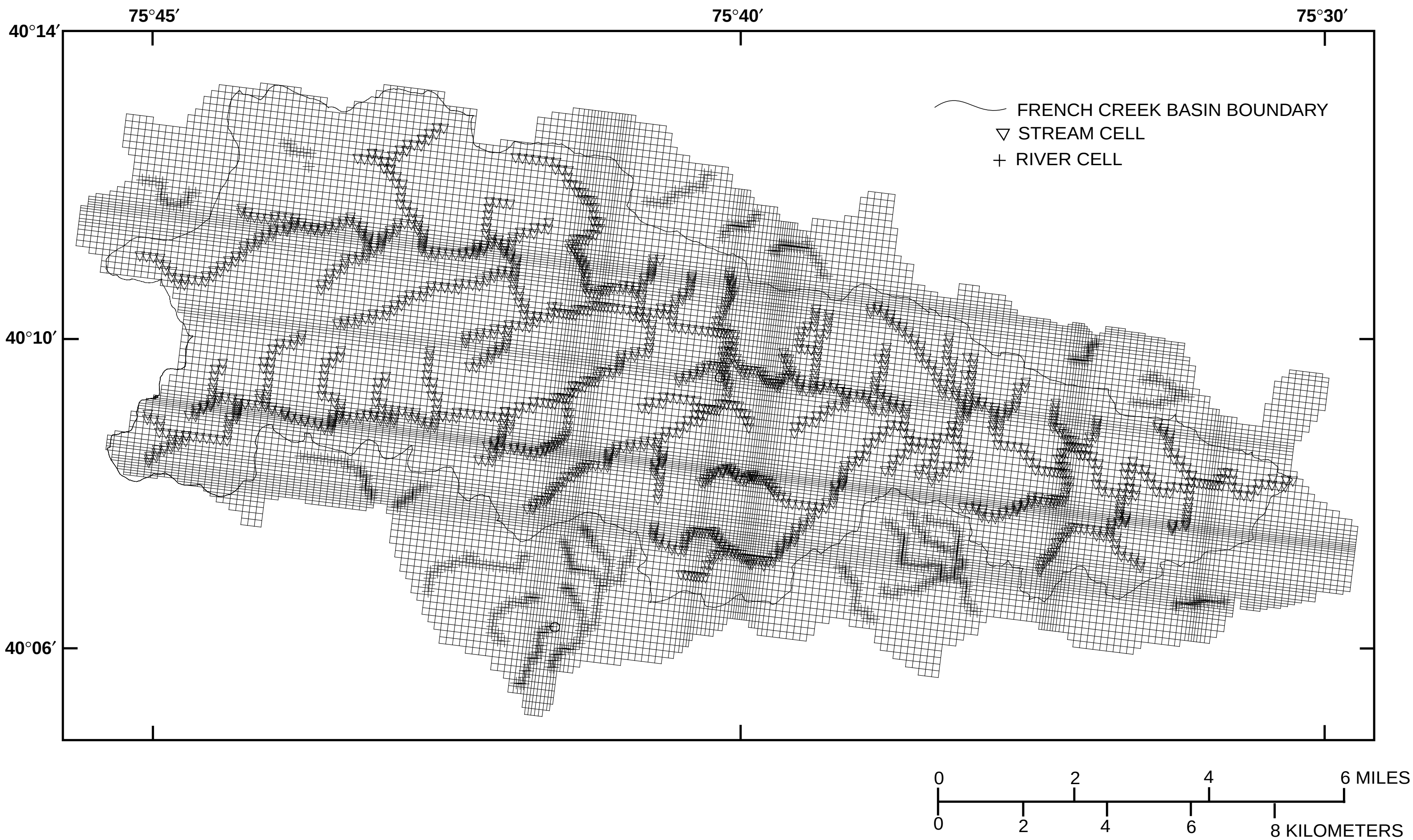


Figure 8. Finite-difference grid, stream cells, and river cells for the model of the French Creek Basin and surrounding area, Pennsylvania.

Table 5. *Specific-capacity values for geologic units in the French Creek Basin and southeastern Pennsylvania (Data are from the U.S. Geological Survey* Ground Water Site Inventory database.)

[<, less than]

Geologic unit	Number of wells	Specific capacity (gallons per minute per foot)		
		Range	Median	Mean
Southeastern Pennsylvania				
Diabase	90	< 0.01 - 5.1	0.13	0.44
Brunswick Group	449	.01 - 186	1.1	4
Hammer Creek Formation	171	.02 - 40	.50	2
Lockatong Formation	86	<.01 - 40	.21	1.3
Stockton Formation	372	.01 - 85	1.2	3.2
Vintage Dolomite	24	.03 - 29	.71	4
Antietam and Harpers Formations, undivided	29	<.01 - 4	.20	.67
Chickies Quartzite	94	<.01 - 5	.17	.45
French Creek Basin				
Diabase	7	<.01 - 3.8	.40	.79
Brunswick Group	84	.07 - 48	.65	2.2
Hammer Creek Formation	55	.03 - 5	.31	.48
Lockatong Formation	11	.02 - 4.8	.17	.87
Stockton Formation	55	.01 - 15	.22	2.1
Vintage Dolomite	9	.12 - 6	.71	1.3
Antietam and Harpers Formations, undivided	4	.02 - .25	--	--
Chickies Quartzite	56	<.01 - 3	.16	.39
Felsic gneiss, amphibolite facies	15	.01 - 1.3	.23	.38
Felsic gneiss, granulite facies	1	3.5	--	--
Felsic and intermediate gneiss, granulite facies	46	.01 - 4.6	.24	.65
Graphitic felsic gneiss, amphibolite facies	59	<.01 - 12	.28	1.29
Graphitic felsic gneiss, granulite facies	10	.01 - 3.7	.55	.93

estimate transmissivity (T) from the estimated transmissivity (T′) in equation 3. Specific-capacity values on the x-axis of the monograph range from 0 to 70 (gal/min)/ft. Because most of the specific capacity values for the French Creek Basin are less than 0.5 (gal/min)/ft (table 5), T was assumed to equal T′. Hydraulic conductivity was obtained by dividing the calculated transmissivity by 400 ft, the approximate saturated thickness of the aquifer based on the vertical distribution of water-bearing zones. The initial hydraulic conductivity of each geologic unit was adjusted during model calibration (table 6). In addition, available aquifer-test data on file with the DRBC were evaluated. A comparison of hydraulic conductivity values computed from specific-capacity data from aquifer tests with final model values are given in table 7.

A spatial (GIS) geology data set was imported into GMS, and a polygon was created for each geologic unit. A total of 26 polygons representing 11 geologic units were created. A value for hydraulic conductivity was assigned to each polygon. Thus, a geologic unit may have more than one value of hydraulic conductivity because it has more than one polygon. For example, the Stockton Formation is represented by five polygons. The main exposure of the Stockton is divided by diabase. In addition, three outliers of the Stockton cap hills of Precambrian and Paleozoic rocks (Bascom and Stose, 1938, p. 68). Each of these five exposures differ in lithologic character and have different hydraulic properties. Hydraulic-conductivity values assigned to Stockton Formation polygons varied from 0.8 to 1.3 (gal/min)/ft.

A single value of hydraulic conductivity was assigned to each occurrence (GIS polygon) of each geologic unit. In reality, hydraulic conductivity and storage varies greatly from place to place within each geologic unit, sometimes by orders of magnitude. The assigned hydraulic conductivity represents the adjusted regional average for that geologic unit.

Table 6. *Estimated and final hydraulic-conductivity values used in the model of the French Creek Basin and surrounding area, Pennsylvania*

[ft/d, feet per day; --, no data available]

Geologic unit	Hydraulic conductivity estimated from specific capacity (ft/d)		Final model hydraulic conductivity (ft/d)
	Range	Mean	
Diabase	0.01 - 2.3	0.47	0.2 - 0.6
Brunswick Group	.04 - 29	1.3	2.1
Hammer Creek Formation	.02 - 3.0	.29	.6 - 3.2
Lockatong Formation	.01 - 2.9	.52	.8
Stockton Formation	.01 - 9.0	1.3	.8 - 4.0
Chickies Quartzite	.01 - 1.8	.23	.1 - .4
Felsic gneiss, amphibolite facies	.01 - 1.6	.46	.6
Felsic gneiss, granulite facies	--	--	.6
Felsic and intermediate gneiss, granulite facies	.01 - 2.7	.39	.25 - .3
Graphitic felsic gneiss, amphibolite facies	.01 - 7.2	.77	1.5
Graphitic felsic gneiss, granulite facies	.01 - 2.2	.56	.65 - .8

Table 7. *Hydraulic conductivity calculated from aquifer-test data, French Creek Basin, Pennsylvania*

[gal/min, gallons per minute; ft^2/d, feet squared per day; ft/d, feet per day; [(gal/min)/ft], gallons per minute per foot; USGS, U.S. Geological Survey]

Well identification number	Pumping rate (gal/min)	Transmissivity (ft^2/d)	Hydraulic conductivity from transmissivity (ft/d)	Specific capacity [(gal/min)/ft]	Hydraulic conductivity from specific capacity (ft/d)	Hydraulic conductivity used in the model (ft/d)	Geologic unit	Source of data
CH-6647	92	520	1.3	3.0	2.0	0.8 - 4	Stockton Formation	Average values from Leggette, Bradshears, and Graham, Inc. (2000)
CH-6646	95	430	1.1	2.3	1.6	.8 - 4	Stockton Formation	Average values from Leggette, Bradshears, and Graham, Inc. (2000)
CH-152	60	300	.75	2.9	1.9	.8 - 4	Stockton Formation	Average values from Environmental Resources Management, Inc. (1989)
CH-1499	300	840	2.1	3.8	2.6	.8 - 4	Stockton Formation	USGS file data
CH-152	60	2,200	5.4	3.5	2.4	.8 - 4	Stockton Formation	Average values from Rima and others (1962)
CH-181	225	940	2.4	2.1	1.4	2.1	Brunswick Group	Longwill and Wood (1965)
CH-4370	8	1.7	.004	.06	.04	.25 - .3	Felsic and intermediate gneiss, granulite facies	Average values from Elverson Water Company data
CH-5282	43	11.9	.03	.20	.12	.25 - .3	Felsic and intermediate gneiss, granulite facies	Average values from Elverson Water Company data
CH-4111	100	180	.44	.44	.26	.25 - .3	Felsic and intermediate gneiss, granulite facies	Groundwater and Environmental Services, Inc. (1989)
CH-4110	60	350	.88	.26	.16	.25 - .3	Felsic and intermediate gneiss, granulite facies	Groundwater and Environmental Services, Inc. (1989)
CH-6649	26.3	470	1.2	.65	.39	.6	Graphitic felsic gneiss, amphibolite facies	Average values from David Blackmore & Associates., Inc.
St. Stephens 3	78	1,300	3.3	1.1	.65	.6	Graphitic felsic gneiss, amphibolite facies	Average values from David Blackmore & Associates., Inc.
CH-6650	23	490	1.2	.82	.49	.6	Graphitic felsic gneiss, amphibolite facies	Average values from David Blackmore & Associates., Inc.
CH-1204	620	1,200	2.9	8.1	4.8	.6	Graphitic felsic gneiss, amphibolite facies	Data from Roy F. Weston, Inc.

Aquifer Thickness

Aquifer thickness was set at 500 ft on the basis of the vertical distribution of water-bearing zones. For each model cell, the top of the aquifer was set equal to land surface, and the bottom of the aquifer was set equal to land surface minus 500 ft. Few water-bearing zones below 500 ft are penetrated. The distribution of 3,392 water-bearing zones in the French Creek Basin reported by drillers in 1,626 wells was analyzed (table 8). This analysis represents 182,659 ft of uncased borehole. Well depths are up to 600 ft. The data are summarized by hydrogeologic unit or rock type and by interval below land surface. The data are expressed in units of water-bearing zones per 100 ft of uncased borehole. Wells drilled in diabase penetrated slightly fewer water-bearing zones than did wells drilled in other hydrogeologic units. The number of water-bearing zones per 100 ft of uncased borehole ranged from 1.15 for diabase to 2.61 for the Hammer Creek Formation. The frequency of occurrence of water-bearing zones generally decreases with depth (table 8). Ninety-three percent of water-bearing zones are above 250 ft below land surface, and 96 percent of water-bearing zones are above 400 ft below land surface.

Evapotranspiration Rate

Ground-water ET is simulated using the ET package in MODFLOW-96 (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). The rate varies linearly with depth from the maximum rate at land surface to 0 at 10 ft below the land surface (extinction depth). The maximum ground-water ET rate at land surface was set to 2 in/yr, which was chosen on the basis of model simulations in the nearby Valley Creek Basin (Sloto, 1990, p. 36).

Pumping Rates

Most of the French Creek Basin is rural. Water is supplied by domestic wells, and wastewater is disposed through septic systems. Public water systems supply the boroughs of Phoenixville and Elverson. Phoenixville, at the mouth of French Creek, is supplied by surface water from the Schuylkill River. Elverson, on the west side of the basin, is supplied by wells (table 9). The model includes 41 wells (fig. 9) with annual pumpage rates ranging from 0.5 to 23.5 Mgal/yr (table 5). The most recent pumpage data available from the Pennsylvania Department of Environmental Protection was used. These rates are equal to continuous pumping rates ranging from 0.9 to 43.1 gal/min; the total pumping rate for the modeled area is 295.4 gal/min.

Table 8. *Number of water-bearing zones reported per 100 feet of uncased borehole drilled in the French Creek Basin, Pennsylvania*

[--, no data]

Interval (feet below land surface)	Number of water-bearing zones		Footage drilled (feet)	Number of water-bearing zones		Footage drilled (feet)
	Total	Per 100 feet of uncased borehole		Total	Per 100 feet of uncased borehole	
	Diabase (24 wells)			Brunswick Group (116 wells)		
0-50	12	4.64	258	11	1.55	711
51-100	15	1.58	948	106	2.42	4,375
101-150	6	.99	607	65	1.85	3,510
151-200	2	.39	508	32	1.59	2,012
201-250	2	.44	450	16	1.36	1,179
251-300	3	.67	450	7	.94	746
301-350	2	.7	285	8	1.45	550
351-400	1	.51	195	2	.55	365
401-450	0	0	40	2	1.08	185
451-500	--	--	--	1	.67	150
501-550	--	--	--	2	2.56	78
551-600	--	--	--	0	0	50
Total (mean)	43	(1.15)	3,741	252	(1.8)	13,971
	Hammer Creek Formation (136 wells)			Lockatong Formation (11 wells)		
0-50	33	3.92	843	0	0	64
51-100	135	3.21	4,200	4	1.25	319
101-150	99	2.77	3,579	8	1.9	421
151-200	41	1.97	2,085	6	1.62	370
201-250	16	1.45	1,105	0	0	200
251-300	12	1.87	643	1	.51	198
301-350	5	1.35	370	0	0	150
351-400	3	1.42	212	3	2.26	133
401-450	2	1.35	148	0	0	100
451-500	0	0	53	1	1	100
501-550	0	0	5	4	4	100
551-600	--	--	--	1	1.75	57
Total (mean)	346	(2.61)	13,243	28	(1.27)	2,212

Table 8. *Number of water-bearing zones reported per 100 feet of uncased borehole drilled in the French Creek Basin, Pennsylvania*—*Continued*

[--, no data]

Interval (feet below land surface)	Number of water-bearing zones		Footage drilled (feet)	Number of water-bearing zones		Footage drilled (feet)
	Total	Per 100 feet of uncased borehole		Total	Per 100 feet of uncased borehole	
	Stockton Formation (79 wells)			Chickies Quartzite (206 wells)		
0-50	21	3.43	612	46	1.81	1,147
51-100	69	2.46	2,808	132	4.01	5,571
101-150	36	1.82	1,979	105	2.37	5,703
151-200	19	1.48	1,281	57	1.84	3,922
201-250	7	1.01	695	42	1.45	2,664
251-300	2	.5	399	16	1.58	1,668
301-350	4	1.36	295	11	.96	807
351-400	8	3.33	240	3	1.36	550
401-450	0	0	102	0	.55	402
451-500	0	0	92	1	0	291
501-550	--	--	--	0	.34	112
551-600	--	--	--	2	0	90
Total (mean)	166	(1.95)	8,503	415	(2.22)	22,927
	Gneiss (892 wells)					
0-50	375	1.92	8120			
51-100	822	4.62	31,313			
101-150	313	2.63	22,604			
151-200	189	1.38	14,361			
201-250	72	1.32	8,721			
251-300	49	.83	5,785			
301-350	30	.85	3,157			
351-400	8	.95	1,706			
401-450	6	.47	689			
451-500	1	.87	306			
501-550	0	.33	145			
551-600	1	0	75			
Total (mean)	1,866	(1.33)	97,037			

Table 9. *Pumping wells in the French Creek Basin, Pennsylvania*

[Data were supplied by the Pennsylvania Department of Environmental Protection. Mgal/yr, millions of gallons per year; gal/min, gallons per minute]

Well identification number	Model row	Model column	Annual pumpage (Mgal/yr)	Continuous pumping rate (gal/min)	Owner
CH-164	57	213	2.43	4.5	Budd Company
CH-6657	78	93	2.24	4.1	Camp Hill Special School 1
CH-6658	80	92	1.49	2.7	Camp Hill Special School 2
CH-3204	57	163	2.34	4.3	Camp Hill Village USA
CH-2407	86	180	21.09	38.7	Citizens Utilities Merlin Hills EP-1
CH-6659	24	91	.91	1.7	Coventry Manor Nursing Home 2
CH-4110	68	21	5.68	10.4	Elverson Water Company 1
CH-4370	67	22	1.5	2.7	Elverson Water Company 2
CH-5282	67	22	5.68	10.4	Elverson Water Company 3
CH-4111	68	22	1.21	2.2	Elverson Water Company 4
CH-2053	90	174	1.2	2.2	Fox Knoll Water Company
BE-1441	17	40	11.42	20.9	French Creek State Park A
BE-1442	18	37	2.05	3.7	French Creek State Park B
CH-5547	64	22	2.6	4.8	Graco Childrens Products
CH-1585	75	177	7.47	13.7	Henry 3
CH-5391	76	177	1.4	2.6	Henry remediation PW-1
CH-5392	74	178	1.4	2.6	Henry remediation PW-2
CH-5393	73	179	1.4	2.6	Henry remediation PW-3
CH-5394	75	179	1.4	2.6	Henry remediation PW-4
CH-5395	75	180	1.4	2.6	Henry remediation PW-5
CH-5396	76	181	1.4	2.6	Henry remediation PW-6
CH-5397	76	181	1.4	2.6	Henry remediation PW-7
CH-5398	77	180	1.4	2.6	Henry remediation PW-8
CH-5399	77	180	1.4	2.6	Henry remediation PW-9
CH-5400	77	181	1.4	2.6	Henry remediation PW-10
CH-6651	76	224	.49	.9	Nichols Mobile Home Park
CH-1499	30	130	11.37	20.8	Owen J. Roberts School
CH-2523	111	86	14.01	25.7	Philadelphia Suburban Water Company Stonehedge 8
CH-6660	84	217	1.13	2.1	Phoenix Mobile Homes 1
CH-6661	83	216	5.8	10.6	Phoenix Mobile Homes 2
CH-6662	75	195	3.06	5.6	Phoenix Mobile Homes 3
CH-2482	77	186	3.43	6.3	Pierce and Stevens Chemical 1
CH-2483	77	186	.81	1.5	Pierce and Stevens Chemical 2
CH-5273	36	122	0	0	Realen Homes Ridgelea SW-1
CH-5274	35	129	0	0	Realen Homes Ridgelea SW-2
CH-6649	103	139	1.43	2.6	St. Stephens Green 2
CH-6650	104	139	1.43	2.6	St. Stephens Green 4
CH-6652	39	74	.55	1	Warwick Land Division Mobile Home Park
CH-4974	36	69	2.69	4.9	Warwick Waterworks Association 1
CH-4975	35	69	2.69	4.9	Warwick Waterworks Association 2
CH-4976	36	69	2.69	4.9	Warwick Waterworks Association 3
CH-4977	36	69	2.69	4.9	Warwick Waterworks Association 4
CH-156	70	205	23.51	43.1	West Company WW-1
Total			161.15	295.4	

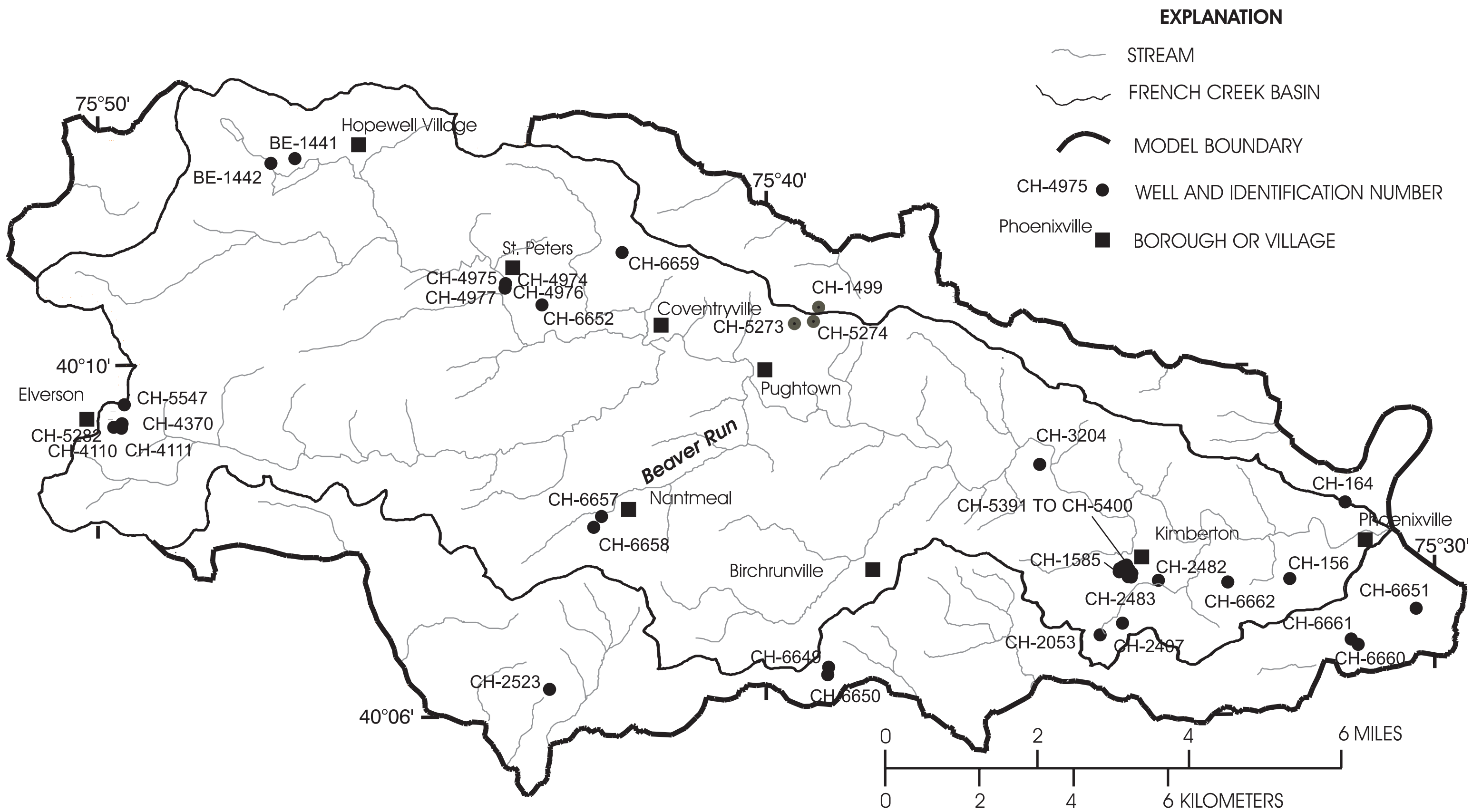


Figure 9. Location of pumping wells in the modeled area, French Creek Basin, Pennsylvania.

Model Calibration

The model was calibrated using stream base-flow measurements (table 2) and water-level measurements (table 10) collected in the French Creek Basin on May 1, September 11, and September 17, 2001. The measurements on May 1 were made during higher than average base-flow conditions. The measurements on September 11 and 17 were made during lower than average base-flow conditions. The model was calibrated for above-average conditions using base-flow and water-level measurements made on May 1, 2001 (tables 2 and 10, respectively), and for below-average conditions using base-flow and water-level measurements made on September 11 and 17, 2001 (tables 2 and 10, respectively). Average conditions were simulated by adjusting the recharge rate until simulated streamflow at streamflow-measurement station 01472157 matched the long-term (1968-2001) average base flow of 54.1 ft^3/s.

Simulated base flows were compared graphically to measured base flows to calibrate the model. Simulated water levels were compared to measured water levels using the root mean squared error (RMSE) between measured and simulated values. The objective of calibration was to minimize the RMSE. RMSE is calculated by

$$RMSE = \sqrt{\frac{\Sigma(h_m - h_s)^2}{n}} \tag{5}$$

where

h_m is measured water level,
h_s is simulated water level, and
n is number of wells.

Table 10. *Water levels measured in the French Creek Basin, Pennsylvania, on May 1, September 11, and September 17, 2001*

[Water-level elevation is in feet above NGVD 29]

Well-identification number	May 1, 2001		September 11, 2001		September 17, 2001	
	Depth to water (feet)	Water-level elevation	Depth to water (feet)	Water-level elevation	Depth to water (feet)	Water-level elevation
BE-368	9.96	610.04	12.90	607.10	13.02	606.98
BE-383	25.28	604.72	25.96	604.04	26.07	603.93
BE-1712	3.28	634.72	7.07	630.93	7.33	630.67
BE-1713	3.70	658.30	10.98	651.02	11.32	650.68
CH-1351	48.93	546.07	52.22	542.78	52.39	542.61
CH-1482	22.37	621.63	30.17	613.83	30.50	613.50
CH-1487	80.08	459.92	83.70	456.30	83.84	456.16
CH-1489	5.51	504.49	7.00	503.00	7.05	502.95
CH-1565	12.93	239.07	16.18	235.82	18.31	233.69
CH-1571	5.88	274.12	10.25	269.75	10.37	269.63
CH-2328	1.31	450.69	4.11	447.89	3.99	448.01
CH-3590	14.11	265.89	15.02	264.98	15.24	264.76
CH-4108	34.88	640.12	[1] 61.95	613.05	50.62	624.38
CH-6281	75.23	234.77	78.67	231.33	78.81	231.19
CH-6282	31.22	210.78	[1] 55.25	186.75	51.00	191.00
CH-6283	24.62	637.38	[1] 42.22	619.78	35.20	626.80
CH-6284	12.03	537.97	19.81	530.19	20.96	529.04
CH-6285	32.80	322.20	36.91	318.09	38.63	316.37
CH-6286	91.54	288.46	96.45	283.55	98.10	281.90
CH-6287	65.06	584.94	72.82	577.18	73.05	576.95
CH-6289	50.58	291.42	62.06	279.94	62.88	279.12
CH-6290	37.32	590.68	44.65	583.35	45.10	582.90

[1] Water level probably affected by recent pumping of well.

For the calibration of above-average conditions using data collected on May 1, 2001, a recharge rate of 20 in/yr was used. This rate is comparable to recharge rates for years of above-average precipitation from the water budgets (table 4). The measured base flow at the streamflow-measurement station on May 1 was 71.7 ft^3/s; the simulated base flow was 71.4 ft^3/s. The measured base flow at the mouth of French Creek on May 1 was 89 ft^3/s; the simulated base flow was 88.3 ft^3/s. The simulated base flow compares well with the base flow for years of above-average precipitation (table 4). A comparison between base flow measured on May 1 at 34 sites and simulated base flow at those sites (fig. 10) shows excellent

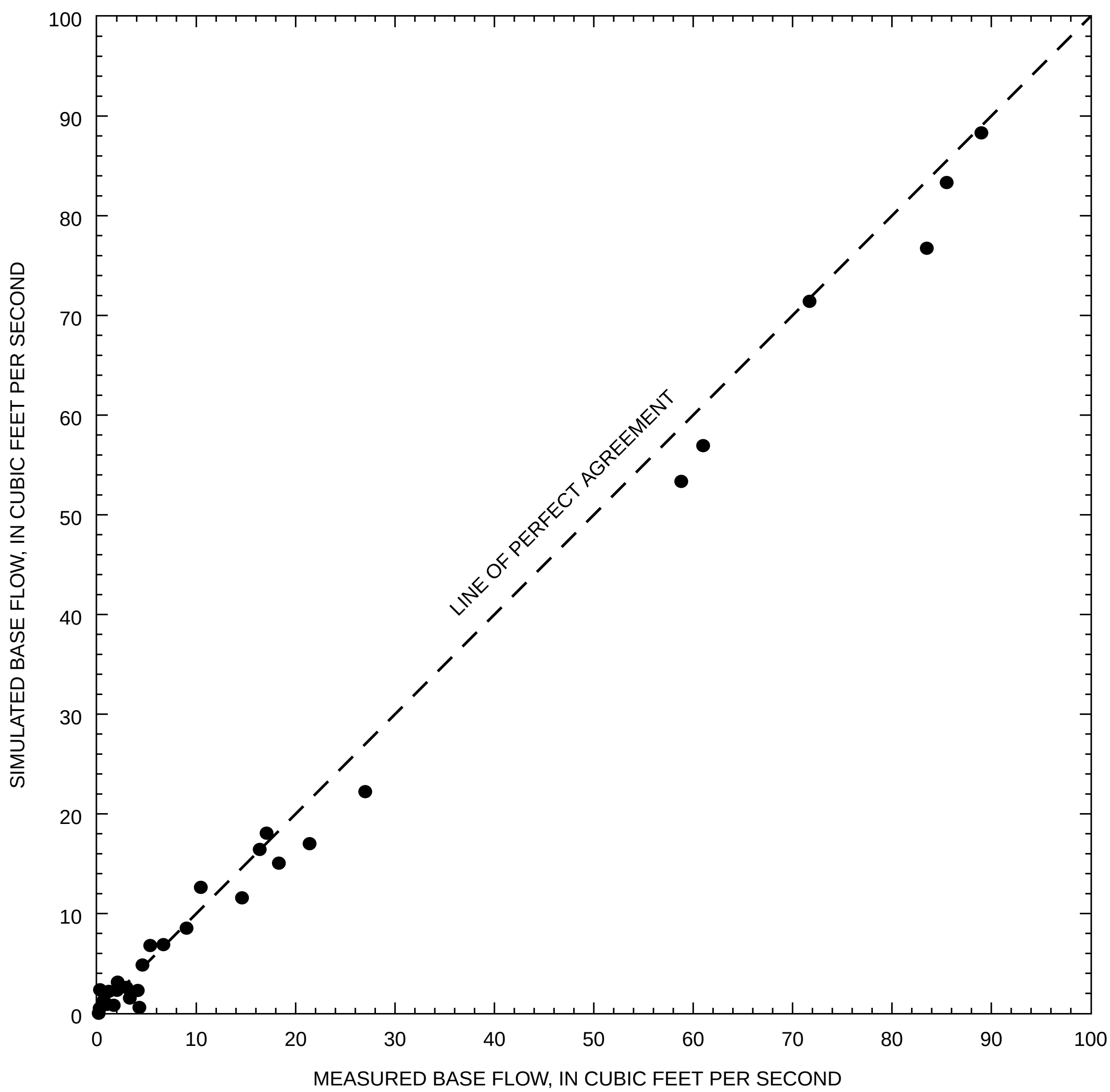


Figure 10. Relation between measured and simulated base flow of French Creek, Pennsylvania, May 1, 2001.

agreement. The RMSE between water levels measured in observation wells and the simulated water level in the cell where the measured wells are located was 23 ft or 5 percent of the total water-level change across the basin. A comparison between water levels measured in 21 wells on May 1 and simulated water levels in the cells where the observation wells are located (fig. 11) shows good agreement. The distribution of differences between water levels measured in observation wells and the simulated water level in the cell where the observation well is located is shown in figure 12.

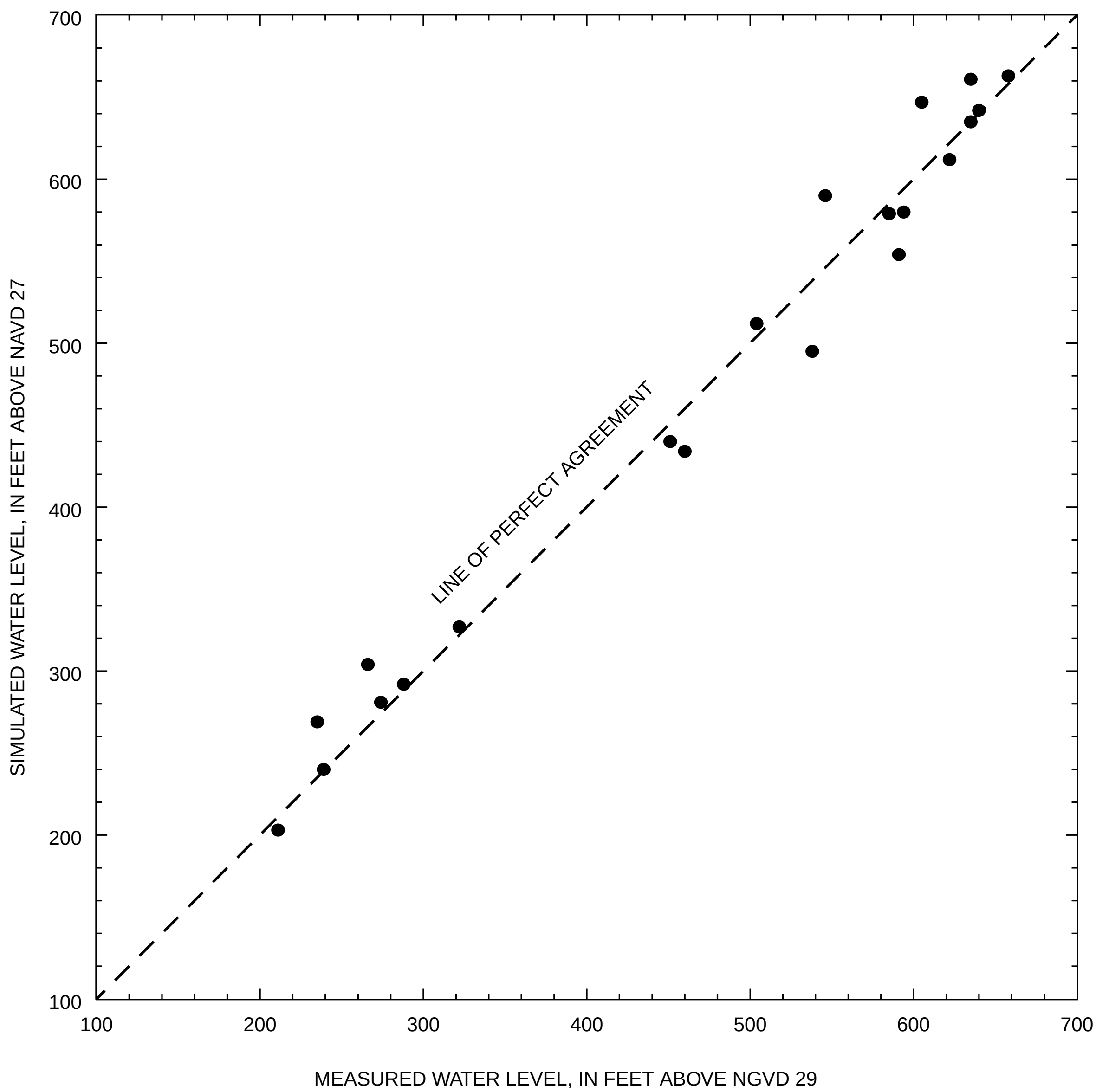


Figure 11. Relation between water levels measured in observation wells in the French Creek Basin, Pennsylvania, and simulated water levels in model cells where the observation wells are located, May 1, 2001.

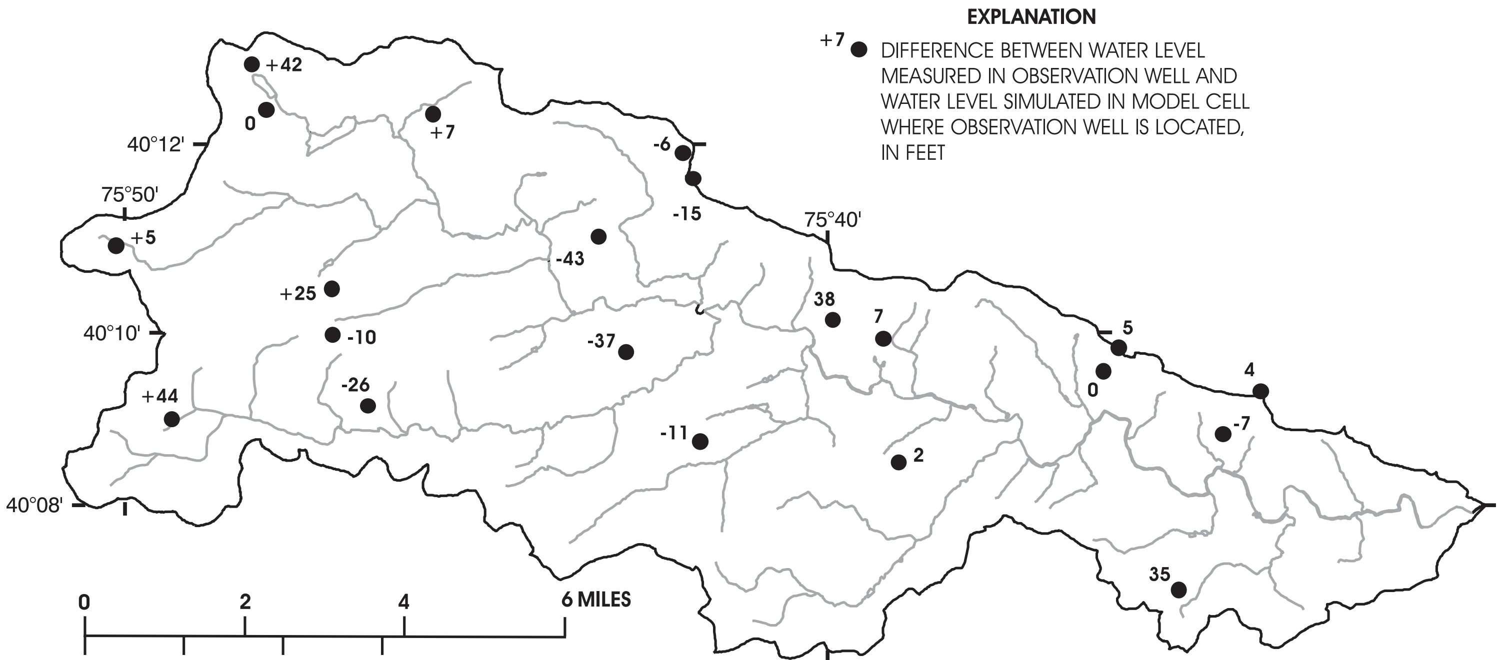


Figure 12. Difference between water levels measured in observation wells on May 1, 2001, in the French Creek Basin, Pennsylvania, and water levels simulated in model cells where observation wells are located.

For the calibration of below-average conditions using data collected on September 11 and 17, 2001, a recharge rate of 6.2 in/yr was used. This rate is less than the recharge rate for years of below-average precipitation in the water budgets (table 4). The measured base flow at the streamflow-measurement station on September 11 was 17.1 ft^3/s; the simulated base flow was 17.1 ft^3/s. Measured base flow at the mouth of French Creek on September 11 was 20.2 ft^3/s; the simulated base flow was 22.5 ft^3/s. The simulated base flow compares well with the average annual base flow for years of below-average precipitation (table 2). A comparison between base flow measured on September 11 and 17 at 34 sites and simulated base flow shows good agreement (fig. 13). The RMSE between measured water levels and

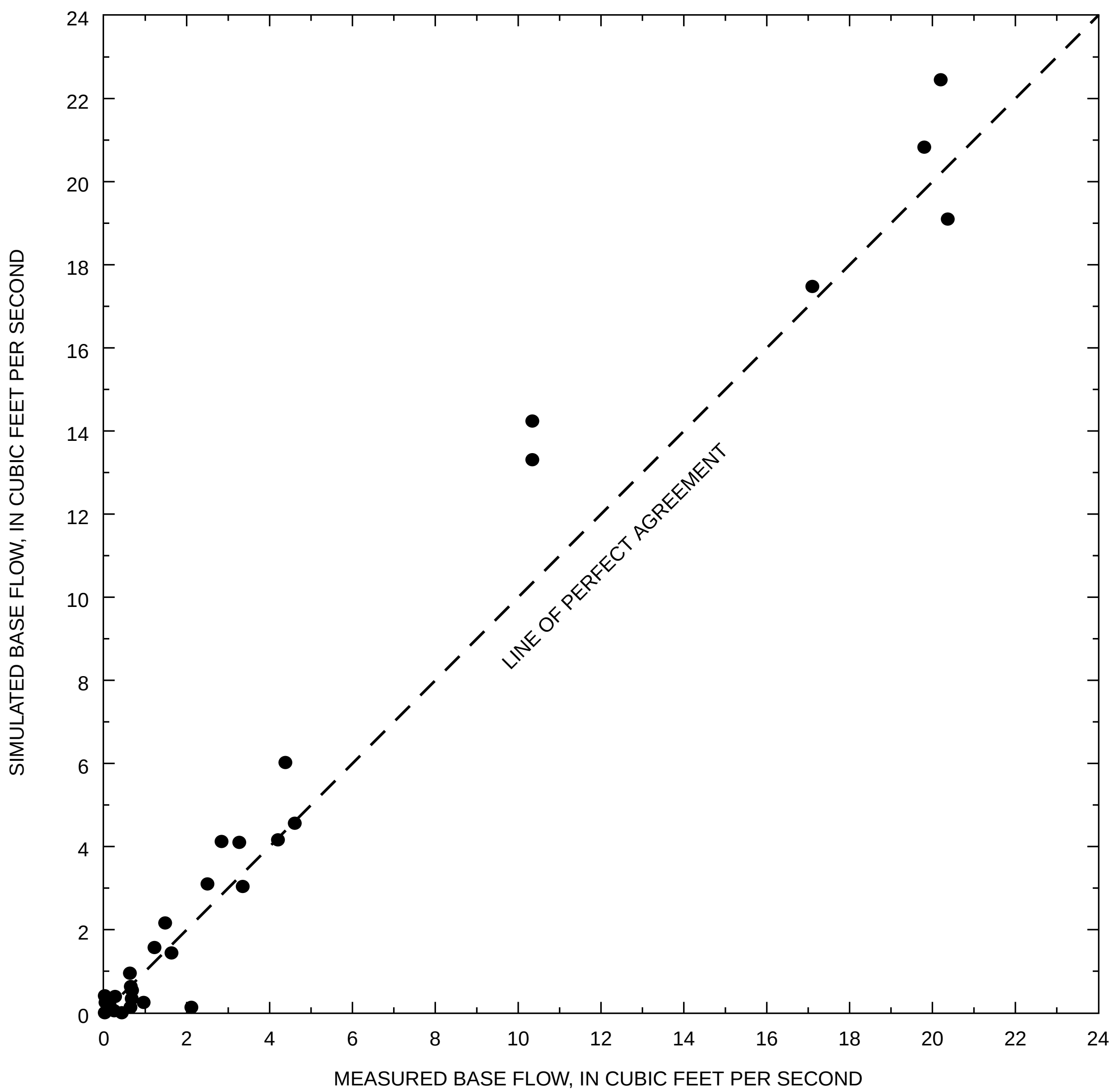


Figure 13. Relation between measured and simulated base flow of French Creek, Pennsylvania, September 11 and 17, 2001.

the simulated water level in the cell in which measured wells are located was 65 ft or 14 percent of the total water-level change across the basin.

A comparison between water levels measured in 21 wells on September 11 and simulated water levels in the cells where the measured wells are located (fig. 14) shows that many simulated water levels are lower than the measured water levels. The distribution of differences between water levels measured in observation wells and the simulated water level in the cell where the observation well is located is shown in figure 15.

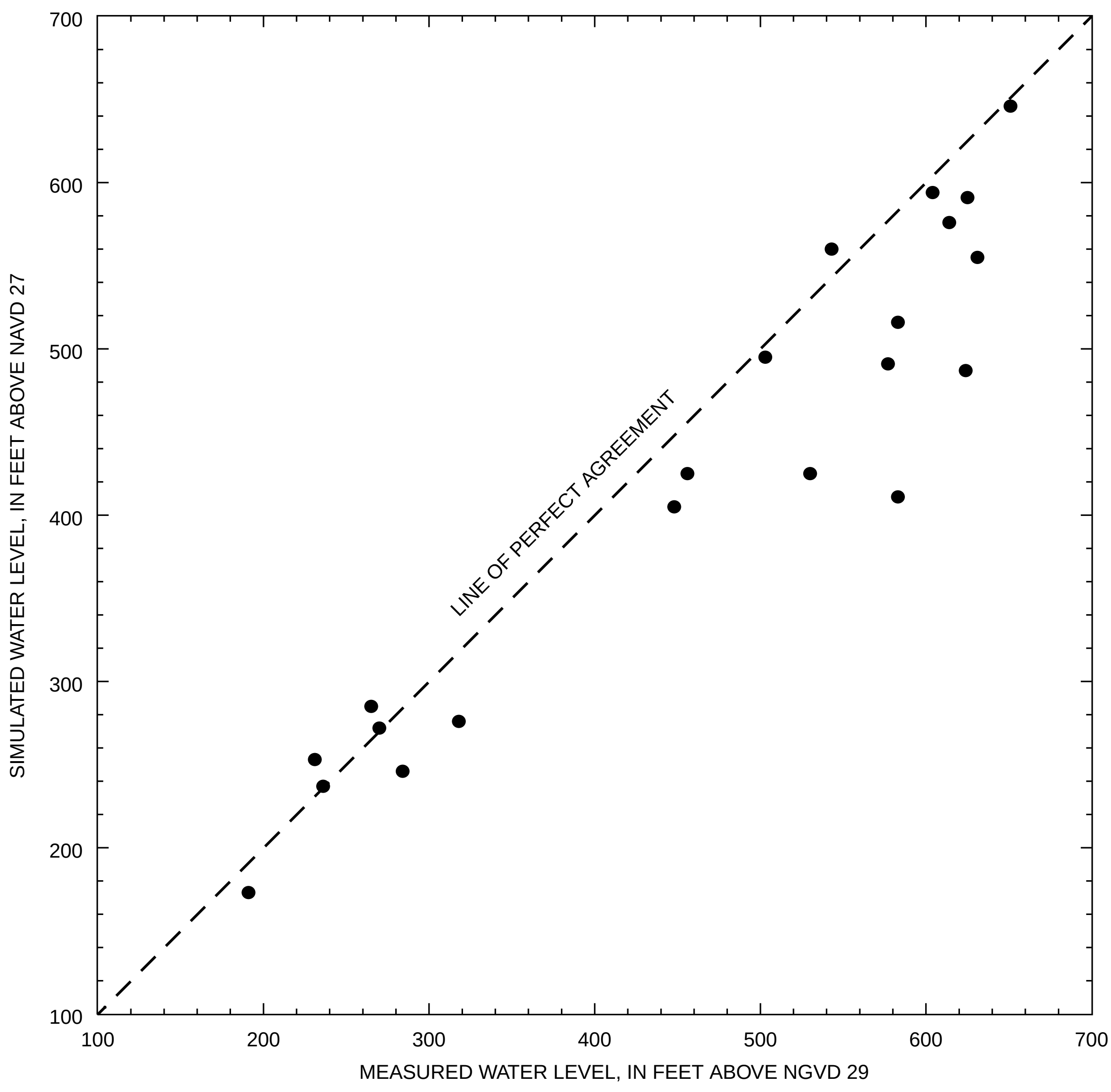


Figure 14. Relation between water levels measured in observation wells in the French Creek Basin, Pennsylvania, and simulated water levels in model cells where the observation wells are located, September 11, 2001.

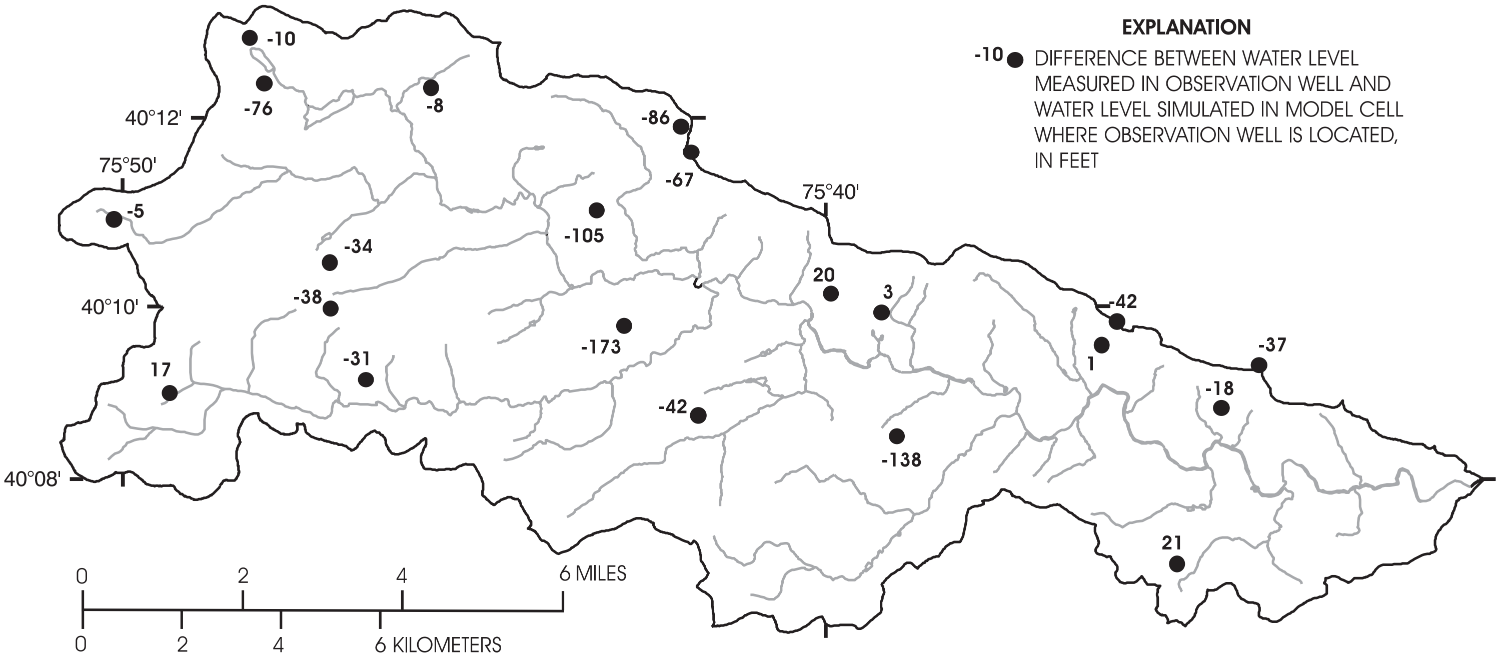


Figure 15. Difference between water levels measured in observation wells on September 11, 2001, in the French Creek Basin, Pennsylvania, and water levels simulated in model cells where observation wells are located.

The model was used to determine the recharge rate for long-term average conditions. Recharge was adjusted until the long-term average base flow at the streamflow-measurement station was simulated. A recharge rate of 15.7 in/yr provided the best fit. This rate compares well with the average long-term (1969-2001) recharge rate of 14.32 in. from the water budget (table 4). Long-term average base flow at the streamflow-measurement station is 54.1 ft^3/s; the simulated base flow was 54.3 ft^3/s. The simulated base flow compares well with the average (1969-2001) base flow of 12.42 in. (table 3), which is equal to 54 ft^3/s at the streamflow-measurement station.

A sensitivity analysis was conducted to determine which model-input parameters had the greatest effect on model output. A sensitivity analysis is the process of varying model input parameters over a reasonable range (the range of uncertainty in values of the model parameters) and observing the relative change in model response (water level and base flow). The purpose of the sensitivity analysis is to demonstrate the sensitivity of the model simulations to uncertainty in values of model-input data. The sensitivity analysis was done by systematically changing the value of a single model-input parameter while holding the values of the other input variables constant. The changes in base flow at the streamflow-measurement station and the RSME for water levels then were graphically compared. A line with little or no slope indicates little sensitivity of the model output to changes in the value of the input parameter. A line with a steep slope indicates greater sensitivity of the model output to changes in the value of the input parameter.

The sensitivity analysis showed that base flow at the streamflow-measurement station was sensitive to changes in recharge and ground-water ET rate (fig. 16). Base flow at the streamflow-measurement station was not sensitive to changes in the values of aquifer anisotropy, aquifer hydraulic conductivity, aquifer thickness, or streambed conductance. This insensitivity indicates that errors in estimating the values of aquifer anisotropy, aquifer hydraulic conductivity, aquifer thickness, and streambed conductance would have little effect on simulated base flow. Errors in estimating the values of recharge and ground-water ET rates would have substantial effect on simulated base flows. Aquifer anisotropy, aquifer hydraulic conductivity, aquifer thickness, and streambed conductance affect the flow of water through the ground-water system; recharge represents an input of water to the system, and ground-water ET represents a removal of water from the system. Recharge rates can be determined reasonably from the water budget. Direct measurement of ground-water ET from the basin is not possible, so it is estimated, and more uncertainty is associated with its value than with values of recharge.

The sensitivity analysis showed that the RMSE between measured and simulated water levels was most sensitive to changes in the values of aquifer hydraulic conductivity, aquifer anisotropy, and decreases in aquifer thickness and least sensitive to changes in the values of streambed conductance, ground-water ET rate, and recharge (fig. 17). Aquifer hydraulic conductivity, aquifer anisotropy, and aquifer thickness are the model parameters that affect the movement of ground water through the system. Water levels particularly are affected by changes in aquifer hydraulic conductivity, and errors in estimating aquifer hydraulic conductivity have a substantial effect on water levels. Neither base flow nor water levels are sensitive to changes in the value of streambed conductance.

Transient Simulations

The only changes to the calibrated steady-state model for transient simulations were the change in recharge rate to simulate average and drought conditions and the addition of a storage coefficient for each geologic unit. A storage coefficient of 0.01 was used for crystalline rocks, 0.005 for Triassic sedimentary rocks, and 0.001 for diabase. A sensitivity analysis was conducted to determine the effect of varying the value of the storage coefficient. For the sensitivity analysis, a well pumping at 200 gal/min in the Stockton Formation for 3 years was simulated, and the storage coefficient of the Stockton was varied from 0.1 to 0.0001. The head (water level) in the cell with the pumped well after 3 years of pumping was 301.1 ft above NGVD 29 using a storage coefficient of 0.1 and 299.40 ft above NGVD 29 using a storage coefficient of 0.01, 0.001, and 0.0001. The model had little sensitivity to changes in the value of the storage coefficient in the expected range (less than 0.01) after about 60 days of pumping. The smaller the storage coefficient, the quicker the simulation reached steady state (fig. 18).

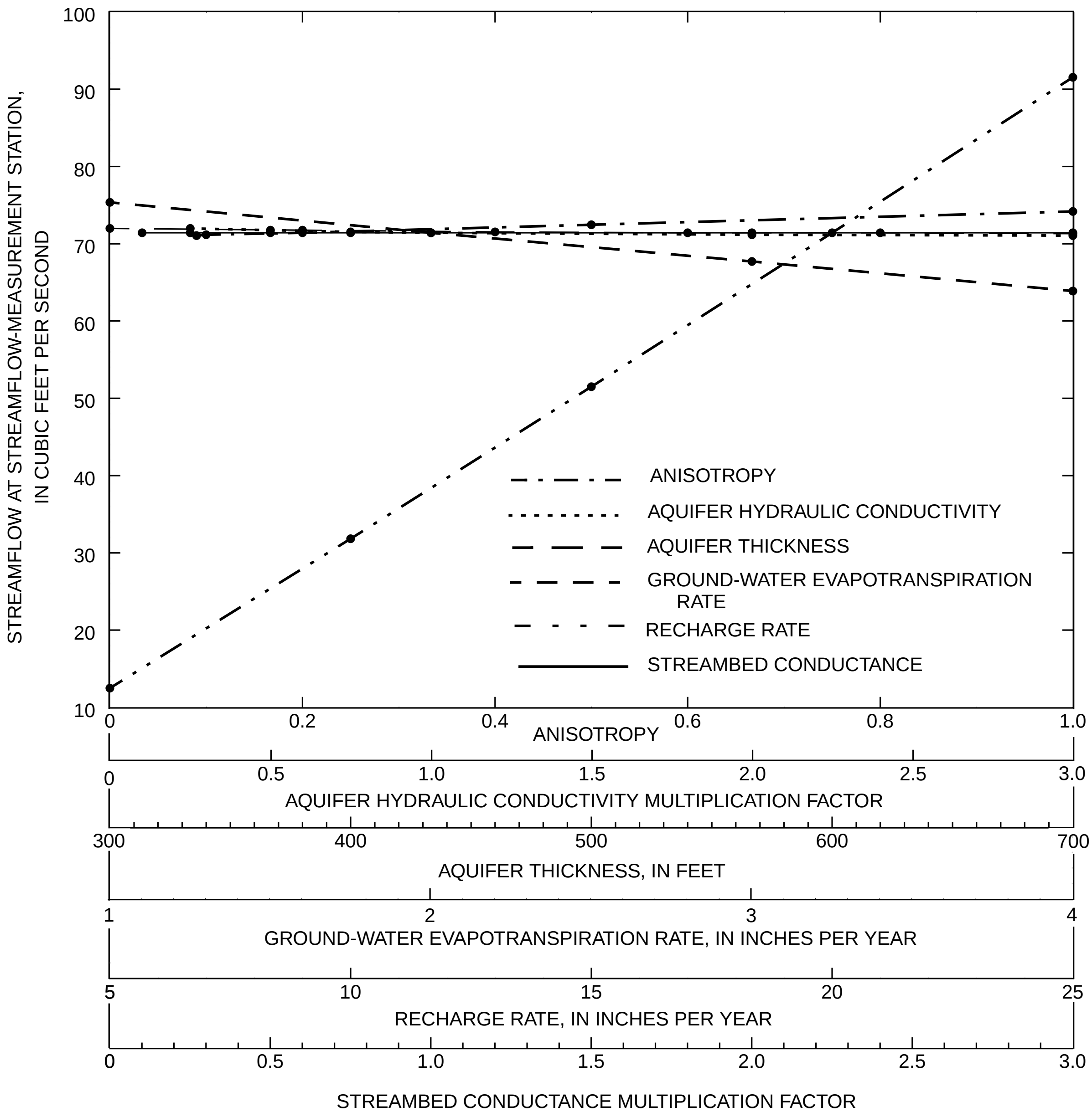


Figure 16. Effect of varying the values of anisotropy, aquifer hydraulic conductivity, aquifer thickness, ground-water evapotranspiration rate, recharge rate, and streambed conductance on simulated streamflow at streamflow-measurement station French Creek near Phoenixville, Pennsylvania (01472157).

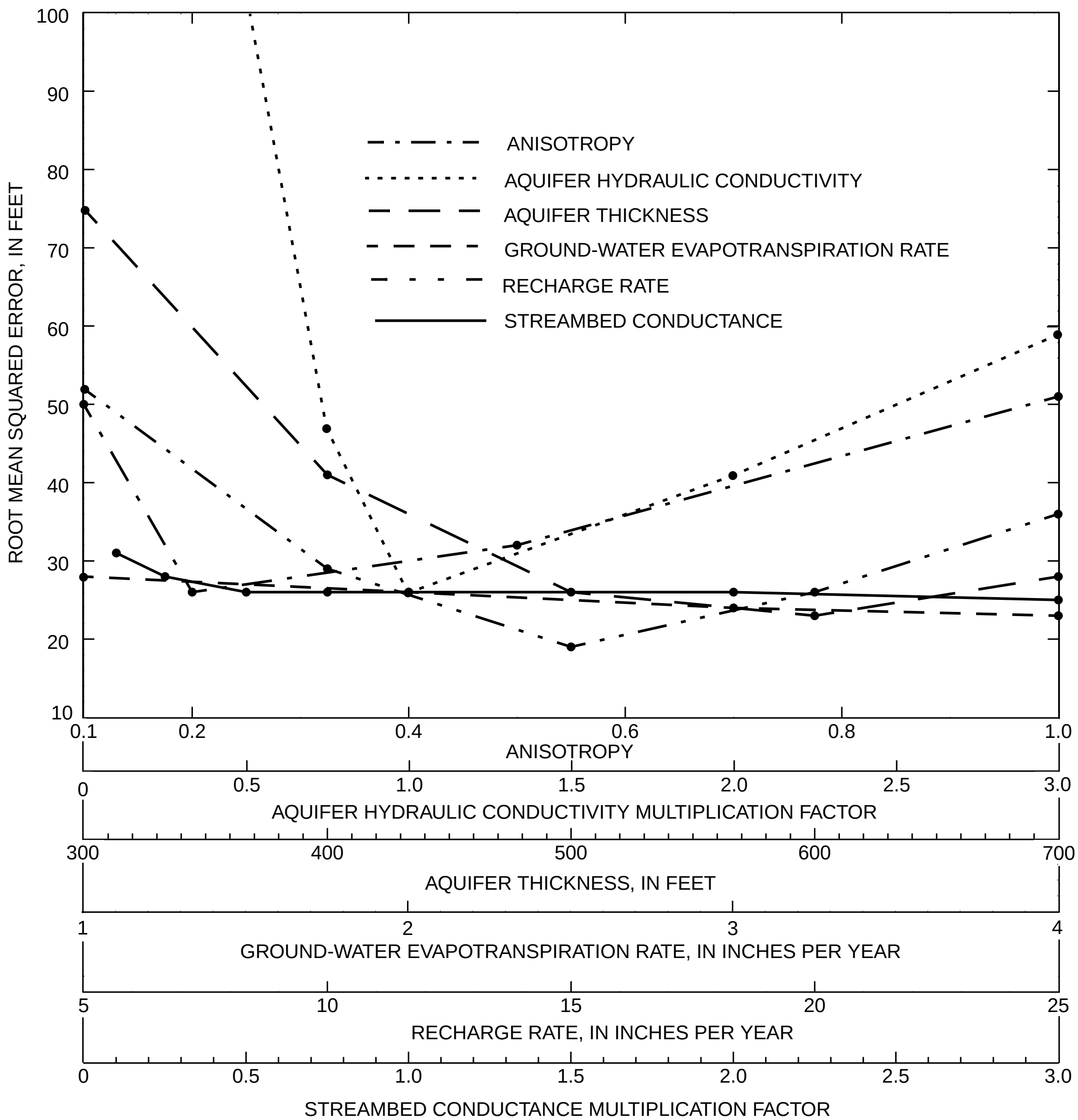


Figure 17. Effect of varying the values of anisotropy, aquifer hydraulic conductivity, aquifer thickness, ground-water evapotranspiration rate, recharge rate, and streambed conductance on the root mean squared error between measured and simulated water levels in the French Creek Basin, Pennsylvania.

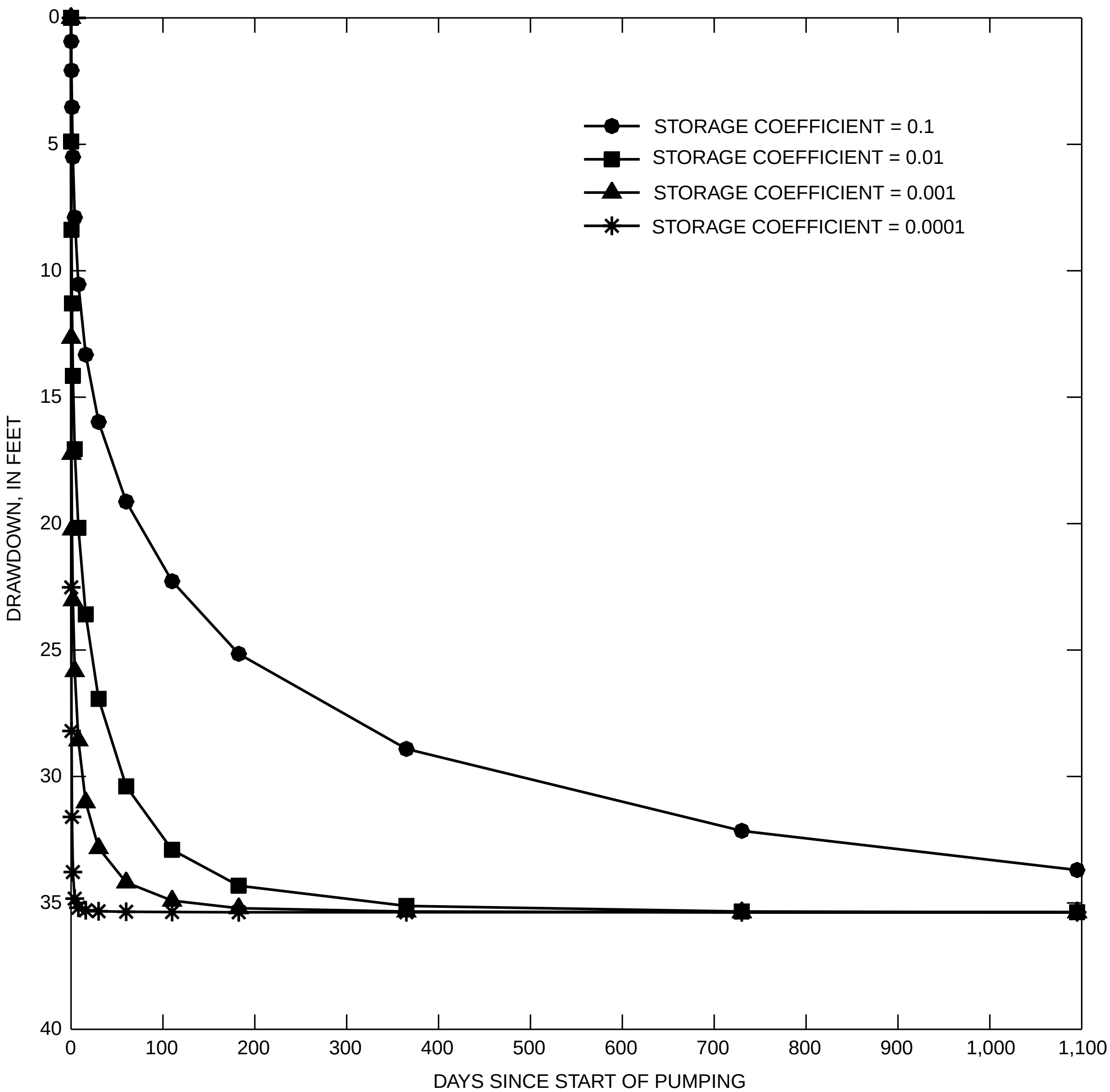


Figure 18. Effect of varying the values of the storage coefficient on drawdown in a cell with a well pumping 200 gallons per minute for the model of the French Creek Basin, Pennsylvania.

Ground-water ET varies seasonally from a high in the summer months to zero or near zero in the winter months. However, no data are available on the temporal variability of ground-water ET in the French Creek Basin. Transient simulations were run to determine the effect of varying the ground-water ET rate between 0 and 6 in/yr on base flow (fig. 19). The calibrated, long-term, average steady-state conditions, which used a ground-water ET rate of 2 in/yr, were used as the base for the simulations. Because the hydrologic system is in equilibrium, a rate of 2 in/yr produces no change in base flow. Rates less than 2 in/yr produce an increase in base flow because less water is being lost from the basin to ET. Rates greater than 2 in/yr produce a decrease in base flow because more water is being lost from the basin to ET. After 90 days, a ground-water ET rate of 0 produced an increase of 5.1 ft^3/s (9.4 percent) at the streamflow-measurement station; a rate of 4 in/yr produced a decrease in base flow of 4.9 ft^3/s (9 percent); and a rate of 6 in/yr produced a decrease in base flow of 9.6 ft^3/s (17.7 percent) (fig. 10).

Model Limitations

The model was used to evaluate the effects of pumping on the regional potentiometric surface. Aquifer characterization of fractured rocks is difficult because measurements of hydraulic properties are local and sparse, permeability varies by orders of magnitude over short distances, and the three-dimensional configuration of transmissive fractures and fracture zones is complex. In the model, a single value of hydraulic conductivity is assigned to a geologic unit or outcrop area of a geologic unit. Therefore, the model may not reproduce exactly drawdowns from a local aquifer test because the assigned regional hydraulic conductivity may differ from the hydraulic conductivity at the pumped well.

The model does not adequately reproduce all measured water levels at lower than average recharge conditions. The difference between measured and simulated water levels is not uniform throughout the modeled area; some simulated water levels may be reasonably close to observed values and others may be lower than observed values by more than 100 ft. Therefore, model simulated water-level declines for lower than average recharge conditions should be used with caution.

The model was calibrated using annual values for recharge and ground-water ET. It then was run using the annual values in a seasonally independent transient mode to show changes with time. The timing and relative magnitude of some of the changes simulated with the model when viewed in terms of a normal climatic year may be subject to considerable uncertainty because of the variability in seasonal recharge and ground-water ET rates. Transient model simulations for short-term periods are indicative of possible hydrologic system response and should be considered an approximation.

Simulations made with the model illustrate some of the typical analyses and results that can be produced. The predictive capabilities of the model could be improved if the level of confidence attached to its predictions can be increased. This increase in confidence would require additional data collection for calibration that would include additional observation wells, especially in geologic units with large water-level simulation errors, and additional concurrent measurements of water levels and base flow for different streamflows. Transient calibration would require values for seasonal and possibly monthly, weekly, or even daily recharge and ground-water ET rates for an average and below average climatic year. Adding additional layers to the model may improve predictive capability, but doing so would require defining the vertical variability of aquifer properties.

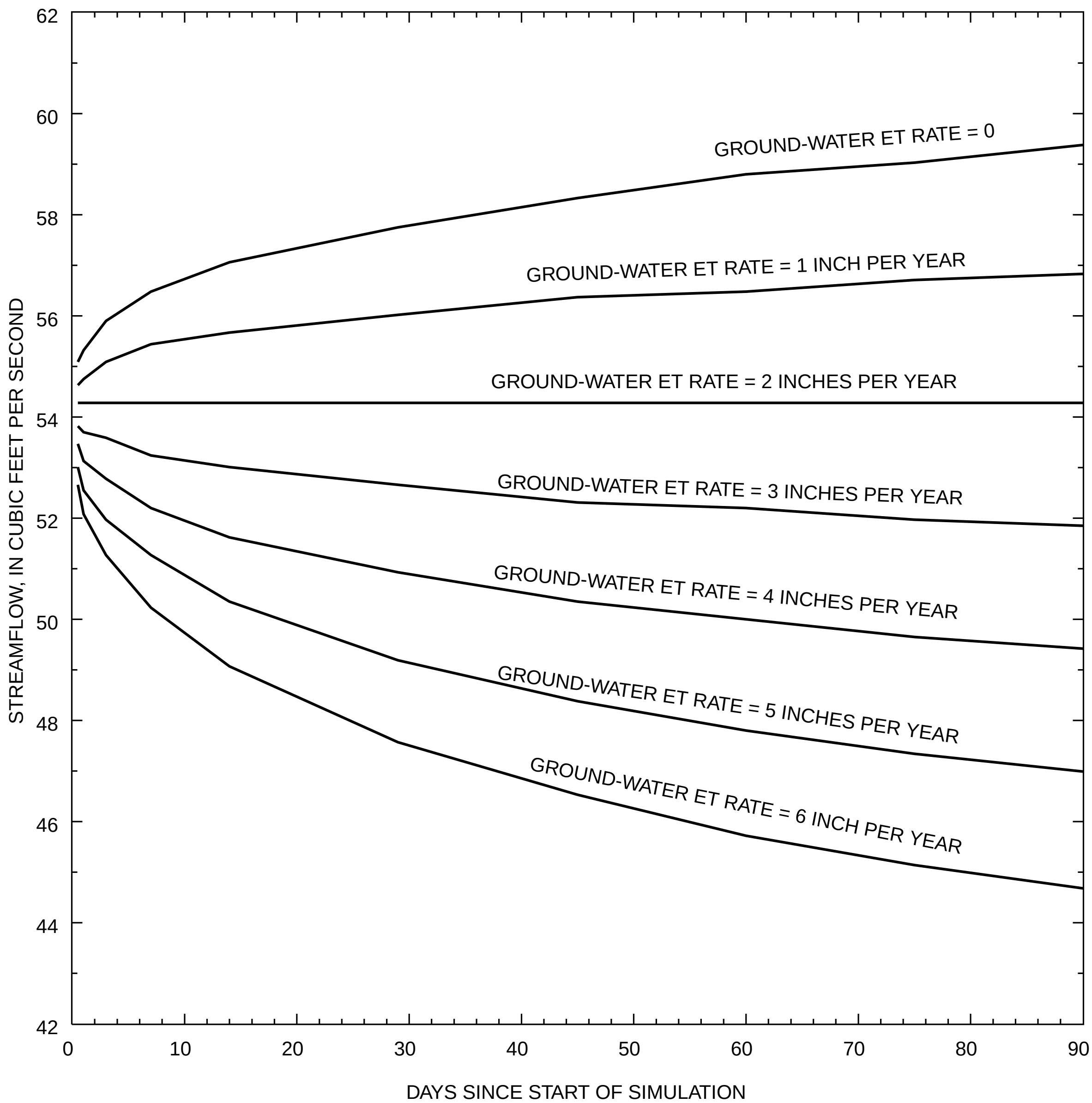


Figure 19. Effect of varying the ground-water evapotranspiration (ET) rate on the simulated streamflow of French Creek at streamflow-measurement station French Creek near Phoenixville, Pennsylvania (01472157).

Effects of Drought on Stream Base Flow and Water Levels

The effect of drought in the French Creek Basin was simulated using an annual drought-year recharge rate of 8 in/yr, which is equal to the annual recharge in 1969 and 2001, the years with the lowest estimated recharge rate in the water budgets (table 4). Each model simulation was run with three recharge periods: period 1 with an average recharge rate (15.7 in/yr) for 90 days, period 2 with a drought recharge rate (8 in/yr) for 90 days, and period 3 with an average (15.7 in/yr) recharge rate for 120 days. Period 1 (average recharge) was used to allow the hydrologic system to come to equilibrium before imposing drought conditions, period 2 (drought recharge) was used to simulate drought conditions, and period 3 (average recharge) was used to allow the system to recover from drought. These simulations do not include changes in flow that occur naturally over the annual cycle; the effects are relative to average annual conditions of flow and water levels.

After 90 days of drought, the simulated streamflow of French Creek at the streamflow-measurement station decreased from 54.2 ft^3/s to 35.7 ft^3/s, a decrease of 18.5 ft^3/s or 34 percent (fig. 20). The simulated streamflow of French Creek at the mouth decreased from 67.8 ft^3/s to 43.4 ft^3/s, a decrease of 24.4 ft^3/s or 36 percent (fig. 20). The simulated water level in the cells where observation wells CH-1571 and CH-2328 are located decreased 3.9 and 10.5 ft, respectively (fig. 21).

The simulation (fig. 20) indicated that streamflow recovered almost completely to pre-drought conditions. Simulated streamflow at the streamflow-measurement station was 54.2 ft^3/s at the start of the simulation and 51.2 ft^3/s after 180 days of recovery from drought. Simulated streamflow at the mouth of French Creek was 67.8 ft^3/s at the start of the simulation and 64.1 ft^3/s after 180 days of recovery from drought. The simulated water level in the cell where observation well CH-1571 is located was 0.2 ft lower after 180 days of recovery from drought than before drought; however, the simulated water level in the cell where observation well CH-2328 is located was 4 ft lower after 180 days of recovery from drought than before drought (fig. 21).

A recharge rate of 17 in/yr for the recovery period was necessary for ground-water levels to recover almost to pre-drought conditions by the end of the recovery period (fig. 20). The water level in the cell where observation well CH-1571 is located was 0.4 ft higher after 180 days of recovery from drought than before drought; however, the water level in the cell where observation well CH-2328 is located was 1.9 ft lower after 180 days of recovery from drought than before drought (fig. 21). Streamflow at the streamflow-measurement station was 54.2 ft^3/s before drought and 54.9 ft^3/s after 180 days of recovery from drought. Streamflow at the mouth of French Creek was 67.8 ft^3/s both before drought and after 180 days of recovery from drought (fig. 20).

Effects of Ground-Water Withdrawals on Stream Base Flow and Water Levels

The French Creek Basin lies within the DRBC Southeastern Pennsylvania Ground Water Protected Area (GWPA). The DRBC GWPA regulations (Delaware River Basin Commission, 1999) set withdrawal limits for the four subbasins (Lower Reach, Middle Reach, Upper Reach, and South Branch) in the French Creek Basin. Under the DRBC GWPA regulations, the withdrawal limit for the South Branch Subbasin (drainage area 13.6 mi^2) is set at 1,393 Mgal/yr. The basin would be considered potentially stressed at a withdrawal rate of 75 percent of the GWPA limit, or 1,044 Mgal/yr (Delaware River Basin Commission, 1999). Ground-water withdrawals from the South Branch French Creek Basin currently (2003) total 30.5 Mgal/yr.

To simulate the effects of increased ground-water withdrawals on stream base flow and water levels in the South Branch French Creek Subbasin, model simulations were run with pumping rates equal to 50 percent of the GWPA withdrawal limit (696.5 Mgal/yr), 75 percent of the GWPA withdrawal limit (1,044 Mgal/yr), and the GWPA withdrawal limit (1,393 Mgal/yr). Withdrawals were simulated from 20 hypothetical wells distributed throughout the basin (fig. 22). The total withdrawal rate was divided by 20, and that rate was assigned to 19 of the 20 hypothetical wells. That rate minus the current (2003) withdrawal rate (30.5 Mgal/yr) was assigned to the 20th well. Withdrawals begin instantaneously at the start of each simulation. The withdrawals are simulated as consumptive use with all water removed from the subbasin and no returns to either the ground-water system or South Branch French Creek. This simulation represents a “worst case scenario” for ground-water withdrawals. Streamflow would be higher if the pumped

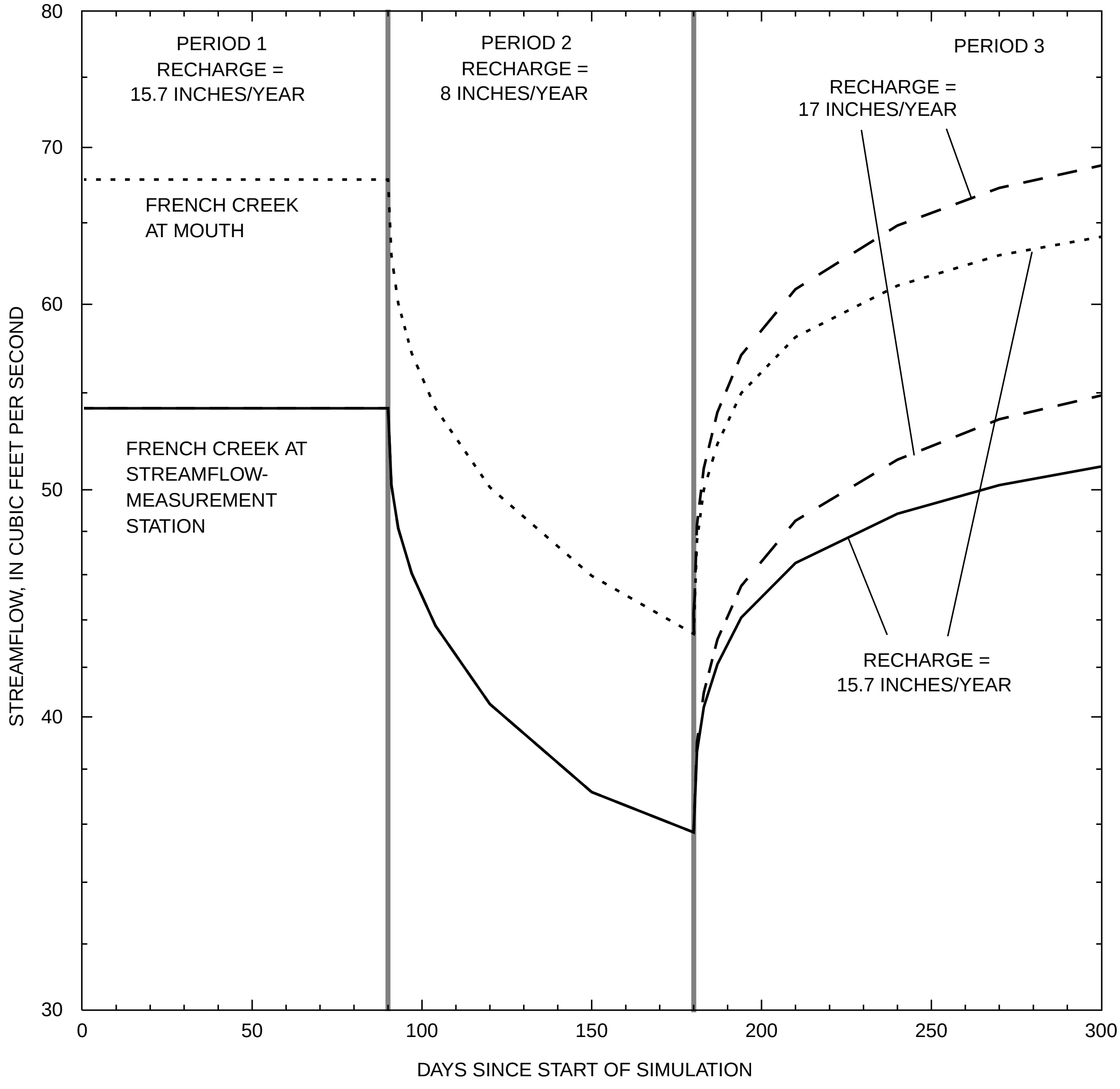
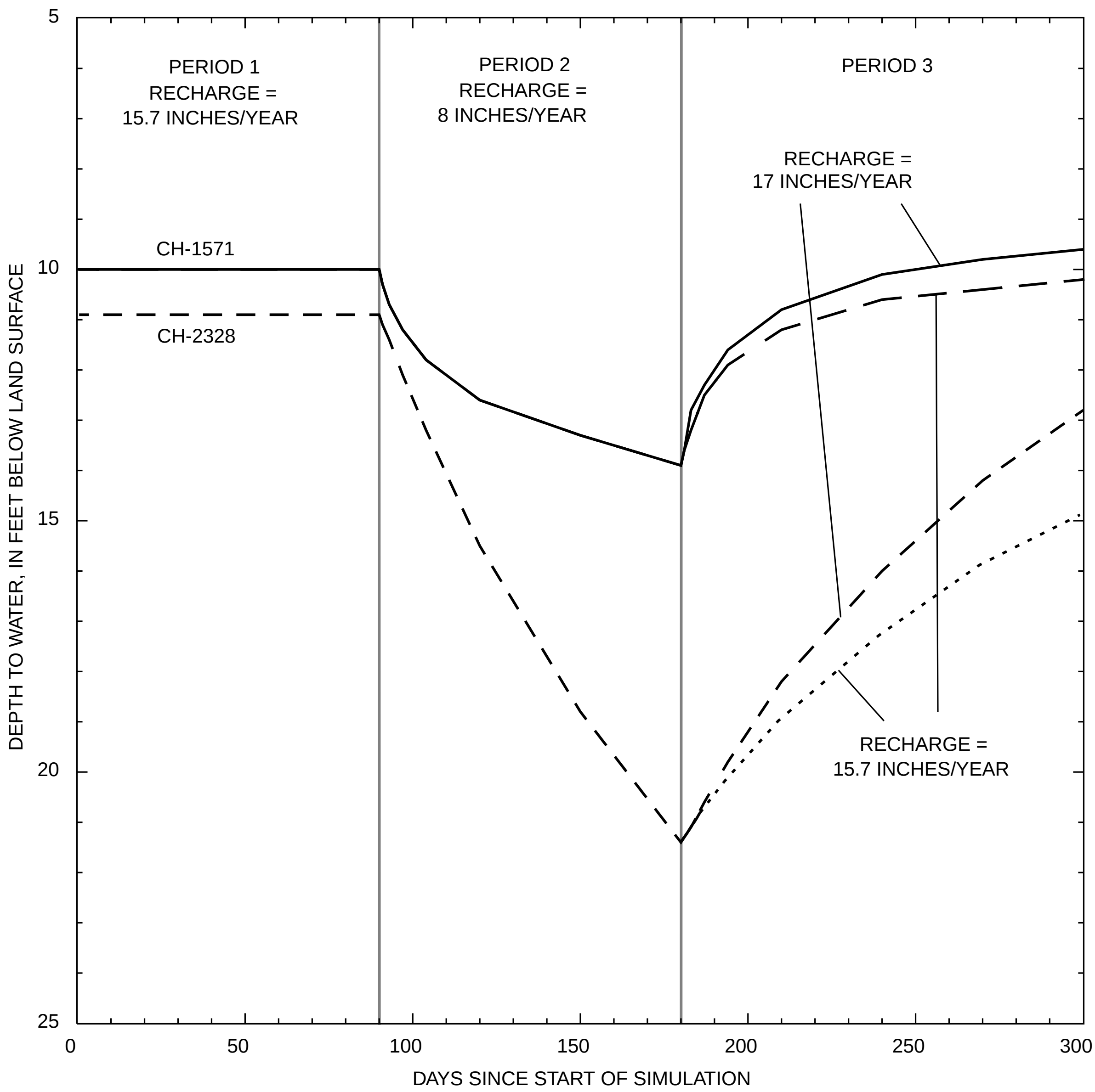


Figure 20. Simulated streamflow of French Creek at streamflow-measurement station French Creek near Phoenixville, Pennsylvania (01472157), and at the mouth during drought and recovery from drought.



PERIOD 1
RECHARGE =
15.7 INCHES/YEAR
PERIOD 2
RECHARGE =
8 INCHES/YEAR
PERIOD 3
RECHARGE =
17 INCHES/YEAR
CH-1571
CH-2328
RECHARGE =
15.7 INCHES/YEAR
5
10
15
20
25
0
50
100
150
200
250
300
DEPTH TO WATER, IN FEET BELOW LAND SURFACE
DAYS SINCE START OF SIMULATION

water was discharged to South Branch French Creek by a sewage treatment plant or if recharge was enhanced by a wastewater spray-irrigation system.

Simulations (table 11) were run for 27 months and included:

(1) average climatic conditions using an average recharge rate of 15.7 in/yr for 27 months,
(2) drought conditions using an average recharge rate of 15.7 in/yr for 24 months followed by a drought recharge rate of 8 in/yr for 3 months, and
(3) extreme drought conditions using an average recharge rate of 15.7 in/yr for 24 months followed by no recharge for 3 months.

Average conditions first were simulated for 24 months, which is about the time required for the hydrologic system to come to equilibrium in response to pumping, before imposing drought conditions. Some recharge occurs during drought periods. It is unlikely that no recharge would occur during a 3-month period; however, this simulation does approximate conditions in the French Creek Basin from June through mid-August 2001, when little recharge occurred.

Average Climatic Conditions

Transient simulations were run using average recharge conditions for 27 months and withdrawal rates equal to 50, 75, and 100 percent of the GWPA withdrawal limit. At a withdrawal rate equal to 50 percent of the GWPA limit, the simulated streamflow at the mouth of South Branch French Creek decreased from 14.1 ft^3/s to 11.5 ft^3/s, a decrease of 2.6 ft^3/s or 18 percent (table 12, fig. 23). The withdrawal rate of 50 percent of the GWPA limit represents a 666 Mgal/yr increase above current (2003) pumping and is equal to 2.82 ft^3/s; therefore, 92 percent of the pumped water is water that would have discharged as base flow to South Branch French Creek. The simulated water level in the cell where observation well CH-1487 is located (fig. 22) decreased 18.7 ft (fig. 24). The simulated drawdowns caused by pumping at a rate of 696.5 Mgal/yr mainly are confined to the South Branch Subbasin; however, some drawdown occurs outside the subbasin (fig. 25). Cones of depression around wells are combined in two areas in the northern part of the subbasin.

Table 11. *Simulated streamflow of South Branch French Creek at mouth for ground-water withdrawals in the South Branch French Creek Subbasin, Pennsylvania, at 50, 75, and 100 percent of the Ground Water Protected Area limit with all pumped water removed from the basin*

[in/yr, inches per year; Mgal/yr, million gallons per year; GWPA, Ground Water Protected Area; ft^3/s, cubic feet per second]

Scenario	Recharge rate (in/yr)	Withdrawal rate (Mgal/yr)	Percent of GWPA withdrawal limit	Streamflow of South Branch French Creek at mouth (ft^3/s)	Percent change in streamflow from current (2003) conditions
Average recharge	15.7	30.5	[1]2	14.1	0
	15.7	696.5	50	11.5	-18
	15.7	1,044	75	10.1	-28
	15.7	1,393	100	8.84	-37
Drought recharge	8	30.5	[1]2	9.78	0
	8	696.5	50	7.15	-27
	8	1,044	75	5.88	-40
	8	1,393	100	4.70	-52
Extreme drought	0	30.5	[1]2	5.97	0
	0	696.5	50	3.53	-41
	0	1,044	75	2.43	-59
	0	1,393	100	1.55	-74

[1] Current (2003) pumping from the South Branch French Creek Subbasin.

Table 12. *Simulated streamflow of South Branch French Creek at the mouth and French Creek at the streamflow-measurement station for ground-water withdrawals in the South Branch French Creek Subbasin, Pennsylvania, at 50, 75, and 100 percent of the Ground Water Protected Area limit with all pumped water removed from the basin*

[ft^3/s, cubic feet per second; GWPA, Ground Water Protected Area]

Months since start of pumping	Simulated streamflow					
	South Branch French Creek (ft^3/s)	Percent change from current (2003) conditions	French Creek at streamflow-measurement station (ft^3/s)	Percent change from current (2003) conditions	French Creek at mouth (ft^3/s)	Percent change from current (2003) conditions
Average recharge						
Current (2003) conditions						
27	14.1	0	54.3	0	68.1	0
Pumping at 50 percent of GWPA withdrawal limit						
6	11.9	-16	52.1	-4	65.9	-3
12	11.7	-17	51.7	-5	65.5	-4
18	11.5	-18	51.6	-5	65.4	-4
24	11.5	-18	51.6	-5	65.3	-4
27	11.5	-18	51.6	-5	65.3	-4
Pumping at 75 percent of GWPA withdrawal limit						
6	10.9	-23	51.0	-6	64.7	-5
12	10.4	-26	50.5	-7	64.2	-6
18	10.2	-28	50.4	-7	64.0	-6
24	10.2	-28	50.2	-8	63.9	-6
27	10.1	-28	50.1	-8	63.9	-6
Pumping at 100 percent of GWPA withdrawal limit						
6	9.79	-31	49.9	-8	63.7	-6
12	9.10	-35	49.2	-9	62.9	-8
18	8.89	-37	49.0	-10	62.6	-8
24	8.87	-37	48.8	-10	62.6	-8
27	8.84	-37	48.8	-10	62.6	-8
Drought recharge						
Current (2003) conditions						
24	14.1	0	54.3	0	68.1	0
27	9.78	0	35.2	0	43.5	0
Pumping at 50 percent of GWPA withdrawal limit						
6	11.9	-16	52.1	-4	65.9	-3
12	11.7	-17	51.7	-5	65.5	-4
18	11.5	-18	51.6	-5	65.4	-4
24	11.5	-19	51.6	-5	65.3	-4
27	7.15	-27	32.4	-8	40.9	-6
Pumping at 75 percent of GWPA withdrawal limit						
6	10.9	-23	51.0	-6	64.7	-5
12	10.4	-27	50.5	-7	64.2	-6
18	10.2	-28	50.4	-7	64.0	-6
24	10.2	-28	50.2	-7	63.9	-6
27	5.88	-40	31.1	-12	39.5	-9
Pumping at 100 percent of GWPA withdrawal limit						
6	9.79	-31	49.9	-8	63.7	-6
12	9.10	-36	49.2	-9	62.9	-8
18	8.89	-37	49.0	-10	62.6	-8
24	8.87	-37	48.8	-10	62.6	-8
27	4.70	-52	29.9	-15	38.3	-12

Table 12. *Simulated streamflow of South Branch French Creek at the mouth and French Creek at the streamflow-measurement station for ground-water withdrawals in the South Branch French Creek Subbasin, Pennsylvania, at 50, 75, and 100 percent of the Ground Water Protected Area limit with all pumped water removed from the basin*—*Continued*

[ft^3/s, cubic feet per second; GWPA, Ground Water Protected Area]

Months since start of pumping	Simulated streamflow					
	South Branch French Creek (ft^3/s)	Percent change from current (2003) conditions	French Creek at streamflow-measurement station (ft^3/s)	Percent change from current (2003) conditions	French Creek at mouth (ft^3/s)	Percent change from current (2003) conditions
Extreme drought recharge						
Current (2003) conditions						
24	14.1	0	54.3	0	68.1	0
27	5.97	0	19.6	0	23.8	0
Pumping at 50 percent of GWPA withdrawal limit						
6	11.9	-16	52.1	-4	65.9	-3
12	11.7	-17	51.7	-5	65.5	-4
18	11.5	-18	51.6	-5	65.4	-4
24	11.5	-19	51.6	-5	65.3	-4
27	3.53	-41	17.0	-13	21.3	-11
Pumping at 75 percent of GWPA withdrawal limit						
6	10.9	-23	51.0	-6	64.7	-5
12	10.4	-27	50.5	-7	64.2	-6
18	10.2	-28	50.4	-7	64.0	-6
24	10.2	-28	50.2	-7	63.9	-6
27	2.43	-59	15.9	-19	20.1	-16
Pumping at 100 percent of GWPA withdrawal limit						
6	9.79	-31	49.9	-8	63.7	-6
12	9.10	-36	49.2	-9	62.9	-8
18	8.89	-37	49.0	-10	62.6	-8
24	8.87	-37	48.8	-10	62.6	-8
27	1.55	-74	14.9	-24	19.2	-19

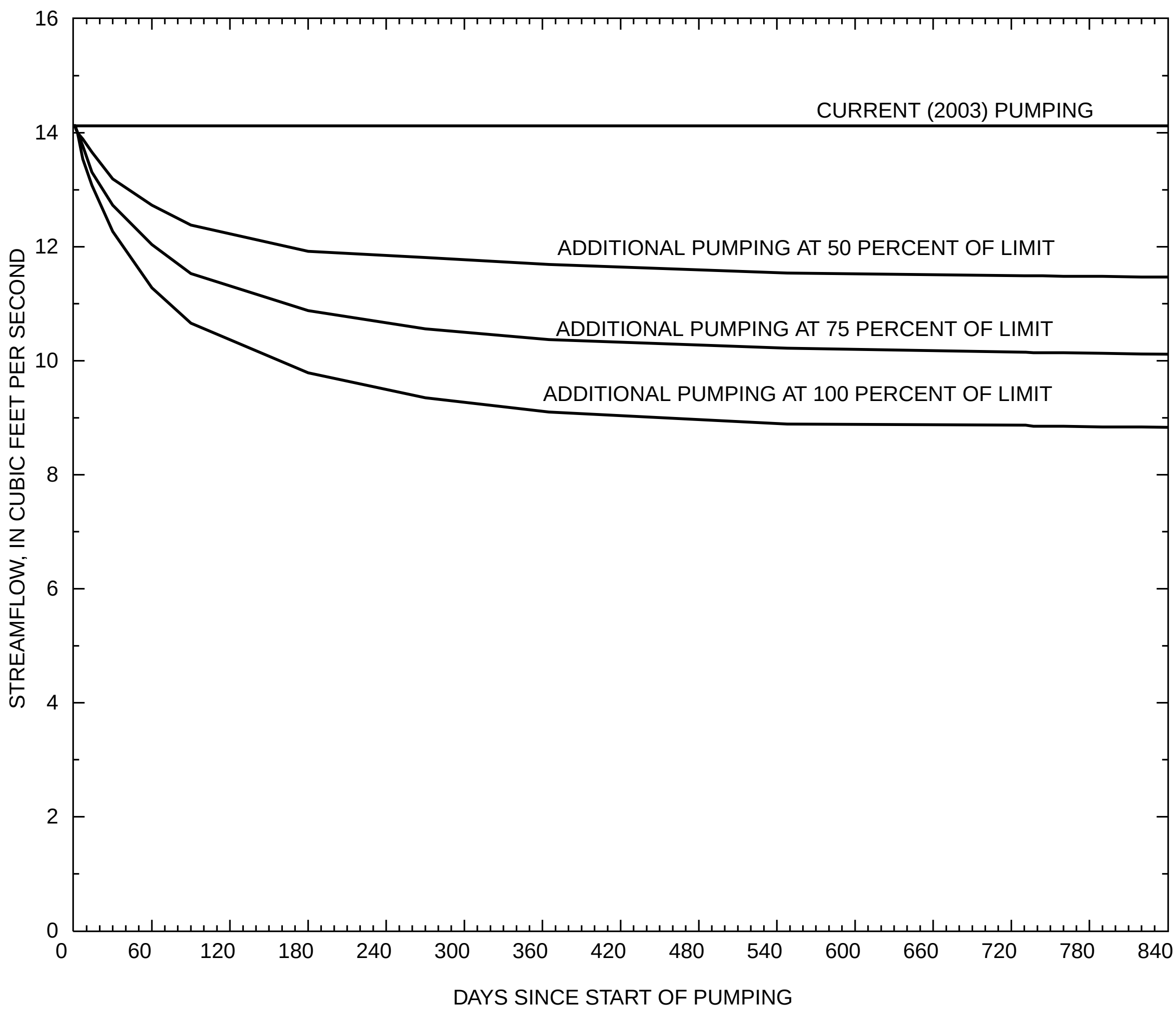


Figure 23. Simulated hydrographs for South Branch French Creek, Pennsylvania, at mouth with ground-water withdrawals equal to 50, 75, and 100 percent of the Ground Water Protected Area limit under average conditions with all pumped water removed from the basin.

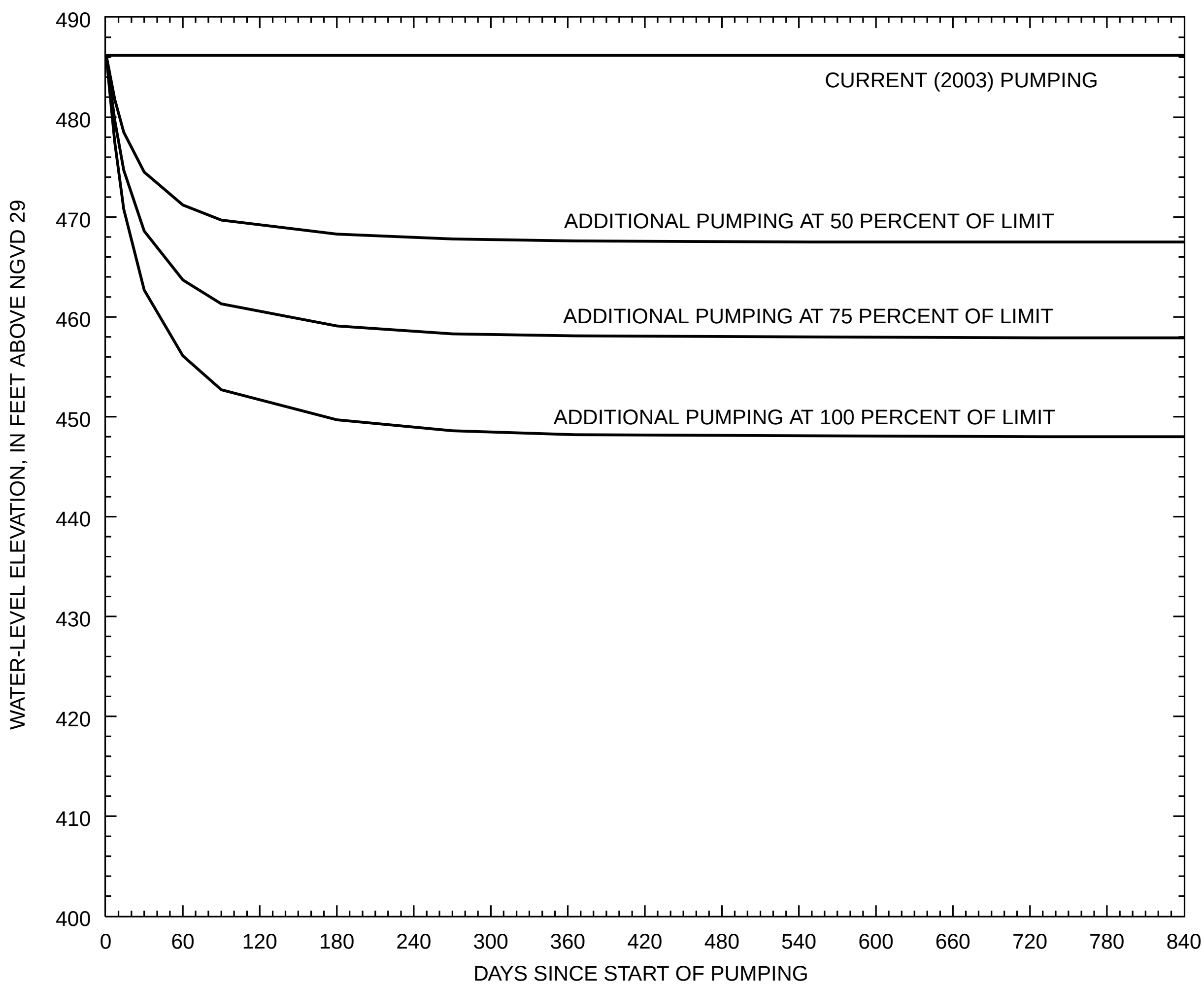


Figure 24. Simulated hydrographs for well CH-1487 with ground-water withdrawals in the South Branch French Creek Subbasin, Pennsylvania, equal to 50, 75, and 100 percent of the Ground Water Protected Area limit under average conditions with all pumped water removed from the basin.

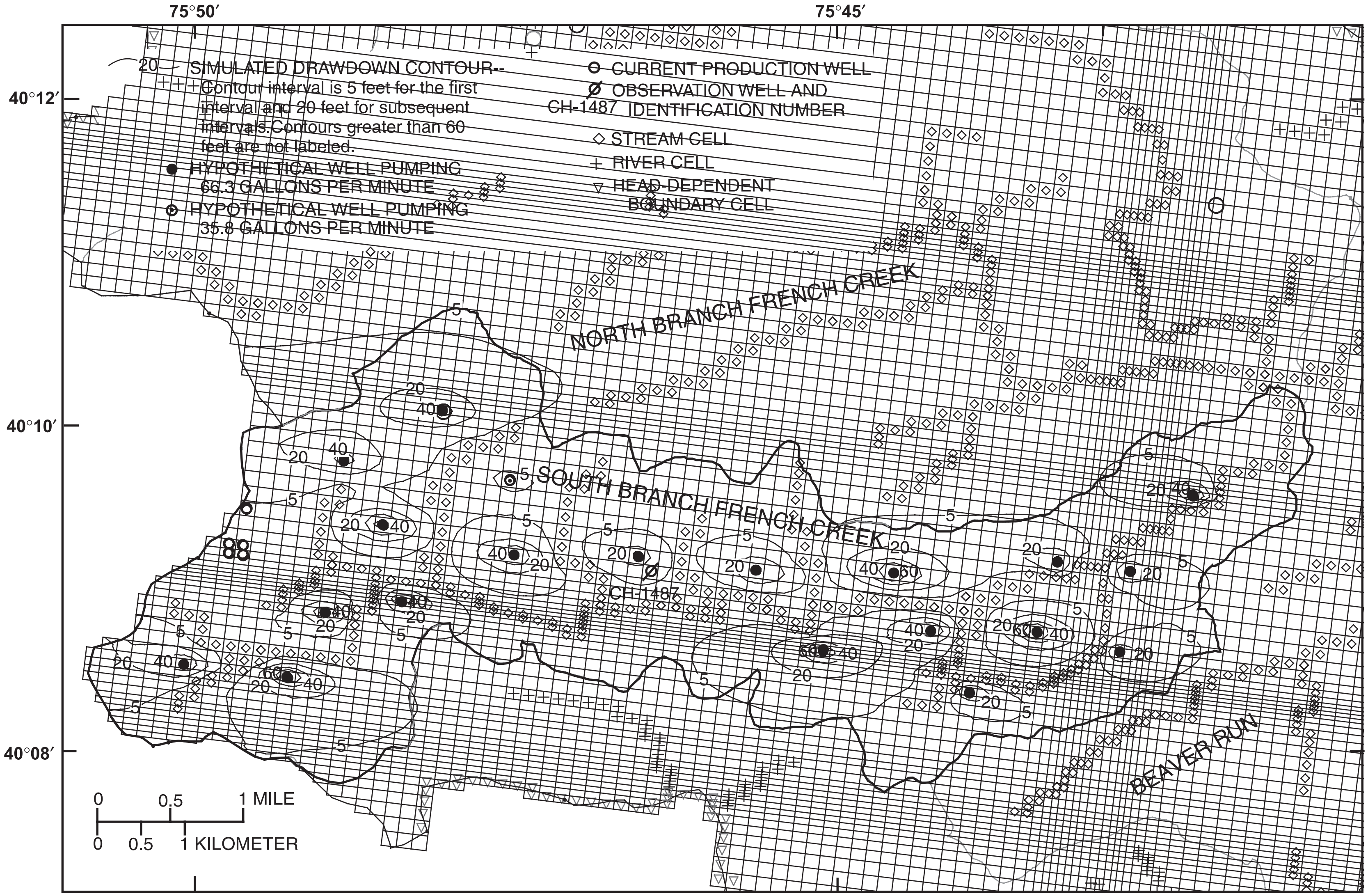


Figure 25. Simulated drawdown in the South Branch French Creek Subbasin, Pennsylvania, from pumping wells with a combined withdrawal rate equal to 50 percent of the Ground Water Protected Area limit during average recharge conditions with all pumped water removed from the basin. (Total pumpage from the South Branch French Creek Subbasin is 696.5 million gallons per year.)

A transient simulation was run using average recharge conditions for 27 months and a withdrawal rate equal to 75 percent of the GWPA limit, which is considered “potentially stressed” conditions (Delaware River Basin Commission, 1999). At a withdrawal rate equal to 75 percent of the GWPA limit, the simulated streamflow at the mouth of South Branch French Creek decreased from 14.1 ft^3/s to 10.1 ft^3/s, a decrease of 4 ft^3/s or 28 percent (table 11, fig. 23). The withdrawal rate of 75 percent of the GWPA limit represents a 1,013.5 Mgal/yr increase above current (2003) pumping and is equal to 4.3 ft^3/s; therefore, 93 percent of the pumped water is water that would have discharged as stream base flow.

The simulated water level in the cell where observation well CH-1487 is located decreased 28.3 ft (fig. 24). The simulated drawdown caused by pumping at a rate of 1,044.8 Mgal/yr extends outside the South Branch Subbasin, particularly to the north into the North Branch Subbasin (fig. 26). The simulated base flow of North Branch French Creek decreased 0.11 ft^3/s. Cones of depression around wells are combined in five areas.

A transient simulation was run using average recharge conditions for 27 months and a withdrawal rate equal to the GWPA limit. At a withdrawal rate equal to the GWPA limit, the simulated streamflow at the mouth of South Branch French Creek decreased from 14.1 ft^3/s to 8.84 ft^3/s, a decrease of 5.26 ft^3/s or 37 percent (table 11, fig. 23). The withdrawal rate equal to the GWPA limit represents a 1,362.5 Mgal/yr increase above current pumping and is equal to 5.78 ft^3/s; therefore, 91 percent of the pumped water is water that would have discharged as stream base flow.

The simulated water level in the cell where observation well CH-1487 is located decreased 38.2 ft (fig. 24). The simulated drawdown caused by pumping at a rate of 1,393 Mgal/yr extends outside the South Branch Subbasin, particularly to the north into the North Branch Subbasin (fig. 27). The simulated base flow of North Branch French Creek decreased 0.11 ft^3/s. Cones of depression around wells are combined in five areas.

Drought Conditions

Drought conditions were simulated in the South Branch French Creek Subbasin by using an average recharge rate (15.7 in/yr) for 24 months to allow the effects of pumping to stabilize and then using a drought recharge rate of 8 in/yr for 3 months. First, a transient drought simulation was run with current (2003) pumping. With no additional ground-water withdrawals under drought conditions, the simulated streamflow at the mouth of South Branch French Creek decreased from 14.1 ft^3/s to 9.78 ft^3/s, a decrease of 4.32 ft^3/s or 27 percent (table 11, fig. 28). The simulated water level in the cell where observation well CH-1487 is located decreased 6.4 ft (fig. 29).

A transient simulation was run using drought recharge conditions and a withdrawal rate equal to 50 percent of the GWPA limit. At a withdrawal rate equal to 50 percent of the GWPA limit under drought conditions, the simulated streamflow at the mouth of South Branch French Creek decreased from 9.78 ft^3/s to 7.15 ft^3/s (table 11, fig. 28), a decrease of 2.63 ft^3/s or 27 percent from drought conditions with current pumping. The simulated water level in the cell where observation well CH-1487 is located decreased 19.1 ft from drought conditions with current pumping (fig. 29).

A transient simulation was run using drought recharge conditions and a withdrawal rate equal to 75 percent of the GWPA limit. At a withdrawal rate equal to 75 percent of the GWPA limit under drought conditions, the simulated streamflow at the mouth of South Branch French Creek decreased from 9.78 ft^3/s to 5.88 ft^3/s (table 11, fig. 28), a decrease of 3.9 ft^3/s or 40 percent from drought conditions with current pumping. The simulated water level in the cell where observation well CH-1487 is located decreased 28.8 ft from drought conditions with current pumping (fig. 29).

A transient simulation was run using drought recharge conditions and a withdrawal rate equal to the GWPA withdrawal limit. At a withdrawal rate equal to the GWPA limit under drought conditions, the simulated streamflow at the mouth of South Branch French Creek decreased from 9.78 ft^3/s to 4.70 ft^3/s (table 11, fig. 28), a decrease of 5.08 ft^3/s or 52 percent from drought conditions with current pumping. The simulated water level in the cell where observation well CH-1487 is located decreased 39.2 ft from drought conditions with current pumping (fig. 29).

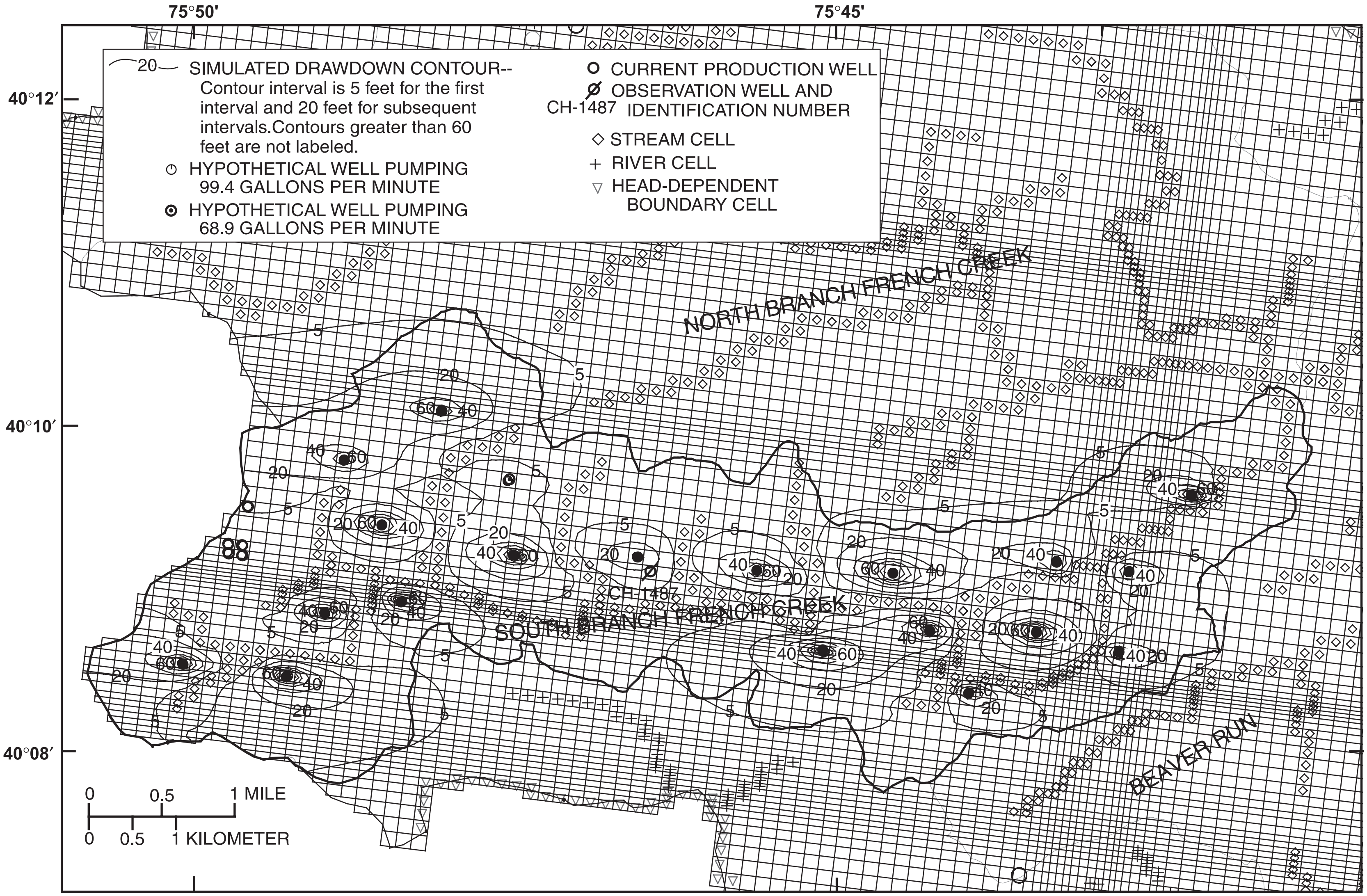


Figure 26. Simulated drawdown in the South Branch French Creek Subbasin, Pennsylvania, from pumping wells with a combined withdrawal equal to 75 percent of the Ground Water Protected Area limit during average recharge conditions with all pumped water removed from the basin. (Total pumpage from the South Branch French Creek Subbasin is 1,044.8 million gallons per year.)

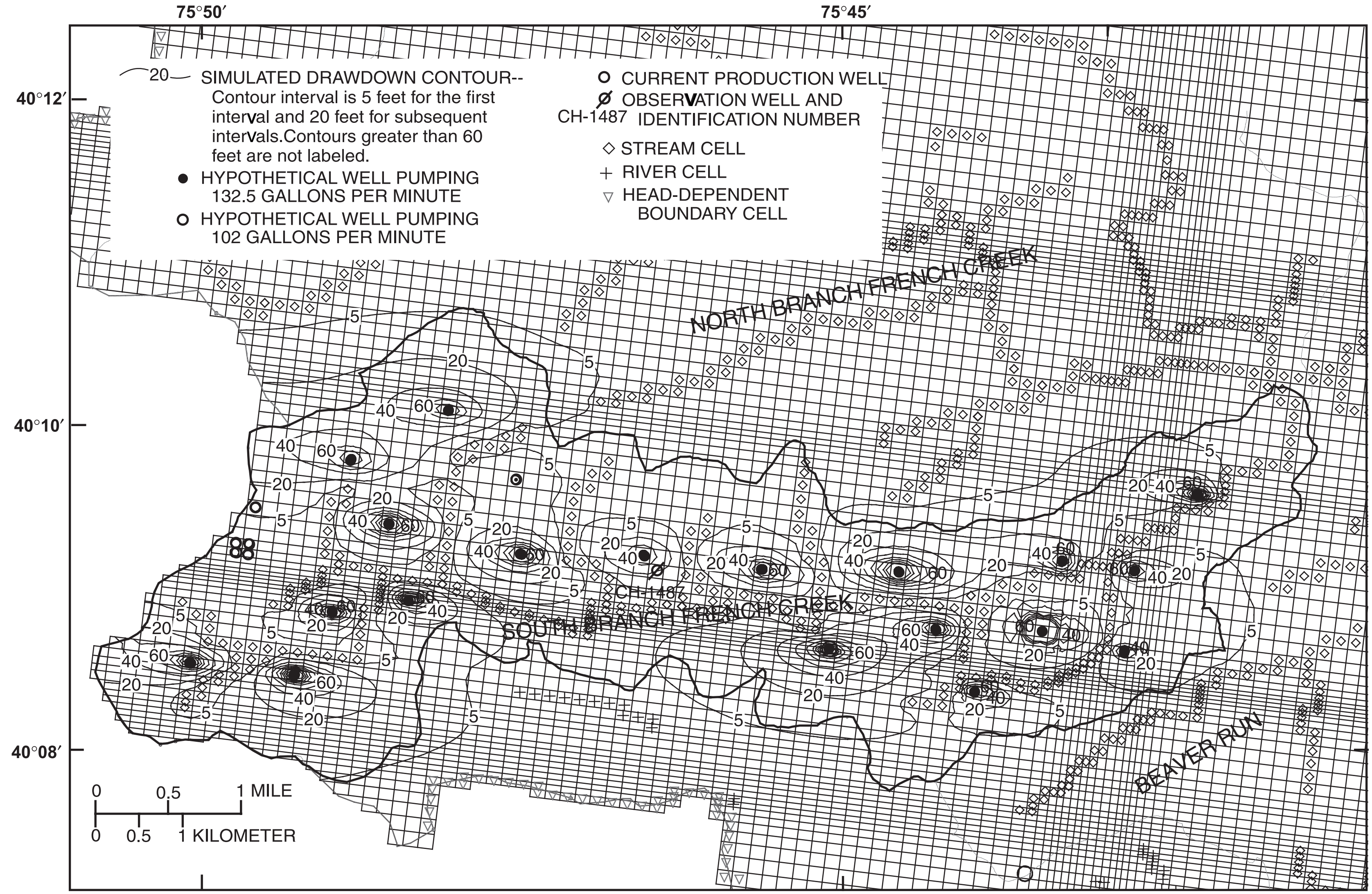
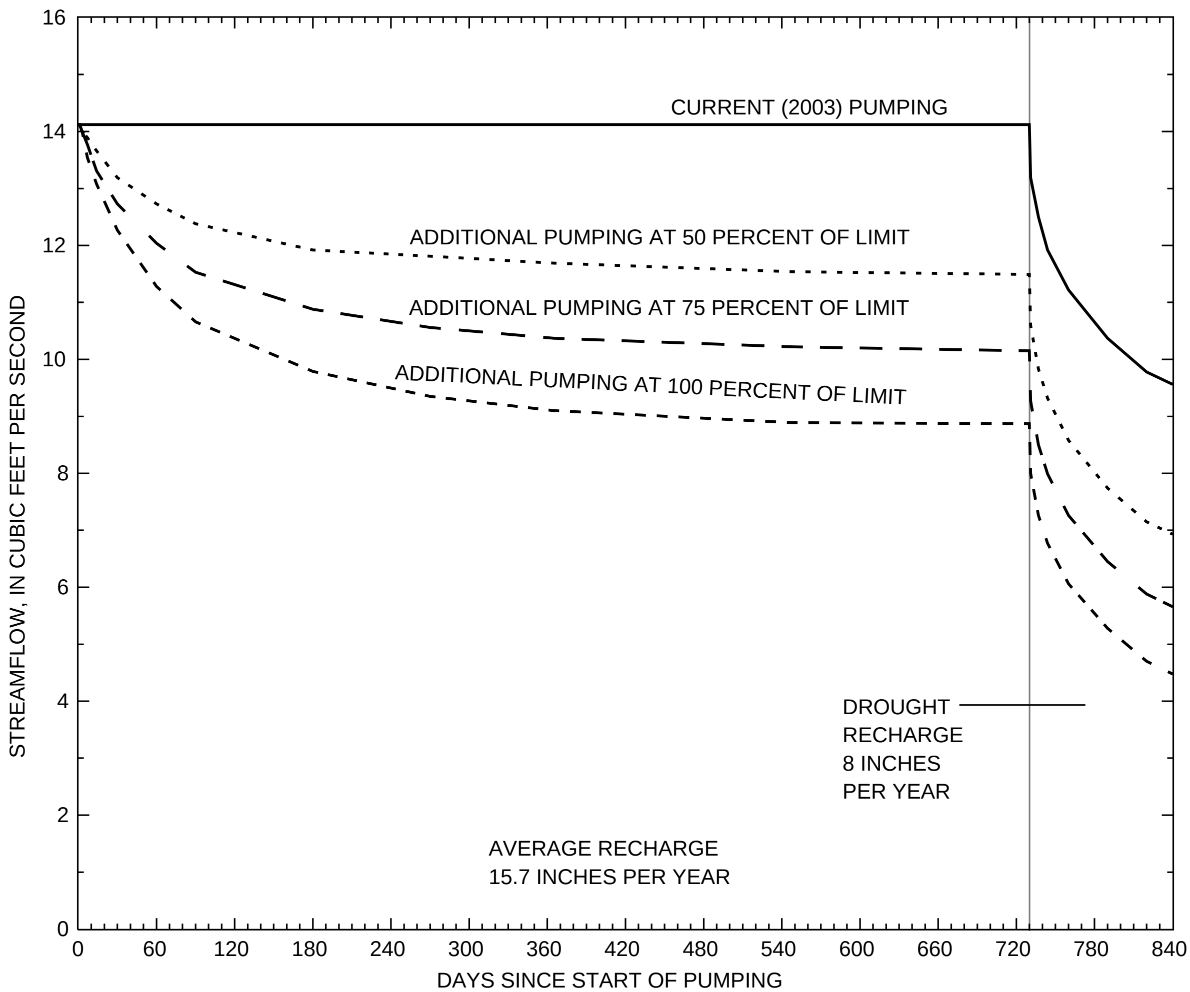


Figure 27. Simulated drawdown in the South Branch French Creek Subbasin, Pennsylvania, from pumping wells with a combined withdrawal equal to the Ground Water Protected Area limit during average recharge conditions with all pumped water removed from the basin. (Total pumpage from the South Branch French Creek Subbasin is 1,393 million gallons per year.)


CURRENT (2003) PUMPING
ADDITIONAL PUMPING AT 50 PERCENT OF LIMIT
ADDITIONAL PUMPING AT 75 PERCENT OF LIMIT
ADDITIONAL PUMPING AT 100 PERCENT OF LIMIT
DROUGHT RECHARGE 8 INCHES PER YEAR
AVERAGE RECHARGE 15.7 INCHES PER YEAR
STREAMFLOW, IN CUBIC FEET PER SECOND
DAYS SINCE START OF PUMPING
0
2
4
6
8
10
12
14
16
0
60
120
180
240
300
360
420
480
540
600
660
720
780
840

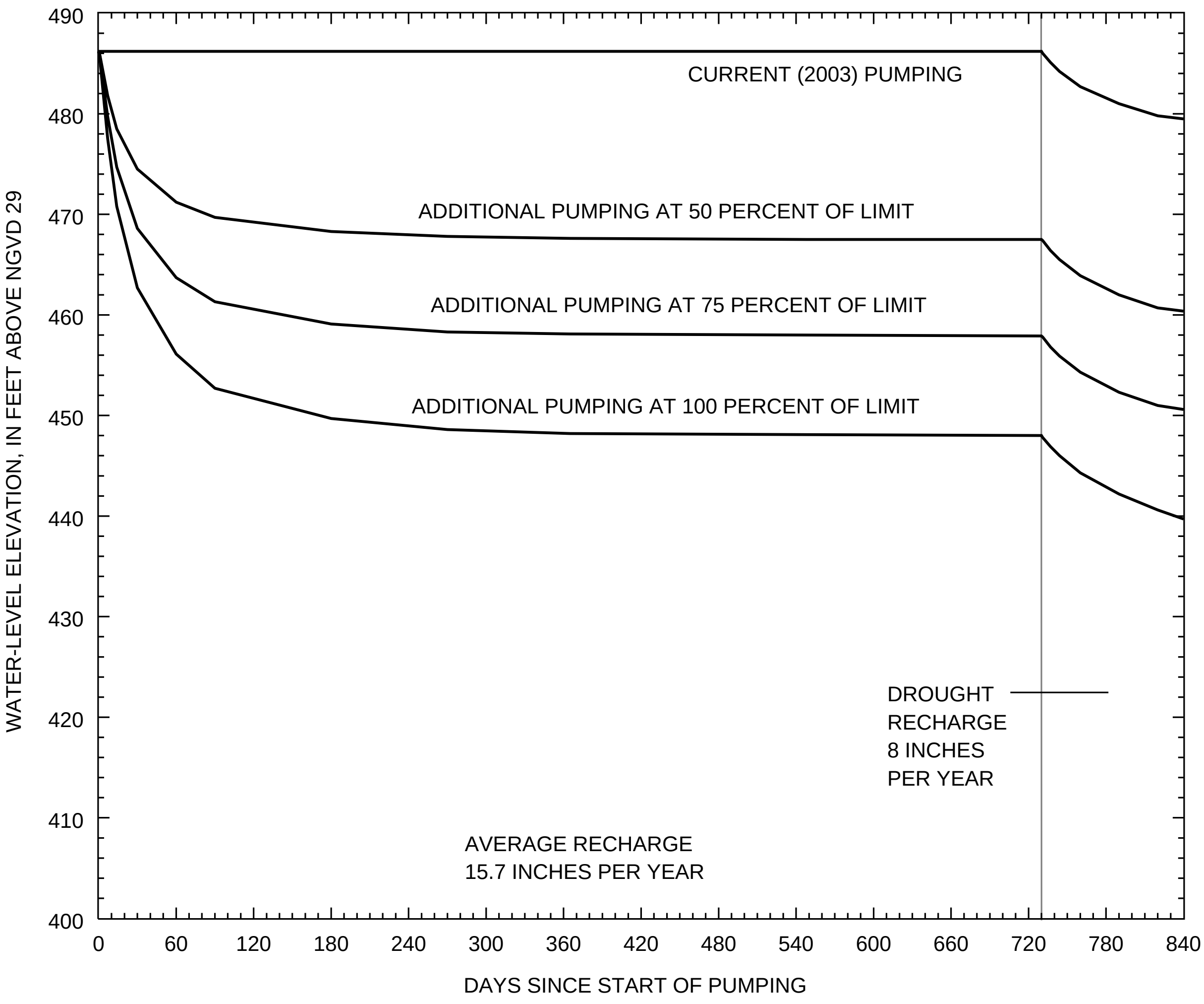


Figure 29. Simulated hydrographs for well CH-1487 with ground-water withdrawals in the South Branch French Creek Subbasin, Pennsylvania, equal to 50, 75, and 100 percent of the Ground Water Protected Area limit during drought recharge conditions with all pumped water removed from the basin.

Extreme Drought Conditions

Extreme drought conditions were simulated in the South Branch French Creek Subbasin by using an average recharge rate (15.7 in/yr) for 24 months to allow the effects of pumping to stabilize and then using no recharge for 3 months. With current (2003) ground-water pumping under extreme drought conditions, the simulated streamflow at the mouth of South Branch French Creek decreased from 14.1 ft^3/s to 5.97 ft^3/s, a decrease of 8.13 ft^3/s or 58 percent from average conditions (table 11, fig. 30). The simulated water level in the cell where observation well CH-1487 is located decreased 12.4 ft from average conditions (fig. 31).

With a ground-water withdrawal rate equal to 50 percent of the GWPA limit under extreme drought conditions, the simulated streamflow at the mouth of South Branch French Creek decreased from 5.97 ft^3/s to 3.53 ft^3/s, a decrease of 2.44 ft^3/s or 41 percent from extreme drought conditions with current pumping (table 11, fig. 30). The simulated water level in the cell where observation well CH-1487 is located decreased 19.8 ft from extreme drought conditions with current pumping (fig. 31).

With a withdrawal rate equal to 75 percent of the GWPA limit under extreme drought conditions, the simulated streamflow at the mouth of South Branch French Creek decreased from 5.97 ft^3/s to 2.43 ft^3/s, a decrease of 3.54 ft^3/s or 59 percent from extreme drought conditions with current

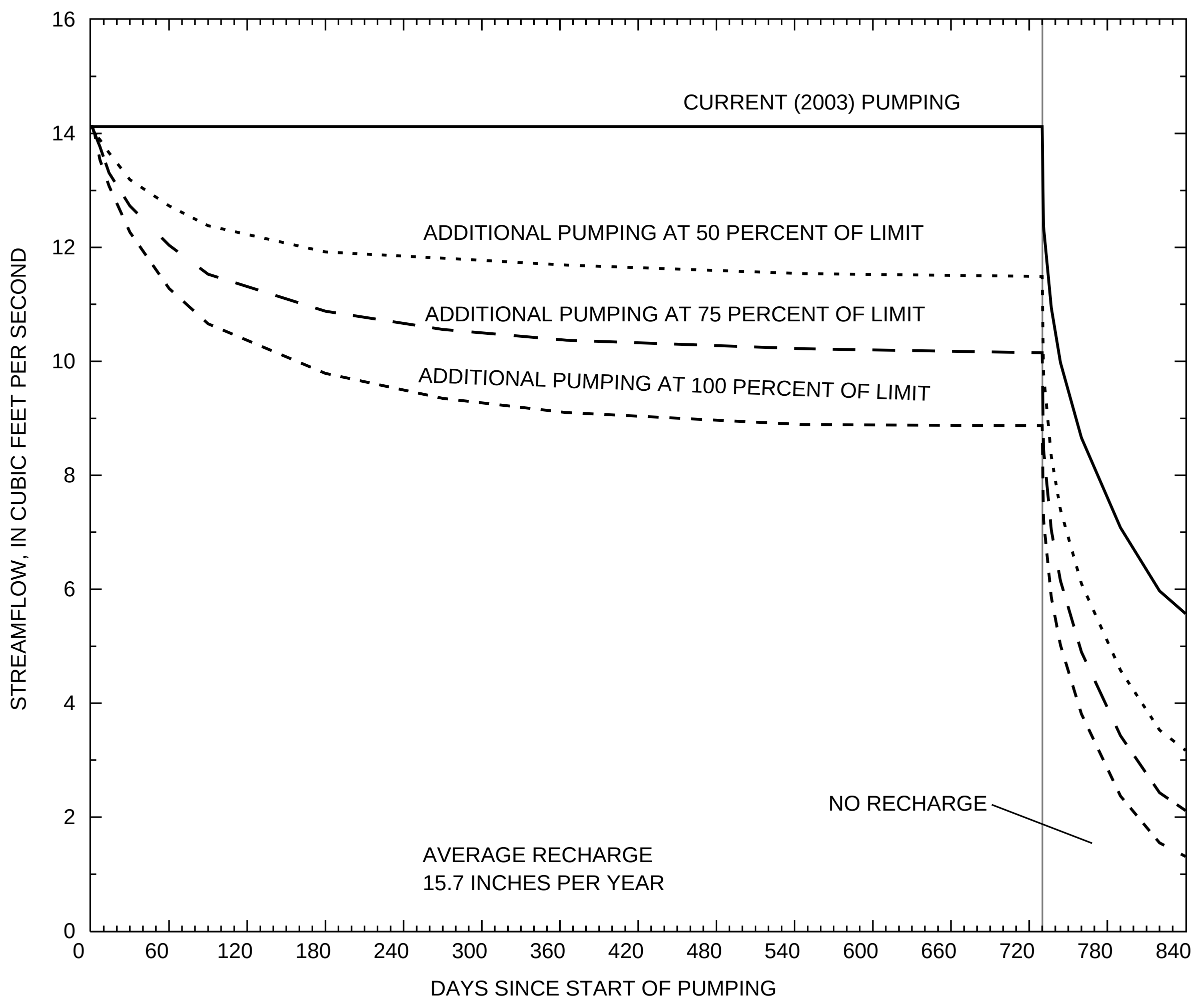


Figure 30. Simulated hydrographs for South Branch French Creek, Pennsylvania, at mouth with ground-water withdrawals equal to 50, 75, and 100 percent of the Ground Water Protected Area limit during extreme drought recharge conditions with all pumped water removed from the basin.

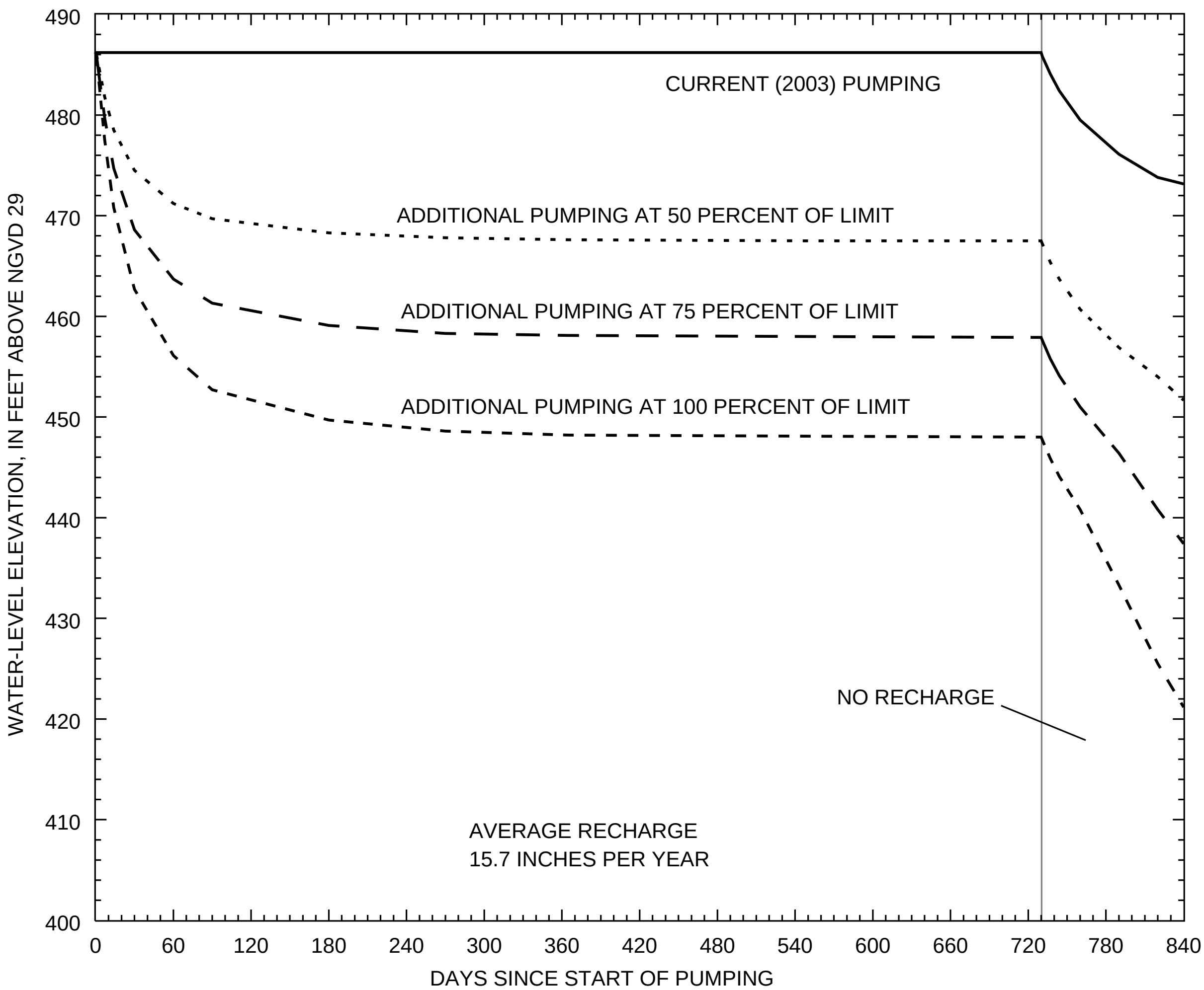


Figure 31. Simulated hydrographs for well CH-1487 with ground-water withdrawals in the South Branch French Creek Subbasin, Pennsylvania, equal to 50, 75, and 100 percent of the Ground Water Protected Area limit during extreme drought recharge conditions with all pumped water removed from the basin.

pumping (table 11, fig. 30). The simulated water level in the cell where observation well CH-1487 is located decreased 33 ft from extreme drought conditions with current pumping (fig. 31).

With a withdrawal rate equal to the GWPA limit under extreme drought conditions, the simulated streamflow at the mouth of South Branch French Creek decreased from 5.97 ft^3/s to 1.55 ft^3/s, a decrease of 4.42 ft^3/s or 74 percent from extreme drought conditions with current pumping (table 11, fig. 30). The simulated water level in the cell where observation well CH-1487 is located decreased 48.3 ft from extreme drought conditions with current pumping (fig. 31).

Effects of Well Location on Stream Base Flow and Water Levels

The source of water to a pumped well depends on the location of the well within a basin. Thus, the effects of a pumped well on base flow and water levels also depends on the location of the well within a basin. To determine the effect of pumping a well in different locations, simulations were run with a hypothetical well pumping at a rate of 200 gal/min in the Beaver Run Subbasin (drainage area 6.5 mi^2) for 3 years. The withdrawal of 200 gal/min is simulated as consumptive use with all water removed from the basin. Transient simulations were run to determine temporal changes in the source of water to the pumped well. Simulations were run with the hypothetical well (1) on the basin drainage divide between the French Creek Basin and the Marsh Creek Basin to the south, (2) on the subbasin drainage divide between Beaver Run and South Branch French Creek, (3) between the Beaver Run and the subbasin divide, (4) close to Beaver Run in a headwaters area, and (5) close to Beaver Run in a downstream location near the confluence with French Creek (fig. 32, table 13). Reduced stream base flow includes both diverted ground water that would have discharged to the stream as base flow and induced recharge from streamflow.

Effects of Pumping a Well on the Basin Divide

To simulate the effects of pumping a well on the French Creek Basin drainage divide, the hypothetical well was placed on the drainage divide between the French Creek Basin and the Marsh Creek Basin to the south (fig. 32). At the end of 3 years of simulated pumping, the simulated base flow of Beaver Run at the mouth was reduced from 5.36 ft^3/s to 5.30 ft^3/s, a reduction of 0.06 ft^3/s or 1 percent (fig. 33). For the first 7 days of pumping, all pumped water is derived from storage (table 14). For the next 23 days, almost all of the pumped water is from storage, but some water also is derived from reduced base flow of streams outside the French Creek Basin. After 30 days of pumping, some water is derived from reduced base flow of Beaver Run. At 3 years after the start of pumping, most of the pumped water (70.9 percent) is derived from the reduced base flow of streams outside the French Creek Basin, 13.2 percent is from the reduced base flow of Beaver Run, 14.8 percent is from storage, and 0.2 percent is from reduced ground-water ET (table 14). As the water table is lowered, water lost to ground-water ET decreases. At the end of 3 years, the ground-water system was not in equilibrium. Running the simulation for an additional 4 years showed that the percentage of water derived from storage continued to decline, the percentage of water derived from sources outside the French Creek Basin continued to increase, and the base flow of Beaver Run decreased only by an additional 0.01 ft^3/s. The map of simulated drawdown shows that water levels are affected in both the Beaver Run Subbasin and the Marsh Creek Basin (fig. 34) and that the ground-water divide has shifted to the south. This scenario produced the least effect on the base flow of Beaver Run and the greatest effect outside the French Creek Basin.

Table 13. Reduction in base flow of Beaver Run at mouth caused by a well pumping at 200 gallons per minute for 3 years in various locations in the Beaver Run Subbasin, Pennsylvania, with all pumped water removed from the basin

[ft^3/s, cubic feet per second]

Location of pumping well	Discharge of Beaver Run at mouth (ft^3/s)	Percentage reduction in base flow	Percentage of pumped water derived from base flow of Beaver Run
No well	5.36	0	0
French Creek/Marsh Creek Basin divide	5.30	1.1	13
Beaver Run/South Branch French Creek Subbasin divide	5.06	5.6	67
Between Beaver Run and subbasin divide	4.92	8.2	98
Close to Beaver Run in headwaters	4.94	7.8	93
Close to Beaver Run near mouth	4.94	7.8	93

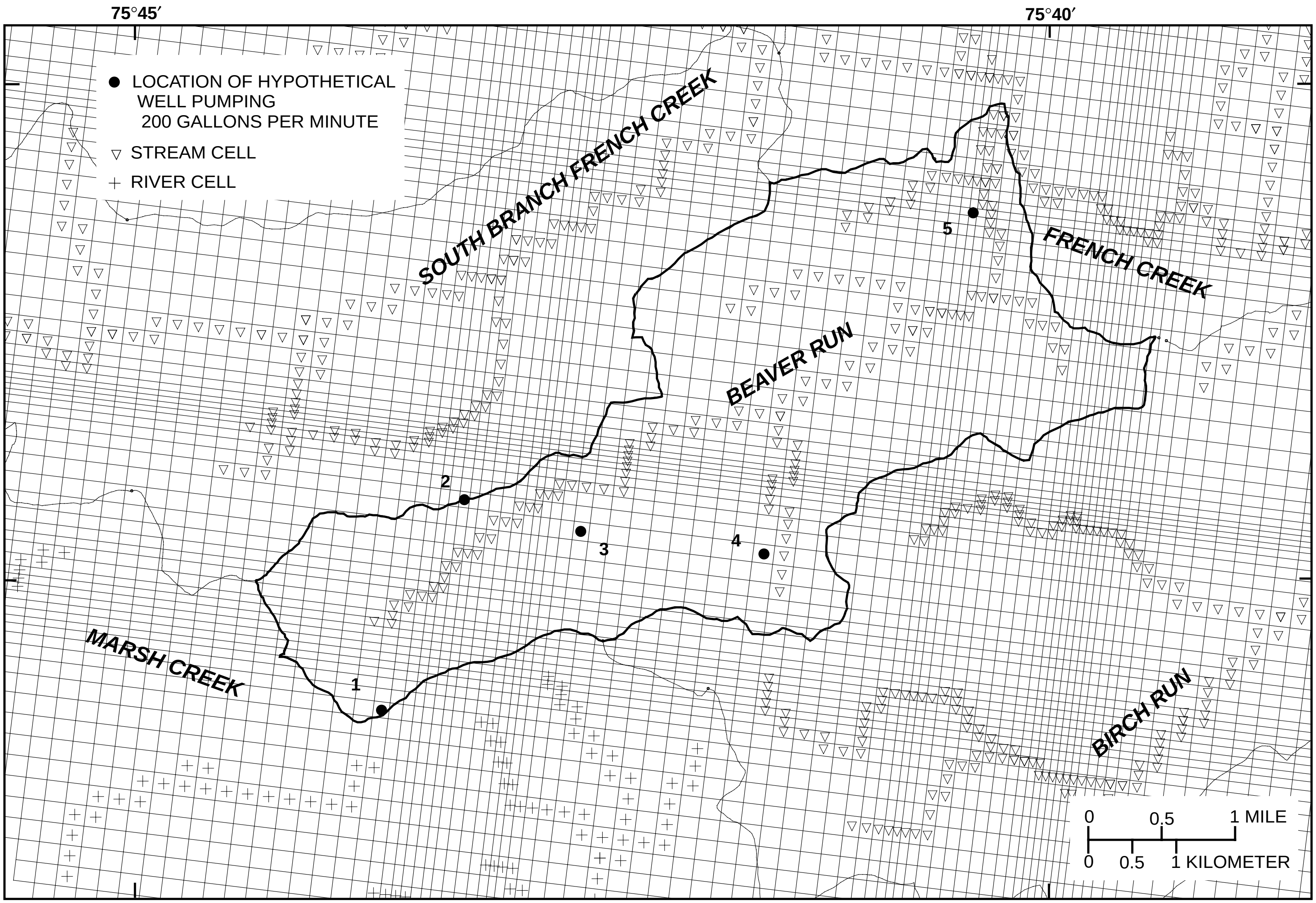


Figure 32. Locations of hypothetical wells in the Beaver Run Subbasin, Pennsylvania. (1 is well on French Creek-Marsh Creek Basin divide, 2 is well on Beaver Run-South Branch French Creek Subbasin divide, 3 is well between Beaver Run and divide, 4 is well close to Beaver Run in headwaters area, and 5 is well close to Beaver Run at confluence with French Creek.)

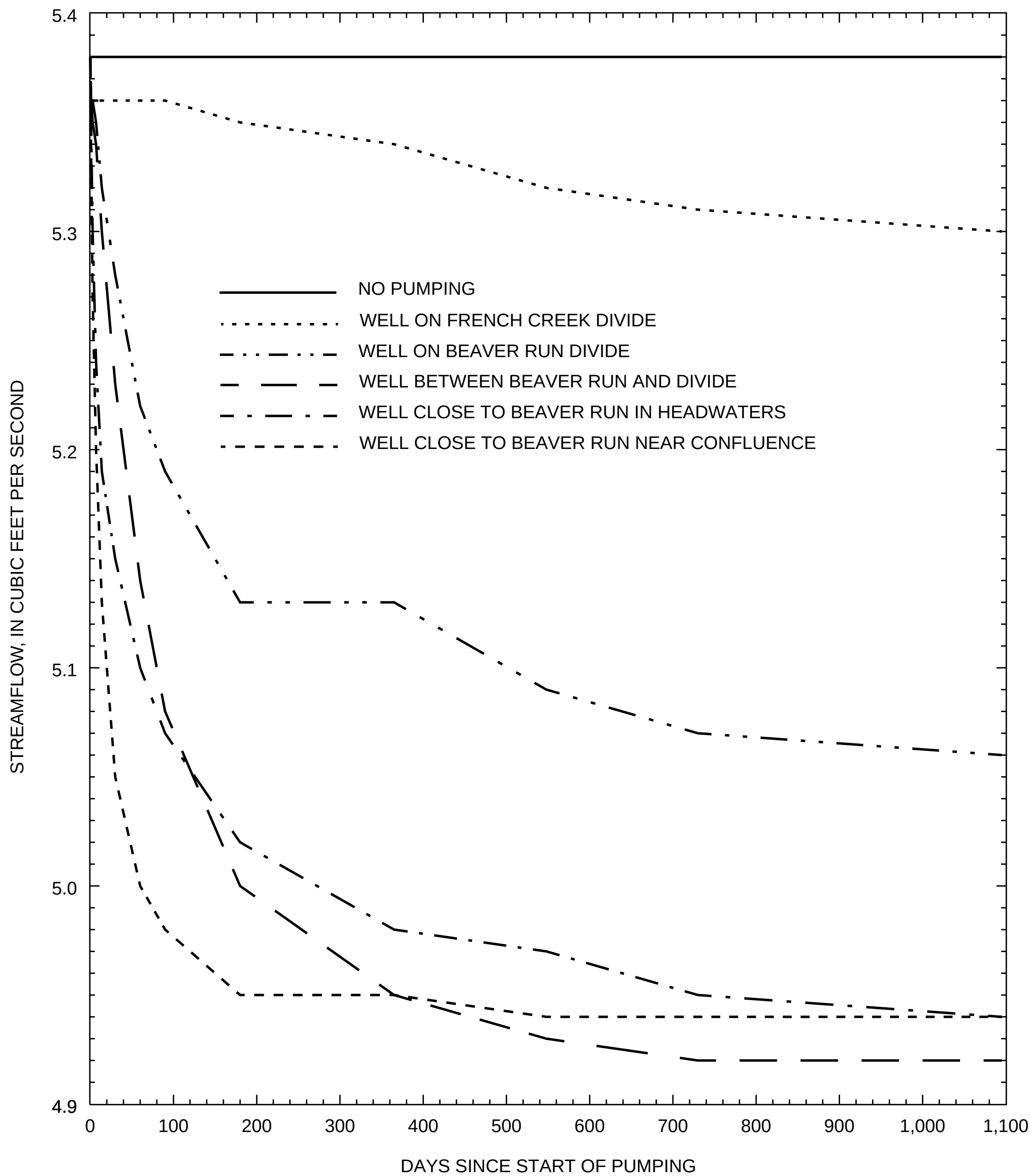


Figure 33. Simulated hydrographs for Beaver Run at mouth showing the effects of pumping a well at 200 gallons per minute in different locations in the Beaver Run Subbasin, Pennsylvania, with all pumped water removed from the basin.

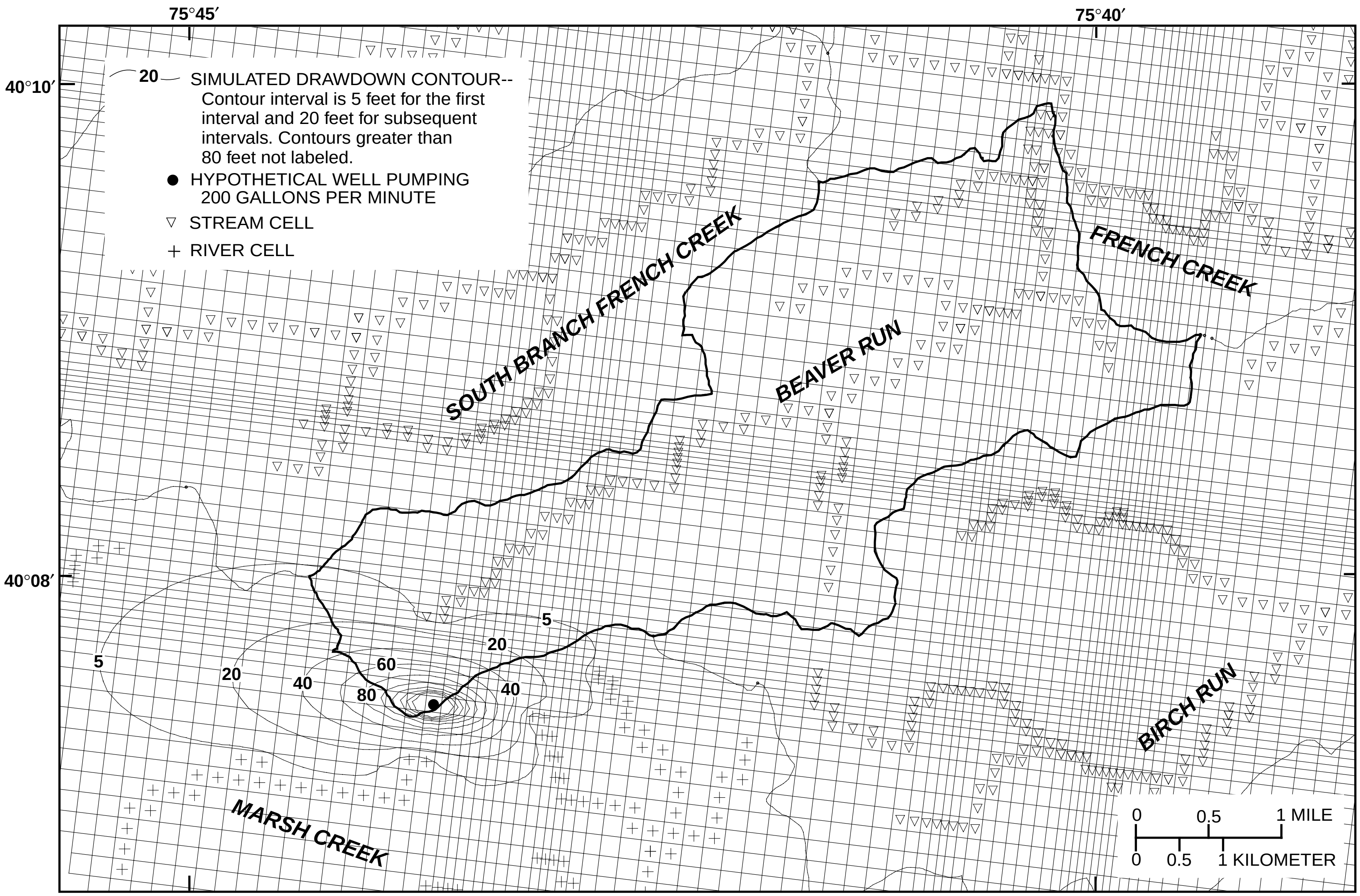


Figure 34. Simulated drawdown in the Beaver Run Subbasin, Pennsylvania, from pumping a well at 200 gallons per minute on the French Creek–Marsh Creek Basin divide with all pumped water removed from the basin.

Table 14. *Source of water to a pumped well in various locations in the Beaver Run Subbasin, Pennsylvania*

Days since start of pumping	Cumulative pumpage (gallons)	Percentage of water from base flow in the French Creek Basin[1]	Percentage of water from storage	Percentage of water from outside the French Creek Basin	Percentage of water from reduction in ground-water evapotranspiration
		Well on the French Creek Basin divide			
1	288,000	0	100.0	0	0
3	864,000	0	100.0	0	0
7	2,016,000	0	100.0	0	0
14	4,032,000	0	99.7	.3	0
30	8,640,000	0	98.1	1.8	0
60	17,280,000	.1	93.2	6.5	0
90	25,920,000	.4	87.4	11.9	.2
180	51,840,000	1.9	71.6	26.1	.2
365	105,120,000	5.4	49.7	44.3	.2
548	157,824,000	8.3	35.3	55.6	.2
730	210,240,000	10.5	25.6	63.0	.2
1,095	315,360,000	13.2	14.8	70.9	.2
Average		8.6	37.0	53.6	.2
		Well on the Beaver Run Subbasin divide			
1	288,000	0	100.0	0	0
3	864,000	.3	99.7	0	0
7	2,016,000	2.0	98.0	0	0
14	4,032,000	6.8	93.1	0	0
30	8,640,000	18.3	81.5	0	0
60	17,280,000	34.2	65.4	0	0
90	25,920,000	45.5	54.0	0	.5
180	51,840,000	65.0	34.3	0	.5
365	105,120,000	71.8	27.4	0	.5
548	157,824,000	82.9	16.1	.1	.5
730	210,240,000	90.0	8.8	.2	.5
1,095	315,360,000	95.1	3.4	.4	.5
Average		80.5	18.4	.2	.4

Table 14. *Source of water to a pumped well in various locations in the Beaver Run Subbasin, Pennsylvania—Continued*

Days since start of pumping	Cumulative pumpage (gallons)	Percentage of water from base flow in the French Creek Basin[1]	Percentage of water from storage	Percentage of water from outside the French Creek Basin	Percentage of water from reduction in ground-water evapotranspiration
Well between Beaver Run and divide					
1	288,000	0.2	99.8	0	0
3	864,000	1.6	98.4	0	0
7	2,016,000	5.6	94.3	0	0
14	4,032,000	13.6	86.3	0	0
30	8,640,000	28.9	70.9	0	0
60	17,280,000	48.2	51.5	0	0
90	25,920,000	61.6	38.0	0	.4
180	51,840,000	80.0	19.5	0	.4
365	105,120,000	92.0	7.4	0	.4
548	157,824,000	96.1	3.2	0	.4
730	210,240,000	97.7	1.5	.1	.4
1,095	315,360,000	98.6	.6	.1	.4
Average		90.8	8.5	.1	.4
Well close to Beaver Run in the headwaters					
1	288,000	4.4	95.6	0	0
3	864,000	13.4	86.6	0	0
7	2,016,000	26.3	73.6	0	0
14	4,032,000	39.3	60.7	0	0
30	8,640,000	47.3	52.6	0	0
60	17,280,000	57.8	42.1	0	0
90	25,920,000	65.1	34.7	0	.2
180	51,840,000	76.5	23.2	0	.2
365	105,120,000	86.7	12.8	.1	.2
548	157,824,000	91.3	8.0	.2	.2
730	210,240,000	93.7	5.4	.4	.2
1,095	315,360,000	96.1	2.8	.6	.2
Average		88.2	11.0	.3	.2

Table 14. *Source of water to a pumped well in various locations in the Beaver Run Subbasin, Pennsylvania—Continued*

Days since start of pumping	Cumulative pumpage (gallons)	Percentage of water from base flow in the French Creek Basin[1]	Percentage of water from storage	Percentage of water from outside the French Creek Basin	Percentage of water from reduction in ground-water evapotranspiration
Well close to Beaver Run downstream near the confluence with French Creek					
1	288,000	5.8	94.2	0	0
3	864,000	19.9	80.1	0	0
7	2,016,000	35.4	64.6	0	0
14	4,032,000	53.7	46.2	0	0
30	8,640,000	72.7	27.2	0	0
60	17,280,000	86.2	13.5	0	0
90	25,920,000	92.6	7.1	0	.2
180	51,840,000	97.8	2.3	0	.2
365	105,120,000	99.2	.5	0	.2
548	157,824,000	99.6	.2	0	.2
730	210,240,000	99.7	.1	0	.2
1,095	315,360,000	99.7	0	0	.2
Average		97.7	2.0	0	.2

[1] Includes diverted ground water that would have discharged as base flow and induced recharge from streams.

Effects of Pumping a Well on a Subbasin Divide

To simulate the effects of pumping a well on a subbasin drainage divide, the hypothetical well was placed on the drainage divide between Beaver Run and South Branch French Creek (fig. 32). For the first day of pumping, all pumped water comes from storage (table 14). After the first day of pumping, the percentage of pumped water derived from storage decreases while the percentage of water derived from the reduced base flow of Beaver Run increases. At 3 years after the start of pumping, most pumped water (95.1 percent) is derived from the reduced base flow of Beaver Run (67.5 percent of pumped water) and South Branch French Creek (27.6 percent of pumped water), 3.4 percent is from storage, 0.4 percent is from the reduced base flow of streams outside the French Creek Basin, and 0.5 percent is from reduced ground-water ET (table 14). The simulated base flow of Beaver Run at the mouth was reduced from 5.36 ft^3/s to 5.06 ft^3/s (table 13), a reduction of 0.3 ft^3/s or 6 percent (fig. 33). The simulated base flow of South Branch French Creek was reduced by 0.12 ft^3/s or 1 percent. The map of simulated drawdown shows that water levels are affected in both the Beaver Run and South Branch French Creek Subbasins (fig. 35).

Effects of Pumping a Well Between a Stream and a Divide

To simulate the effects of a pumping well between a stream and a divide, the hypothetical well was placed between Beaver Run and the Beaver Run drainage divide (fig. 32). For the first day of pumping, almost all the pumped water is derived from storage (table 14). After the first day, the percentage of pumped water derived from storage decreases while the percentage of water derived from the reduced base flow of Beaver Run increases. At 3 years after the start of pumping, most pumped water (98.6 percent) is derived from reduced base flow of Beaver Run, 0.6 percent is from storage, 0.1 percent is from the reduced base flow of streams outside the French Creek Basin, and 0.4 percent is from reduced ground-water ET (table 14). The simulated base flow of Beaver Run at the mouth is reduced from 5.36 ft^3/s to 4.92 ft^3/s (table 13), a reduction of 0.44 ft^3/s or 8 percent (fig. 33). The base flow of South Branch French Creek is reduced by less than 0.01 ft^3/s. The map of simulated drawdown shows that water levels are affected only in the Beaver Run Subbasin (fig. 36).

Effects of Pumping a Well Close to a Headwater Stream

To simulate the effects of pumping a well close to a headwater stream, the hypothetical well was placed near Beaver Run in a headwaters area (fig. 32). After 1 day of pumping, 4.4 percent of the pumped water was derived from the reduced base flow of Beaver Run and 95.6 percent was from storage (table 14). After the first day, the percentage of pumped water derived from storage decreases while the percentage of water derived from the reduced base flow of Beaver Run increases. At 3 years after the start of pumping, most pumped water (96.1 percent) is derived from the reduced base flow of Beaver Run (93.9 percent of pumped water) and Birch Run (2.2 percent of pumped water), 2.8 percent is from storage, 0.6 percent is from reduced base flow of streams outside the French Creek Basin, and 0.2 percent is from reduced ground-water ET (table 14). The simulated base flow of Beaver Run at the mouth was reduced from 5.36 ft^3/s to 4.94 ft^3/s (table 13), a reduction of 0.42 ft^3/s or 8 percent (fig. 33). The simulated base flow of Birch Run was reduced by 0.01 ft^3/s. The map of simulated drawdown shows that water levels mostly are affected in the Beaver Run Subbasin, but some drawdown also results in the adjacent Birch Run Subbasin (fig. 37).

Effects of Pumping a Well Close to the Confluence of a Stream

To simulate the effects of pumping a well near the confluence of a stream (downstream location), the hypothetical well was placed close to Beaver Run near its confluence with French Creek (fig. 32). By the end of the first day of pumping, 5.8 percent of the pumped water was derived from the reduced flow of Beaver Run (table 14). After the first day, the percentage of pumped water derived from storage decreases while the percentage of water derived from the reduced base flow of Beaver Run increases. At 3 years after the start of pumping, water no longer is derived from storage; all pumped water is from reduced base flow. At 3 years after the start of pumping, most pumped water (99.7 percent) is derived from the reduced base flow of Beaver Run (93 percent of pumped water) and French Creek (6.7 percent of pumped water) and 0.2 percent is from reduced ground-water ET (table 14). The simulated base flow of Beaver Run at the mouth was reduced from 5.36 ft^3/s to 4.94 ft^3/s (table 13), a reduction of 0.42 ft^3/s or 8 percent (fig. 33). This amount is the

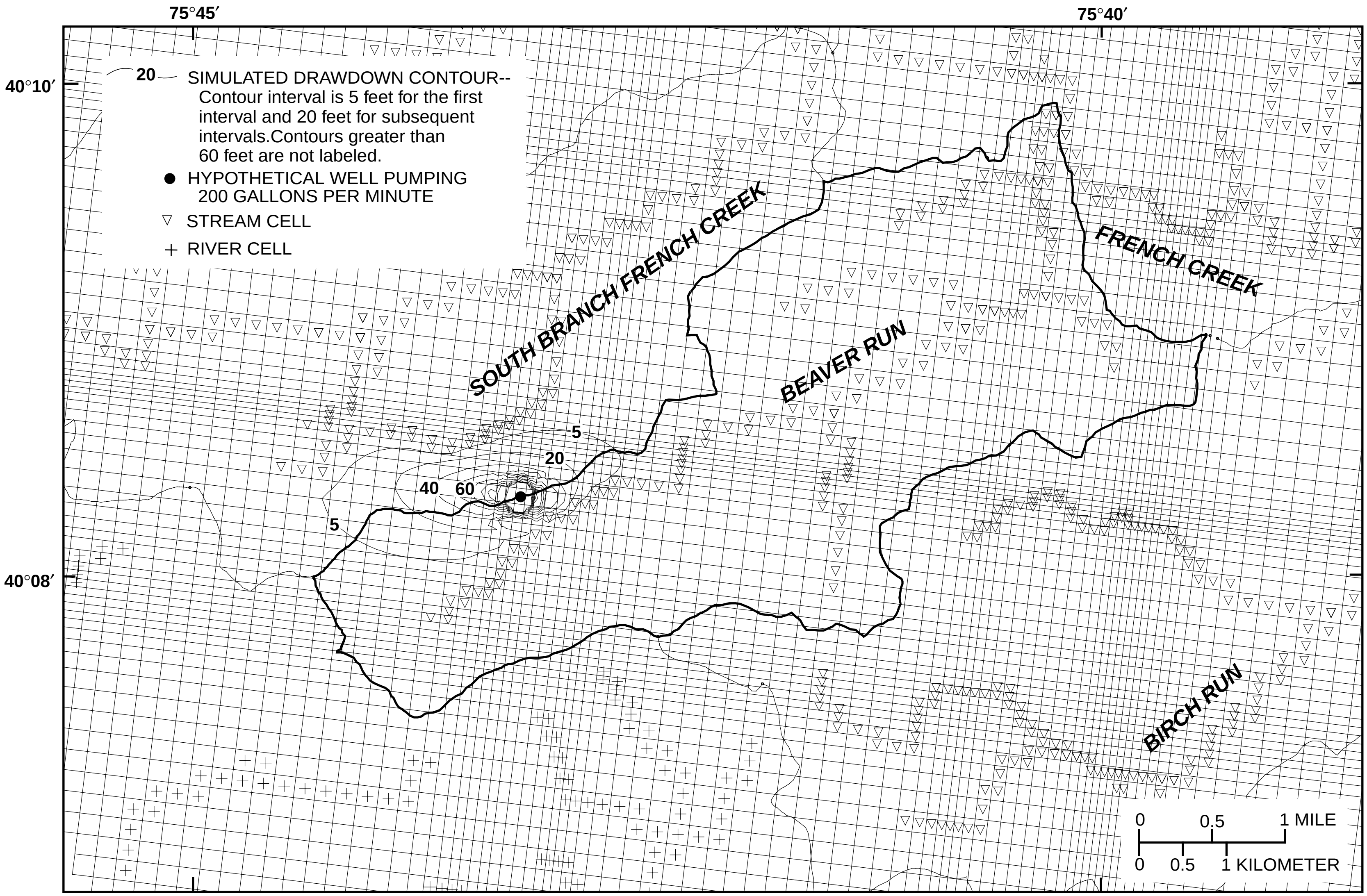


Figure 35. Simulated drawdown in the Beaver Run Subbasin, Pennsylvania, from pumping a well at 200 gallons per minute on the Beaver Run-South Branch French Creek Subbasin divide with all pumped water removed from the basin.

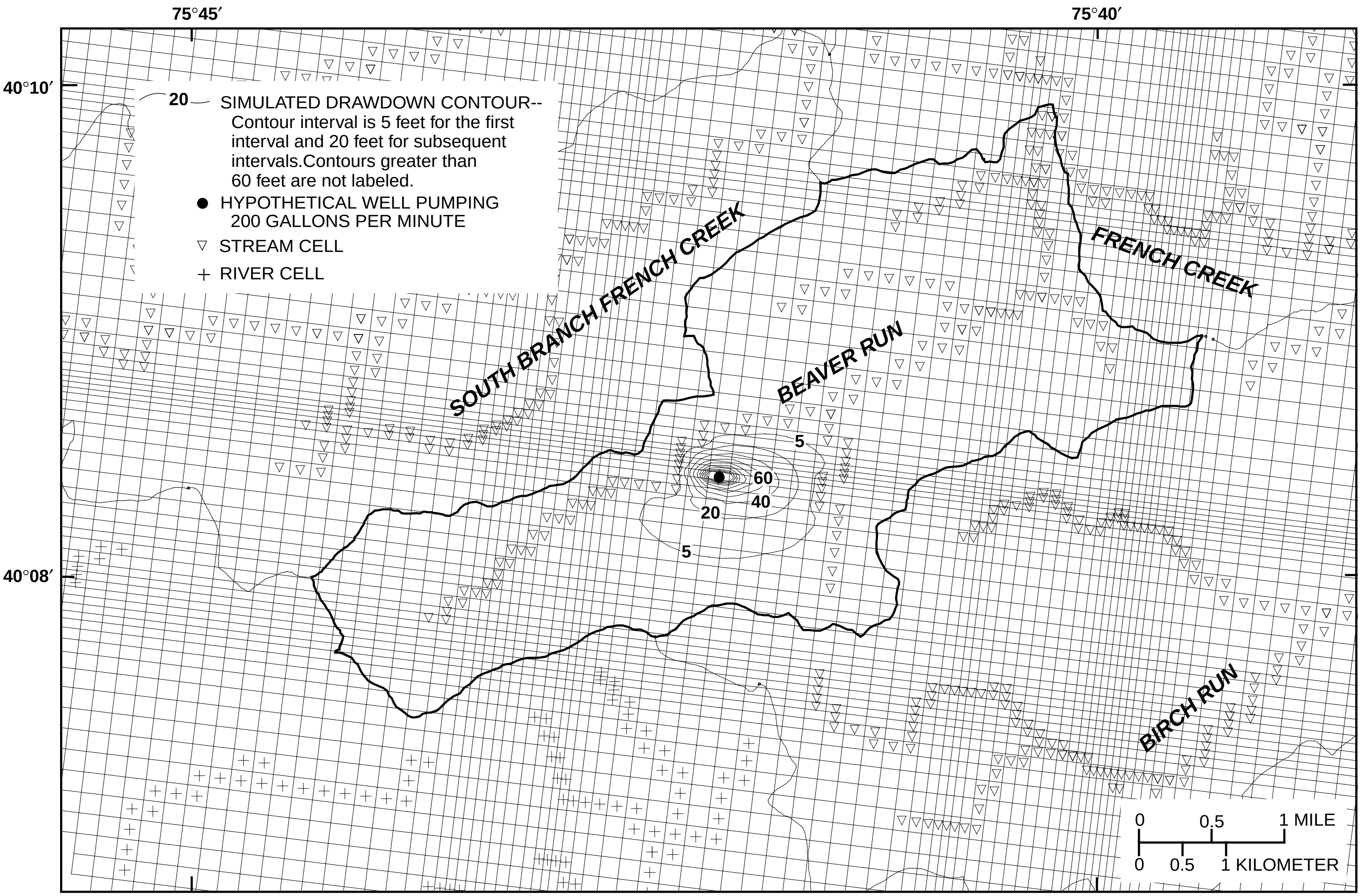


Figure 36. Simulated drawdown in the Beaver Run Subbasin, Pennsylvania, from pumping a well at 200 gallons per minute between Beaver Run and the Beaver Run Subbasin divide with all pumped water removed from the basin.

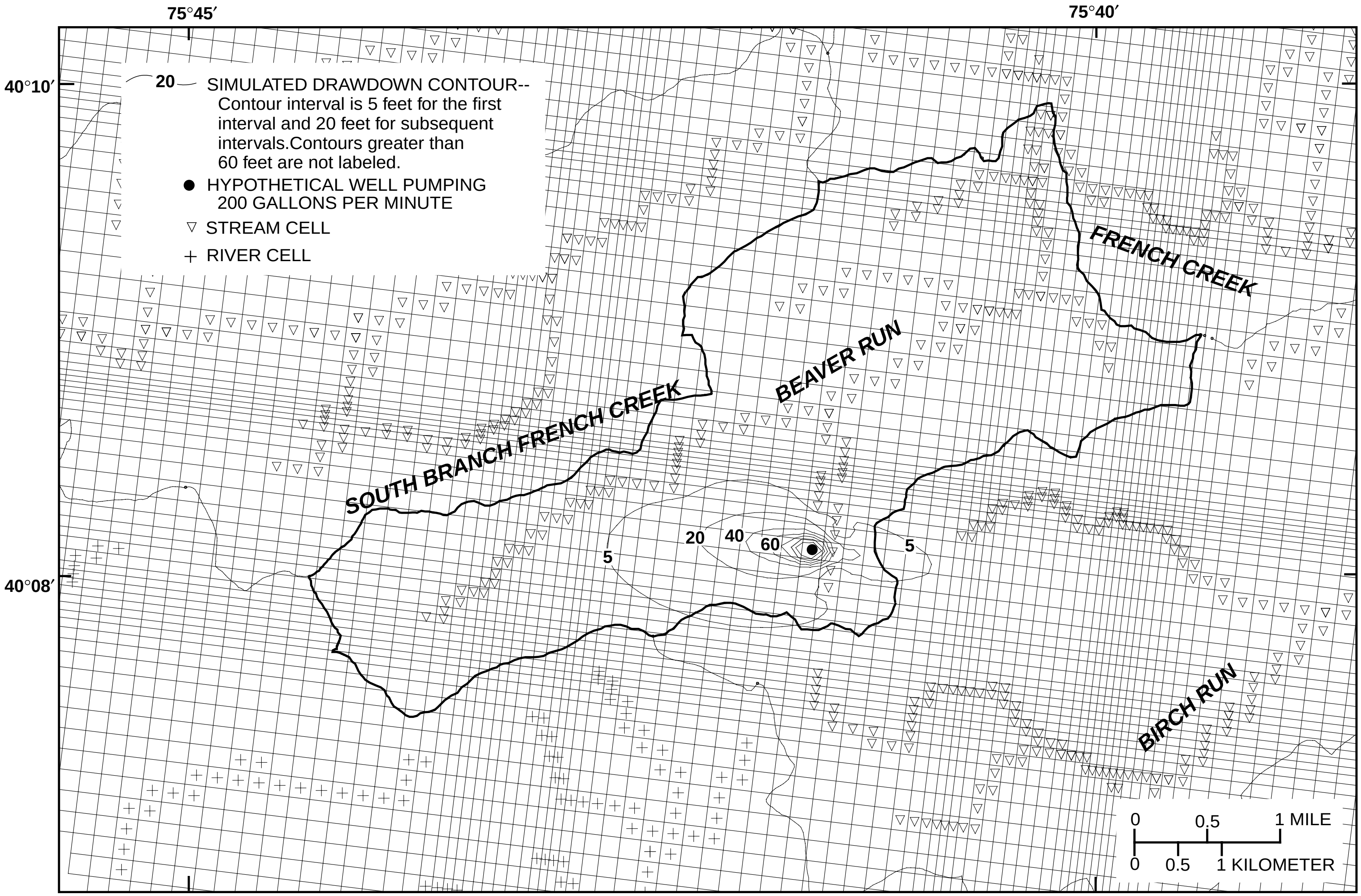


Figure 37. Simulated drawdown in the Beaver Run Subbasin, Pennsylvania, from pumping a well at 200 gallons per minute close to Beaver Run in the headwaters with all pumped water removed from the basin.

same reduction in the base flow of Beaver Run caused by pumping a well near Beaver Run in a headwaters area. No water is derived from reduced base flow outside the French Creek Basin. The simulated base flow of French Creek was reduced by 0.03 ft^3/s. This scenario produced the least effects outside the French Creek Basin. The map of drawdown shows that water levels mainly are affected in the Beaver Run Subbasin; however, some drawdown results in the adjacent main stem French Creek Subbasin (fig. 38).

Source of Water to a Well

The simulations of a hypothetical pumping well in the Beaver Run Subbasin show that (1) if the contributing area of a well is in a basin, pumping will affect stream base flow and water levels in that basin whether the well is inside or outside that basin; (2) wells in different areas of a basin away from a divide produce a similar reduction in base flow; (3) a well within a basin will derive more water from diverted base flow and less water from storage than a well on or near a basin divide; and (4) the reduction in base flow at the mouth of the stream is the same for a well in the headwaters and a well downstream near the confluence.

The source of water to a pumped well changes until equilibrium with the hydrologic system is reached. Initially, water is derived from storage in the vicinity of the pumped well (table 14, fig. 39). As the cone of depression caused by pumping spreads outward from the pumped well, it reaches a stream where ground water is discharged from the aquifer to the stream as base flow (figs. 35-38). The hydraulic gradient from the pumped well to the stream is reduced, and the rate of discharge of ground water to the stream is reduced, thereby reducing the base flow of the stream. When the reduction in base flow equals the rate of water pumped from the well, the pumped well reaches equilibrium with the hydrologic system and all pumped water is water that would have been discharged to the stream as base flow; no additional water is withdrawn from storage.

If the pumped well is close enough to the stream and the pumping is continued long enough, ground-water discharge to the stream in the vicinity of the well may cease, the hydraulic gradient between the aquifer and the stream may reverse, and water may be induced to flow from the stream into the aquifer (induced streamflow). The stream then becomes a losing stream in the reach in the vicinity of the pumped well. The cone of depression may spread beneath and beyond the stream (fig. 37). If the streamflow is small enough or the loss great enough, all of the streamflow may be induced into the aquifer, and the stream may become dry in the vicinity of the pumped well. For the simulations of a well close to a stream, the well in the headwaters area initially derived more water from base flow than did the well downstream near the confluence. At about 114 days after the start of pumping, the well near the confluence began producing a greater percentage of water from base flow (fig. 40) and less water from storage (fig. 39) than did the well in the headwaters area. At about 114 days after the start of pumping, the well in the headwaters area is inducing the entire flow of the nearby tributary to Beaver Run, and the cone of depression expands under and beyond the stream taking additional water from storage (fig. 37).

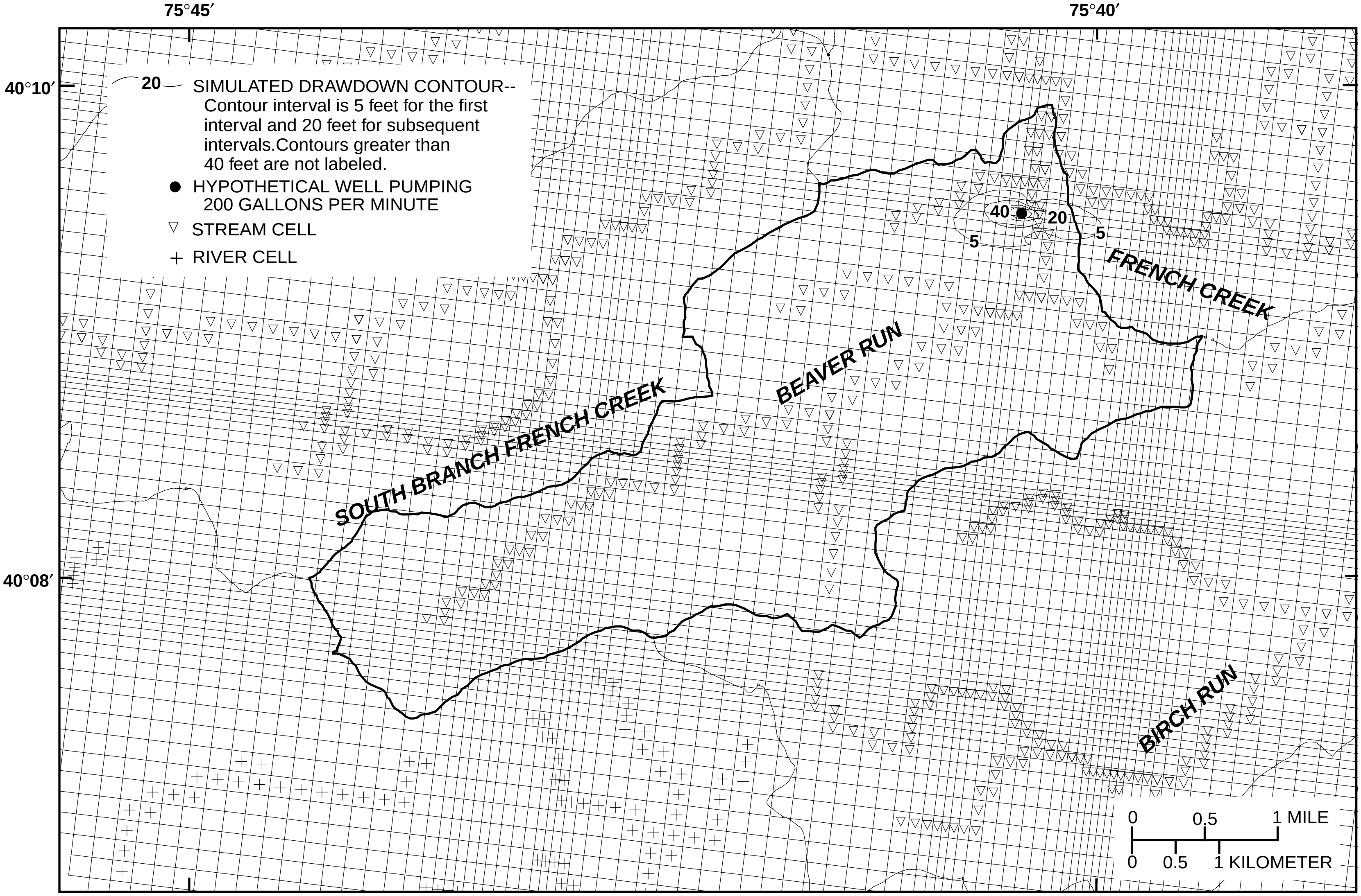


Figure 38. Simulated drawdown in the Beaver Run Subbasin, Pennsylvania, from pumping a well at 200 gallons per minute close to Beaver Run near the confluence with French Creek with all pumped water removed from the basin.

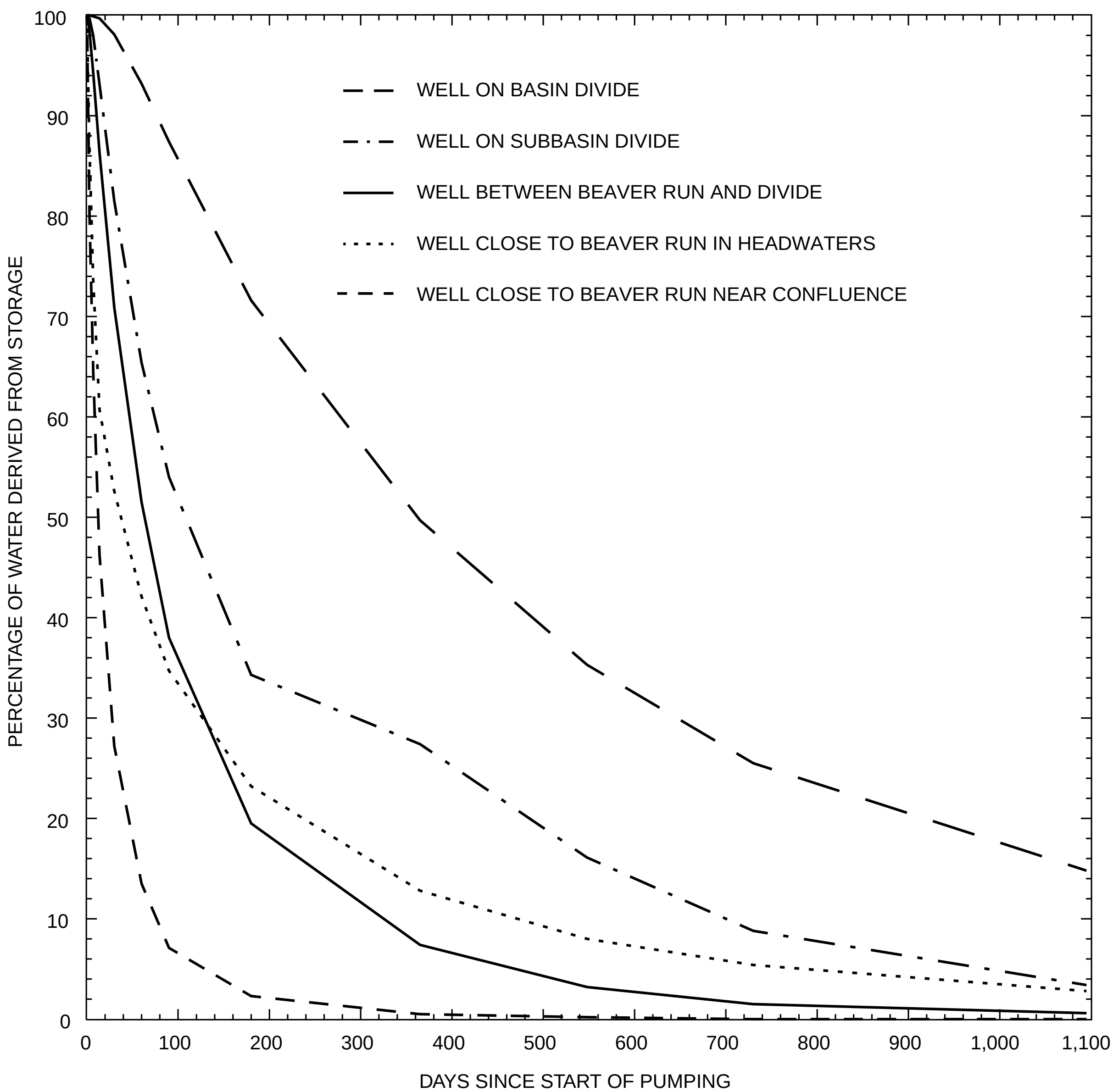


Figure 39. Percentage of water to a pumped well derived from storage in the Beaver Run Subbasin, Pennsylvania.

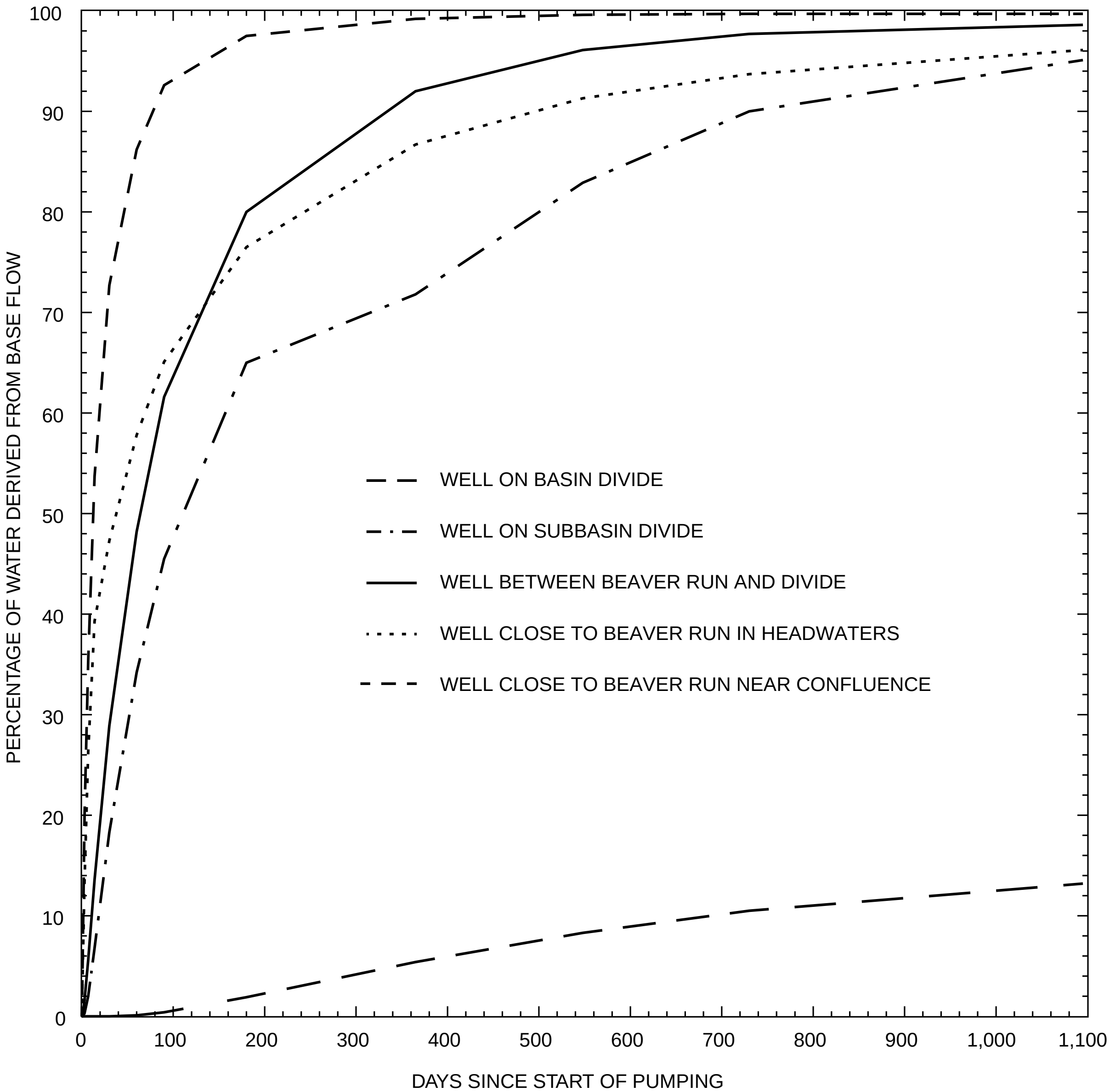


Figure 40. Percentage of water to a pumped well derived from base flow in the Beaver Run Subbasin, Pennsylvania.

SUMMARY

In response to concerns over increasing use of ground water in an area with a limited ground-water resource, the Delaware River Basin Commission (DRBC) in 1980 established the Southeastern Pennsylvania Ground Water Protected Area (GWPA), which covers about 1,250 mi^2. Special regulations were issued by the DRBC for the GWPA to provide for the effective management of ground-water resources, to protect the rights of present and future water users, and to acquire additional information to more accurately plan and manage water resources. As demand for use of limited water resources increases in the future, water allocations may be subject to conjunctive use and conservation requirements established in the GWPA. The effects of pumping ground water on ground-water availability and streamflow during low-flow (drought) conditions in the GWPA have not been quantified. This report describes the results of a study by the U.S. Geological Survey in cooperation with the DRBC to develop a regional ground-water-flow model of the French Creek Basin in Chester County, Pa. The model was used to assist water-resource managers by illustrating the interconnection between ground-water and surface-water systems. The 70.7-mi^2 French Creek Basin is in the Piedmont Physiographic Province and is underlain by crystalline, sedimentary, and intrusive fractured-rock aquifers. Annual water budgets were calculated for 1969-2001 for the French Creek Basin above streamflow-measurement station French Creek near Phoenixville (01472157). Average annual precipitation was 46.28 in., average annual streamflow was 20.29 in., average annual base flow was 12.42 in., average annual change in ground-water storage was a decrease of 0.11 in., and estimated average annual ET was 26.10 in. Average annual streamflow is equal to 44 percent of the average annual precipitation, average annual base flow is equal to 27 percent of the average annual precipitation, and estimated average annual ET is equal to 56 percent of the average annual precipitation. Base flow made up an average of 61 percent of streamflow.

Ground-water flow in the French Creek Basin was simulated using the finite-difference MODFLOW-96 computer program. The model structure is based on a simplified two-dimensional conceptualization of the ground-water-flow system. The modeled area is 111 mi^2, which includes 70.7 mi^2 of the French Creek Basin and 40.3 mi^2 of adjacent areas. The modeled area was extended outside the French Creek Basin to natural hydrologic boundaries. The model includes 41 wells with annual pumpage rates ranging from 0.5 to 23.5 Mgal/yr; the total pumping rate for the modeled area is 295.4 gal/min.

Data collected for model calibration include synoptic measurements of stream base flow and ground-water levels. Base-flow measurements were made on May 1, 2001, during a period of higher than average base flow. Streamflow at streamflow-measurement station 01472157 on May 1 was 71.7 ft^3/s; the average base flow at the station for 1968-2001 is 54.1 ft^3/s. Base-flow measurements were made on September 11 and 17, 2001, during a period of less than average base flow. Streamflow at the streamflow-measurement station was 17.1 ft^3/s on September 11 and 12.8 ft^3/s on September 17. Water levels were measured in 22 wells on May 1, September 11, and September 17, 2001. The difference between the higher May 1 water levels and the lower September 17 water levels ranged from 0.79 to 19.78 ft.

The model was calibrated for above-average flow conditions by simulating base-flow and water-level measurements made on May 1, 2001, using a recharge rate of 20 in/yr. The model was calibrated for below-average conditions by simulating base-flow and water-level measurements made on September 11 and 17, 2001, using a recharge rate of 6.2 in/yr. Average conditions were simulated by adjusting the recharge rate until simulated streamflow at streamflow-measurement station 01472157 matched the long-term (1968-2001) average base flow of 54.1 ft^3/s. The recharge rate used for average conditions is 15.7 in/yr.

The effect of drought in the French Creek Basin was simulated using a drought year recharge rate of 8 in/yr for 3 months. After 3 months of drought, the simulated streamflow of French Creek at streamflow-measurement station 01472157 decreased from 54.2 ft^3/s to 35.7 ft^3/s (34 percent). The simulated water level in the cells where observation wells CH-1571 and CH-2328 are located decreased 3.9 and 10.5 ft, respectively. Model simulations show that after 6 months of average recharge (15.7 in/yr) following drought, streamflow and water levels almost fully recovered to pre-drought conditions. Simulated discharge recovered to 53.8 ft^3/s at the streamflow-measurement station, and simulated water levels in the cells where observation wells CH-1571 and CH-2328 are

located were 0.2 and 4.0 ft below pre-drought conditions, respectively. A recharge rate of 17 in/yr for 6 months following drought resulted in a discharge of 54.9 ft^3/s at the streamflow-measurement station; water levels in model cells where observation wells CH-1571 and CH-2328 are located were 0.4 above and 1.9 ft below pre-drought conditions, respectively.

The effects of increased ground-water withdrawals on stream base flow and water levels in the South Branch French Creek Subbasin were simulated with pumping rates equal to 50, 75, and 100 percent of the GWPA withdrawal limit (1,393 Mgal/y) with all pumped water removed from the basin. Transient simulations included: (1) average conditions using an average recharge rate of 15.7 in/yr for 27 months, (2) drought conditions using an average recharge rate of 15.7 in/yr for 24 months followed by a drought recharge rate of 8 in/yr for 3 months, and (3) extreme drought conditions using an average recharge rate of 15.7 in/yr for 24 months followed by no recharge for 3 months.

For average recharge conditions, the simulated streamflow of South Branch French Creek at the mouth decreased 18 percent, 28 percent, and 37 percent from current (2003) pumping conditions at a withdrawal rate equal to 50 percent, 75 percent, and 100 percent of the GWPA limit, respectively, with all pumped water removed from the basin. Ninety-one to ninety-three percent of the pumped water is water that would have discharged as stream base flow. The simulated water level in the cell where observation well CH-1487 is located decreased 18.7 ft, 28.3 ft, and 38.2 ft from current pumping conditions at a withdrawal rate equal to 50 percent, 75 percent, and 100 percent of the GWPA limit, respectively.

For drought recharge conditions, the simulated streamflow of South Branch French Creek at the mouth decreased 27 percent, 40 percent, and 52 percent from current pumping under drought conditions at a withdrawal rate equal to 50 percent, 75 percent, and 100 percent of the GWPA limit, respectively, with all pumped water removed from the basin. The simulated water level in the cell where observation well CH-1487 is located decreased 6.4 ft, 19.1 ft, and 39.2 ft from current pumping under drought conditions at a withdrawal rate equal to 50 percent, 75 percent, and 100 percent of the GWPA limit, respectively.

For extreme drought recharge conditions, the simulated streamflow of South Branch French Creek at the mouth decreased 41 percent, 59 percent, and 74 percent from current pumping under extreme drought conditions at a withdrawal rate equal to 50 percent, 75 percent, and 100 percent of the GWPA limit, respectively, with all pumped water removed from the basin. The simulated water level in the cell where observation well CH-1487 is located decreased 19.8 ft, 33 ft, and 48.3 ft from current pumping under extreme drought conditions at a withdrawal rate equal to 50 percent, 75 percent, and 100 percent of the GWPA limit, respectively.

The effect of pumping a hypothetical well at 200 gal/min in various locations in the Beaver Run Subbasin on stream base flow, water levels, and the source of water to the well was simulated. All pumped water was removed from the basin. To simulate the effects of pumping a well located on the French Creek Basin drainage divide, the hypothetical well was placed on the drainage divide between the French Creek Basin and the Marsh Creek Basin to the south. The simulated base flow of Beaver Run was reduced by 1 percent. At 3 years after the start of pumping, most pumped water (70.9 percent) was derived from the reduced base flow of streams outside the French Creek Basin, 13.2 percent was from the reduced base flow of Beaver Run, 14.8 percent was from storage, and 0.2 percent was from reduced ground-water ET. This scenario had the least effect on the base flow of Beaver Run.

To simulate the effects of pumping a well on a subbasin drainage divide, the hypothetical well was placed on the drainage divide between Beaver Run and South Branch French Creek. Water levels were affected in both the Beaver Run and South Branch French Creek Subbasins. The simulated base flow of Beaver Run was reduced by 6 percent, and the simulated base flow of South Branch French Creek was reduced by 1 percent. At 3 years after the start of pumping, most pumped water (95.1 percent) was derived from the reduced base flow of Beaver Run (67.5 percent) and South Branch French Creek (27.6 percent), 3.4 percent was from storage, 0.4 percent was from reduced base flow of streams outside the French Creek Basin, and 0.3 percent was from reduced ground-water ET.

To simulate the effects of a pumping well between a stream and a divide, the hypothetical well was placed between Beaver Run and the Beaver Run drainage divide. Water levels were affected only in the Beaver Run Subbasin. The simulated base flow of Beaver Run was reduced by 8 percent. At 3 years after the start of pumping, most pumped water (98.6 percent) was derived from reduced base flow of Beaver Run, 0.6 percent was from storage, 0.1 percent was from the reduced base flow of streams outside the French Creek Basin, and 0.3 percent was from reduced ground-water ET.

To simulate the effects of pumping a well close to a headwater stream, the hypothetical well was placed close to Beaver Run in a headwaters area. Water levels mostly were affected in the Beaver Run Subbasin. The simulated base flow of Beaver Run was reduced by 8 percent. At 3 years after the start of pumping, most of the pumped water (96.1 percent) was derived from the reduced base flow of Beaver Run (93.9 percent) and Birch Run (2.2 percent), 2.8 percent was from storage, 0.6 percent was from reduced base flow of streams outside the French Creek Basin, and 0.2 percent was from reduced ground-water ET.

To simulate the effects of pumping a well near the confluence of a stream (downstream location), the hypothetical well was placed close to Beaver Run near its confluence with French Creek. Water levels mainly were affected in the Beaver Run Subbasin. The simulated base flow of Beaver Run was reduced by 8 percent. This is the same reduction in the base flow of Beaver Run caused by pumping a well located near Beaver Run in a headwaters area. At 3 years after the start of pumping, most pumped water (99.7 percent) was derived from the reduced base flow of Beaver Run (93 percent) and French Creek (6.7 percent), and 0.2 percent was from reduced ground-water ET.

The simulations of a hypothetical well pumping in the Beaver Run Subbasin show that (1) if the contributing area of a well is in a basin, pumping will affect stream base flow and water levels in that basin whether the well is inside or outside that basin; (2) wells in different areas of a basin away from a divide produce a similar reduction in base flow; (3) a well within a basin will derive more water from diverted base flow and less water from storage than a well on or near a basin divide; and (4) the reduction in base flow at the mouth of the stream is the same for a well in the headwaters and a well downstream near the confluence.

The model was used to evaluate the effects of pumping on the regional potentiometric surface. In the model, a single value of hydraulic conductivity is assigned to a geologic unit or outcrop area of a geologic unit. Therefore, the model may not reproduce exactly drawdowns from a local aquifer test because the assigned regional hydraulic conductivity may differ from the hydraulic conductivity at the pumped well. The model does not adequately simulate all measured water levels at lower than average recharge conditions. Therefore, water-level declines simulated with the model for lower than average recharge conditions should be used with caution. The model was calibrated using annual values for recharge and ground-water ET. It then was run using the annual values in a seasonally independent transient mode to show changes with time. The timing and relative magnitude of some of the model-simulated changes when viewed in terms of a normal climatic year may be subject to considerable uncertainty because of the variability in seasonal recharge and ground-water ET rates. Therefore, transient model predictions for short-term periods are indicative of possible hydrologic system response and should be considered an approximation.

Simulations made with the model illustrate some of the typical analyses and results that can be produced. The predictive capabilities of the model could be improved if the level of confidence attached to its predictions can be increased. This increased confidence would require additional data collection for calibration that would include additional observation wells, especially in geologic units with large water-level simulation errors, and additional concurrent measurements of water levels and base flow for different streamflows. Transient calibration would require values for seasonal and possibly monthly, weekly, or even daily recharge and ground-water ET rates for an average and below average climatic year. Adding additional layers to the model may improve predictive capability, but doing so would require defining the vertical variability of aquifer properties.

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