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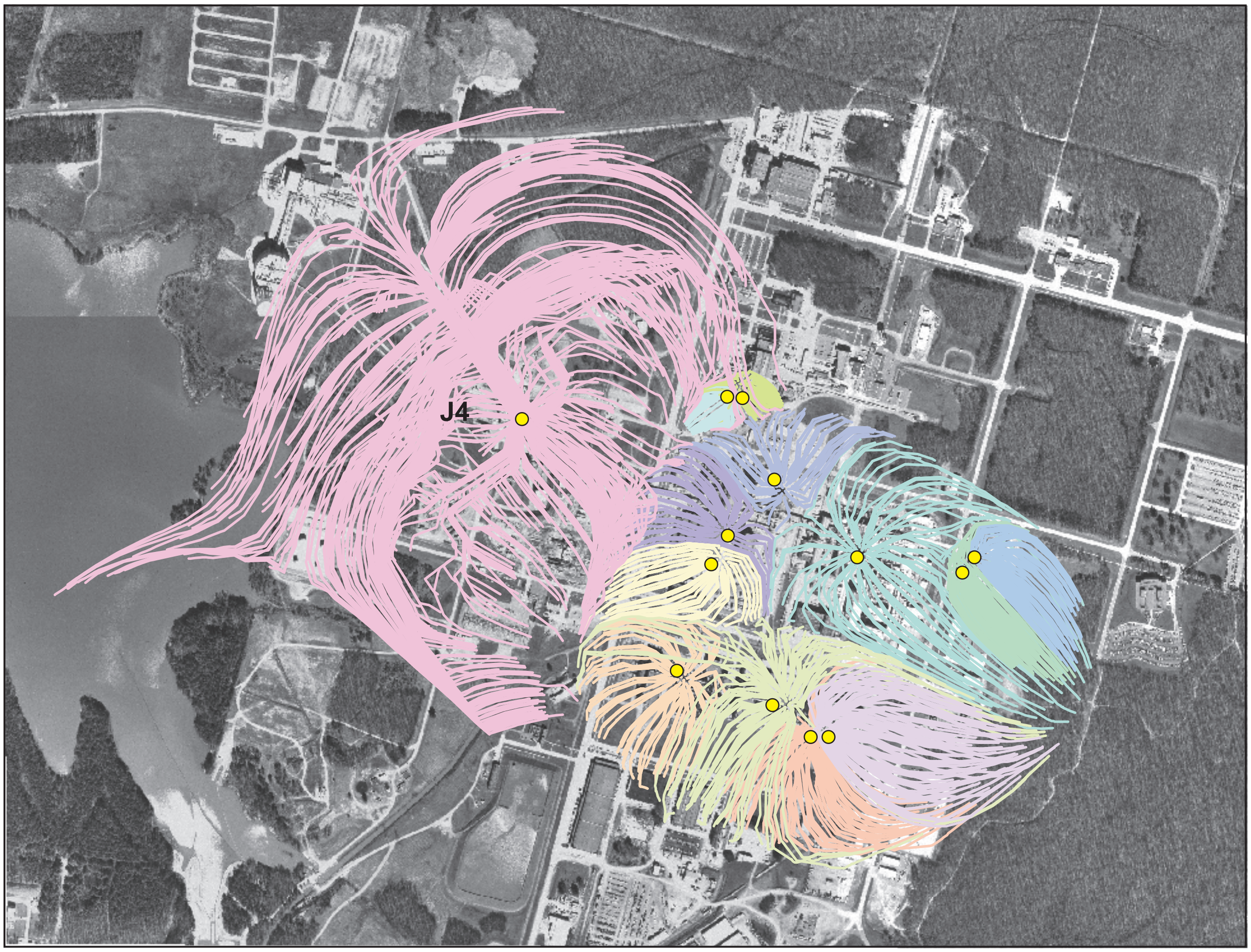
Hydrogeology and Simulation of Ground-Water Flow at Arnold Air Force Base, Coffee and Franklin Counties, Tennessee—2002 Update



Scientific Investigations Report 2006–5157

U.S. Department of the Interior
U.S. Geological Survey

Cover. Map showing backward particle tracking from dewatering facilities at the Main Test Area at Arnold Air Force Base. (Aerial photograph courtesy of the U.S. Air Force, Arnold Air Force Base.)

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By Connor J. Haugh

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

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

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

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

Hydrogeology and Simulation of Ground-Water Flow at Arnold Air Force Base, Coffee and Franklin Counties, Tennessee—2002 Update

By Connor J. Haugh

Abstract

Arnold Air Force Base (AAFB) occupies about 40,000 acres in the eastern part of the Highland Rim physiographic region in Coffee and Franklin Counties, Tennessee. The area is characterized by fractured carbonate rock terrane that complicates evaluation of ground-water flow. Numerous site-specific ground-water contamination investigations have been conducted at designated Solid Waste Management Units (SWMUs) at AAFB. Several synthetic volatile organic compounds (VOCs), primarily chlorinated solvents, have been identified in the ground water at AAFB. Two ground-water contaminant plumes that originate at AAFB, the "SWMU 8 plume" and the "northwest plume," have been shown to extend to regional discharge points outside the AAFB boundary. In 2002, the U.S. Geological Survey (USGS), in cooperation with the U.S. Air Force, AAFB, began an investigation to further refine the understanding of the regional ground-water system in the AAFB area and to update the previous computer ground-water flow model incorporating new data and information collected since 1992.

The updated ground-water flow model incorporates revised structure maps of the top-of-rock surface and the top of the Chattanooga Shale and the preferential regional flow paths identified by investigations conducted since 1992. The preferential regional flow paths play an important role in ground-water movement and contaminant transport in the AAFB area. The model is calibrated to steady-state conditions defined by detailed water-level and streamflow data collected in 2002. Particle-tracking simulations were used with the model to simulate ground-water flow paths and travel times from selected sites at AAFB. The flow paths indicated by the particle-tracking simulations agree reasonably well with maps of interpreted contaminant plumes.

Currently (2005), ground-water withdrawal wells are operating at SWMU 1&2, SWMU 5, SWMU 8, and SWMU 10, and dewatering occurs at many facilities at the Main Test Area (MTA). Particle-tracking results show that no particles leave these SWMUs while the ground-water withdrawal wells are pumping. Three particle-tracking simulations were run to analyze the effects of dewatering facilities on flow paths at the MTA. These simulations indicate that the dewatering facilities have a substantial effect on flow paths from the MTA and are effective in containing most of the ground water in this area.

Introduction

Arnold Air Force Base (AAFB) occupies about 40,000 acres in Coffee and Franklin Counties, Tennessee (fig. 1). The primary mission of AAFB is to support the development of aerospace systems. The mission is accomplished in part through test facilities at Arnold Engineering Development Center (AEDC), which occupies about 4,000 acres in the center of AAFB.

Numerous site-specific ground-water contamination investigations have been conducted at designated Solid Waste Management Units (SWMUs) at AAFB (fig. 2). Several synthetic volatile organic compounds (VOCs), primarily chlorinated solvents, have been identified in the ground water at AAFB. In 1992, the U.S. Geological Survey (USGS) completed a study of the hydrogeology of the AAFB area. This study included defining the regional ground-water flow system and simulating the flow system using a computer model (Haugh and Mahoney, 1994). Since then (1992), two ground-water contaminant plumes that originate at AAFB, the "SWMU 8 plume" and the "northwest plume," have been shown to extend to regional discharge points outside the AAFB boundary (fig. 2) (CH2M Hill, 1999, 2001). In 2002, the USGS, in cooperation with the U.S. Air Force, AAFB, began an investigation to further refine the understanding of the regional ground-water system in the AAFB area and to update the previous computer ground-water flow model by incorporating new data and information collected since 1992.

Purpose and Scope

Revisions to maps and interpretation of the hydrogeology of the AAFB area that appeared in previously published reports prepared by the USGS are provided in this report. Information from the previous reports is updated for use in the construction and calibration of an updated regional ground-water flow model. This report documents the updated

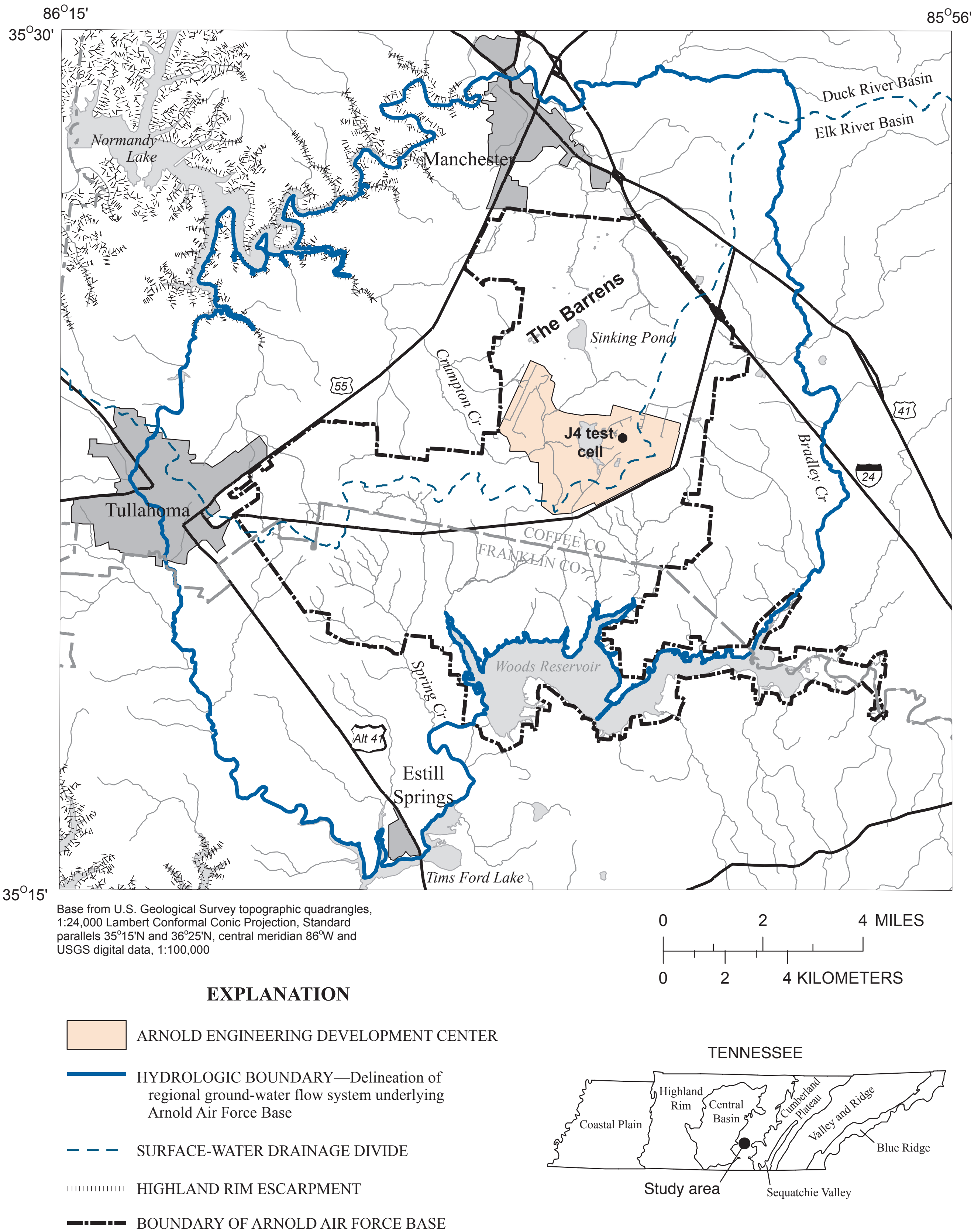


Figure 1. Location of study area at Arnold Air Force Base, Coffee and Franklin Counties, Tennessee.

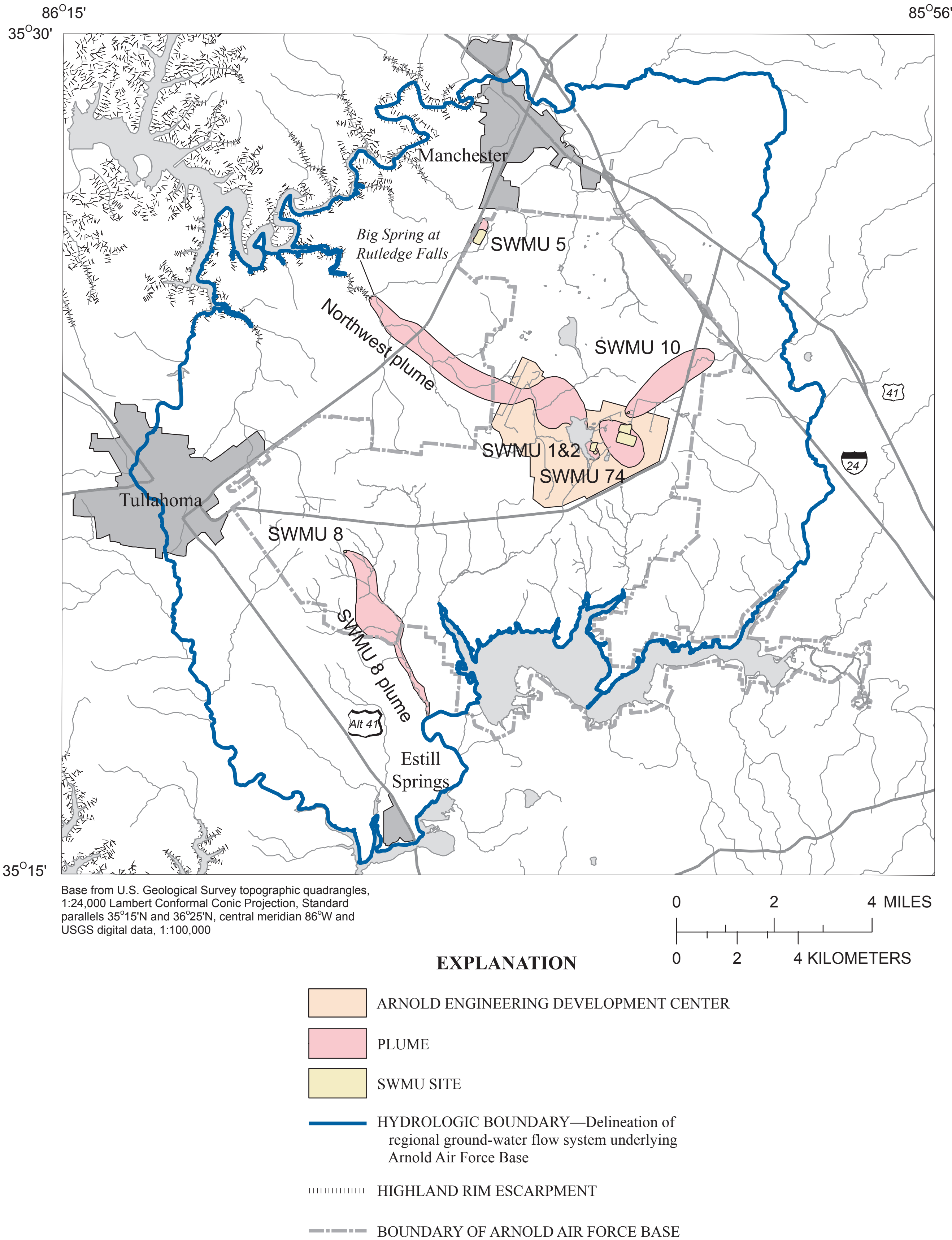


Figure 2. Location of Solid Waste Management Units (SWMUs) and ground-water contaminant plumes at Arnold Air Force Base.

regional flow model and presents a description and the results of advective-flow particle-tracking simulations that were used to evaluate ground-water flow directions and to estimate time-of-travel from selected locations at AAFB. The updated ground-water flow model will provide a tool to help manage the ground-water resources in the AAFB area.

Previous Studies

Haugh and Mahoney (1994) summarized important studies published prior to 1990. Since then, studies of interest include:

1. site-specific ground-water contamination studies that investigate the “SWMU 8” plume (CH2M Hill, 1999; ATA, 2004), the “northwest plume” (CH2M Hill, 2001), and the SWMU 10 site (COLOG, 2002; CH2M Hill, written commun.);
2. water-quality data and local potentiometric surface maps (Aycock and Haugh, 2001; Williams and Aycock, 2001; Williams, 2003);
3. a detailed study of the effect of the J4 rocket motor test cell on the local hydrogeology (Haugh, 1996a, 1996b);
4. studies about the Sinking Pond area (Wolfe, 1996; Wolfe and League, 1996; and Wolfe and others, 2004);
5. study of stream base flows (Robinson and Haugh, 2004); and
6. regional potentiometric surface maps (Mahoney and Robinson, 1993; CH2M Hill, 2001; Robinson and others, 2005).

Description of Study Area

AAFB lies on the eastern Highland Rim physiographic region of Tennessee (Miller, 1974) and ranges from poorly drained, flat uplands to valley-dissected, sloping escarpments. A major surface-water divide separating the Duck and Elk River drainages bisects AAFB extending from the southwest to the northeast (fig. 1). Land-surface elevations range from 1,120 feet (ft) above NGVD 29 in the northeastern corner of the study area at the crest of the drainage divide to about 890 ft above NGVD 29 at the southern tip of the study area near Tims Ford Lake.

Geology

The AAFB area is located in a fractured carbonate terrane covered by regolith derived from the in-situ weathering of carbonate rocks of Mississippian age. The stratigraphy underlying the AAFB area consists predominantly of impure carbonate rocks and some shales (fig. 3). From oldest to youngest, the strata are Devonian and Mississippian Chattanooga Shale and Mississippian Fort Payne Formation, Warsaw Limestone, and

Stratigraphy	Thickness, in feet	Lithology	Hydrogeologic unit		AAFB unit designation	Model layer	Remarks
Regolith derived from in-situ weathering of the St. Louis Limestone, Warsaw Limestone, or Fort Payne Formation	10–100	Clay, silt, and sand with some chert and rock fragments.	Highland Rim aquifer system	Shallow aquifer	Shallow aquifer	1	Low-producing wells, shallow ground-water circulation, low dissolved solids, and bicarbonate dominant anion.
		Rock fragments, chert gravel, and rubble with some clay.		Manchester aquifer, upper part	Intermediate aquifer	2	Good-producing wells, rapid ground-water circulation, low dissolved solids, and bicarbonate dominant anion.
Fort Payne Formation	20–240	Fractured and dissolutioned cherty limestone and siltstone.		Manchester aquifer, lower part	Deep aquifer	3	
		Dark gray siltstone; dense, cherty limestone; and bedded chert. Few fractures.		Fort Payne aquifer		4	Low well yield, slow ground-water circulation, high dissolved solids, and high sulfates.
Chattanooga Shale	20–30	Dark grayish black, carbonaceous shale.		Chattanooga confining unit	Chattanooga confining unit	--	Confining unit. Base of fresh ground-water flow system.

Figure 3. Stratigraphy, lithology, and hydrogeologic units in the Arnold Air Force Base (AAFB) area (modified from Haugh and Mahoney, 1994).

St. Louis Limestone. Both the Chattanooga Shale and the Fort Payne Formation crop out in the northwest section of the study area along the escarpment of the Highland Rim. Since the 1992 regional study (Haugh and Mahoney, 1994) many new wells and geophysical studies have yielded additional data about the structure of the top of the Chattanooga Shale and the top of the bedrock surface. Maps of both of these surfaces have been reinterpreted and updated jointly by the USGS and AEDC (figs. 4 and 5).

The Chattanooga Shale ranges from 20 to 30 ft thick in the study area and is dark grayish black, fissile, and carbonaceous. The Chattanooga Shale surface shows an anticline that crests under AEDC and is nearly coincident with the regional drainage divide (fig. 4). The Chattanooga Shale is an important marker bed throughout parts of the eastern United States because it is a widespread unit with consistent characteristics.

The Chattanooga Shale is overlain by the Fort Payne Formation. In the AAFB area, the Fort Payne Formation as rock ranges from less than 20 to 240 ft thick (fig. 6) and consists of dark gray siltstone and cherty limestone with thin beds of crinoidal limestone and minor amounts of shale. Weathering of the Fort Payne Formation has occurred to irregular depths, and may be structurally controlled in some areas. Several troughs are evident in the bedrock surface. The most prominent trough is northwest of AEDC in the Crumpton Creek Basin where the top-of-bedrock elevation drops from 980 ft to 920 ft along a 2-mile-long linear feature (fig. 5). Fracturing is evident within the Fort Payne Formation with the largest fractures generally near the bedrock/regolith contact where they have been enlarged through dissolution. These dissolution enlarged openings typically are a couple of inches in height; however, solution enlarged cavities as much as 6 ft in height have been observed in the Fort Payne Formation at AAFB (Haugh and others, 1992). Cavities are more common in the northern part of the study area where the unweathered section of bedrock is the thickest (Haugh and others, 1992; COLOG, 2002). Most cavities contain mud, gravel, chert, and rock fragments. Fractures appear to be less common in the lower part of the unit with the exception of the contact with the Chattanooga Shale where water-bearing fractures have been noted (COLOG, 2002).

Regolith derived from weathering of carbonate rocks of Mississippian age (including in ascending order, the Fort Payne Formation, Warsaw Limestone, and/or St. Louis Limestone) is 10 to 100 ft thick in the AAFB area. Regolith thickness tends to decrease in the northern half of the study area. The Warsaw and St. Louis Limestones have been weathered almost completely to chert, silt, sand, gravel, and clay. Typically, the regolith grades upward from gravel-size chert rubble at the top of bedrock to clay-size chert particles with silt, sand, and clay at land surface (Burchett, 1977). A more thorough description of the geology and hydrogeologic framework of the AAFB and surrounding area is presented in previous reports by Haugh and Mahoney (1994) and Haugh (1996a).

Hydrogeology

The Highland Rim aquifer system is the ground-water system of interest in the study area (Brahana and Bradley, 1986a, 1986b). The Highland Rim aquifer system can be divided into several different zones or aquifers (fig. 3). Hydrogeologic investigations by AEDC have typically designated the aquifers as shallow, intermediate, and deep (CH2M Hill, 2001). The 1992 regional ground-water study (Haugh and Mahoney, 1994) divided the system into three aquifers: the shallow, Manchester, and Fort Payne aquifers (fig. 3). The aquifers differ from one another in degree of weathering, amount of chert, and type of weathering product. The aquifers are not separated by confining units of substantial lateral extent; therefore, water is able to flow between these zones at most locations. The Chattanooga Shale is the base of the Highland Rim aquifer system.

Aquifers

Hydraulic-conductivity data are available from slug or aquifer tests conducted at 187 wells in the Highland Rim aquifer system (figs. 7 and 8) (ATA, 2004; Battelle Columbus Division, 1988, 1989a, 1989b; Battelle Denver Operations, 1989; Benham Group, 1989a, 1989b; CH2M Hill, 1999, 2001; Dames and Moore, 1975; Engineering Science, 1984; Oak Ridge National Laboratory, 1989a, 1989b; Post, Buckley, Schuh and Jernigan, Inc., 1989a, 1989b, 1989c, 1989d, 1989e; Science Applications International Corporation, 1990; U.S. Army Corp of Engineers, Mobile District, 1988a, 1988b; and Woodward-Clyde Consultants, 1990). If a well had more than one reported hydraulic-conductivity value, an average value was calculated for the well. Values of hydraulic conductivity from well tests range from 0.09 to 450 feet per day (ft/d) (fig. 8). Additionally, hydraulic-conductivity measurements are available for 88 discrete fracture zones in 10 wells to the north and northeast of AEDC where the bedrock thickens (COLOG, 2002). Values of hydraulic conductivity from discrete fracture zones range from 0.08 to 3,980 ft/d (fig. 8).

The shallow aquifer, as designated by the USGS and AEDC, is described as consisting of alluvium, residual silt, clay, sand, and clay-size chert particles of the upper part of the regolith (Haugh and Mahoney, 1994). Ground water in the shallow aquifer occurs under water-table conditions and may be perched in some locations. Based on 54 well tests, hydraulic conductivity within the shallow aquifer ranges from 0.09 to 40 ft/d with a median value of 1.5 ft/d (fig. 8). The thickness of the shallow aquifer ranges from 0 to 100 ft with an average of about 30 ft.

The Manchester aquifer, the primary source of drinking water in the area, consists of chert gravels at the base of the regolith and solution openings in the upper part of the bedrock (Burchett and Hollyday, 1974). The upper part of the

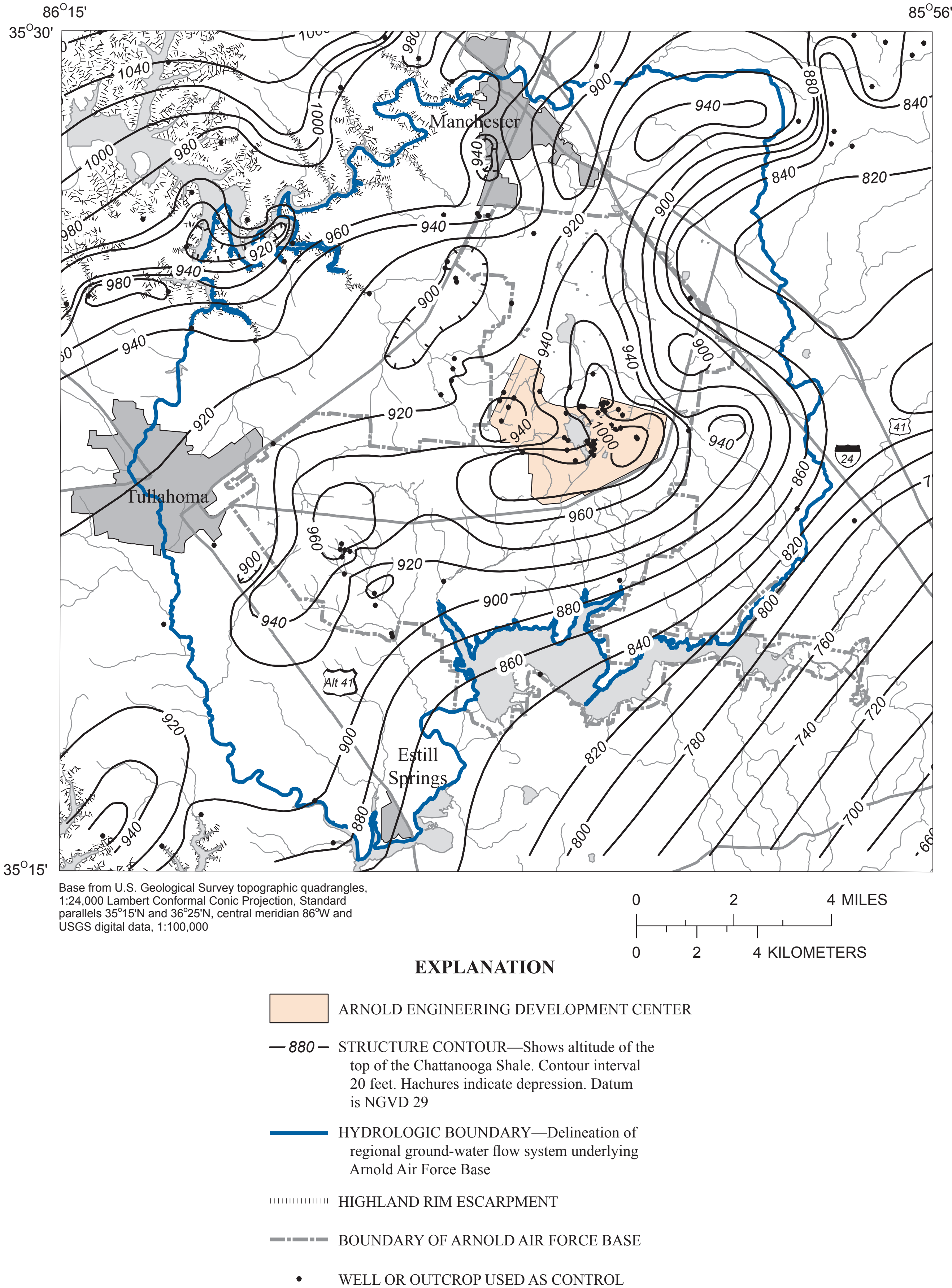
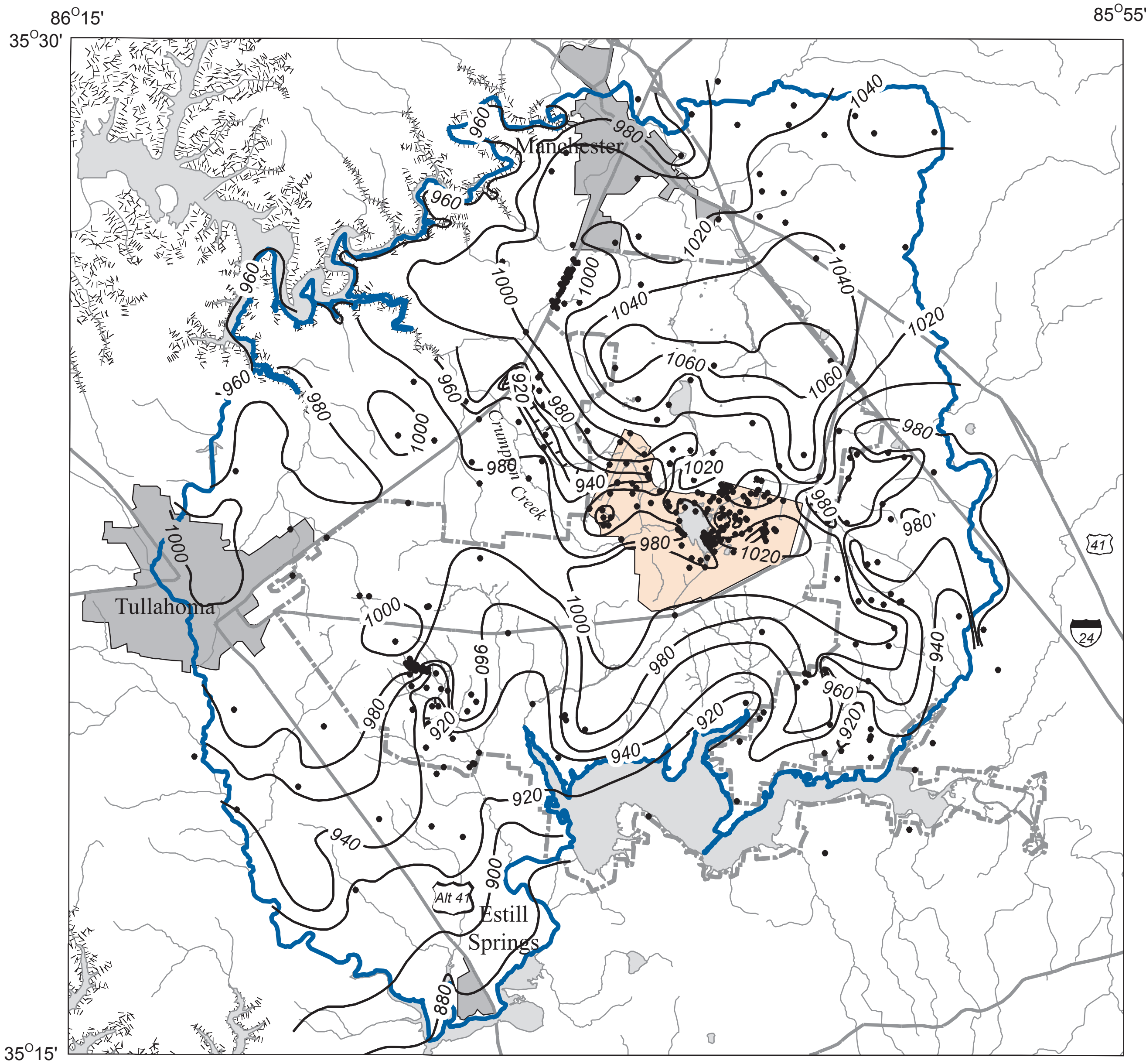


Figure 4. Altitude of the top of the Chattanooga Shale in the Arnold Air Force Base area.



Base from U.S. Geological Survey topographic quadrangles, 1:24,000 Lambert Conformal Conic Projection, Standard parallels 35°15'N and 36°25'N, central meridian 86°W and USGS digital data, 1:100,000

EXPLANATION

ARNOLD ENGINEERING DEVELOPMENT CENTER

—*900*— TOP OF ROCK CONTOUR—Shows altitude of the top of the bedrock surface. Contour interval 20 feet. Hachures indicate depression. Datum is NGVD 29

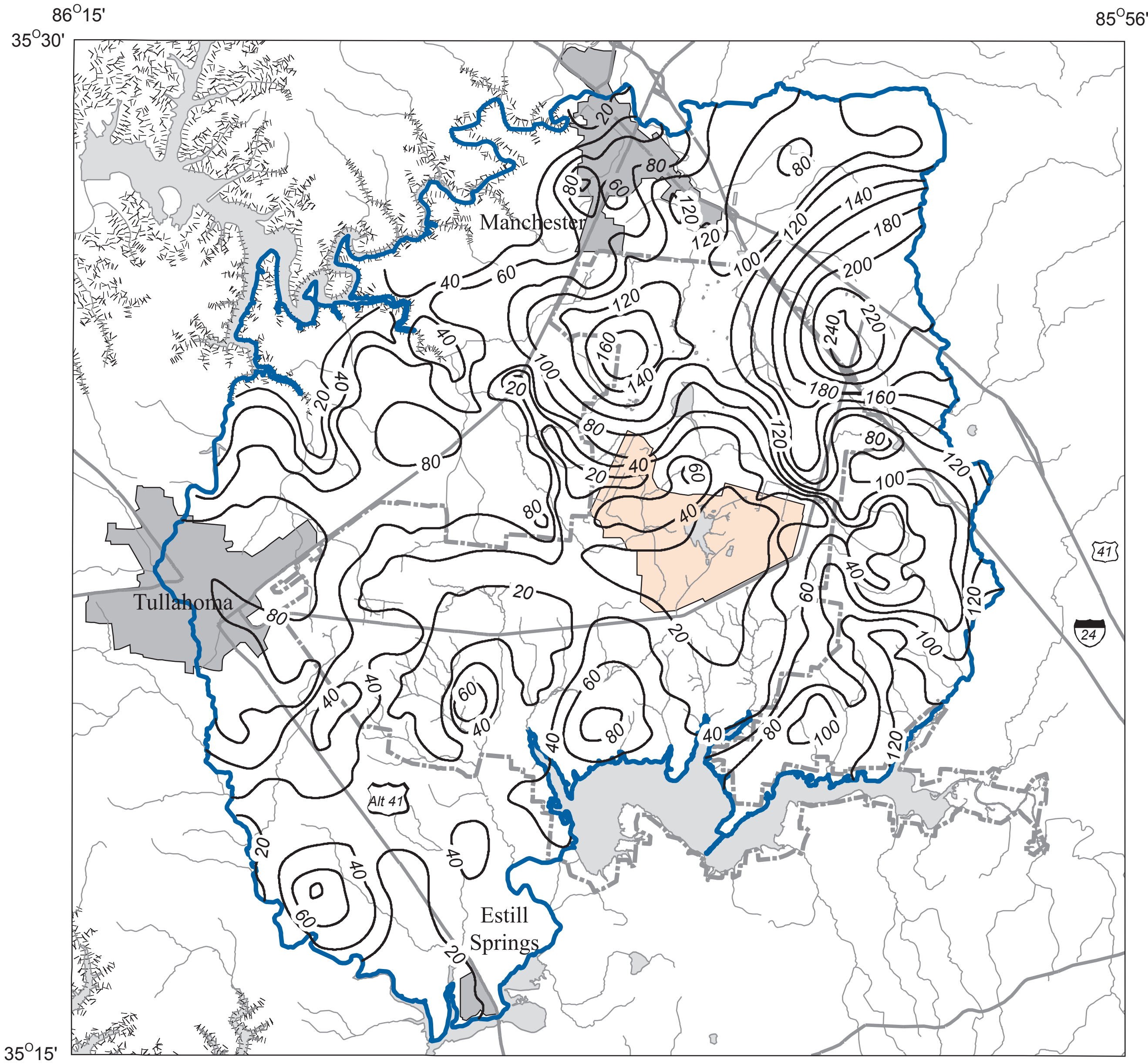
HYDROLOGIC BOUNDARY—Delineation of regional ground-water flow system underlying Arnold Air Force Base

HIGHLAND RIM ESCARPMENT

BOUNDARY OF ARNOLD AIR FORCE BASE

• WELL USED AS CONTROL

Figure 5. Altitude of the top of the bedrock surface in the Arnold Air Force Base area.



Base from U.S. Geological Survey topographic quadrangles, 1:24,000 Lambert Conformal Conic Projection, Standard parallels 35°15'N and 36°25'N, central meridian 86°W and USGS digital data, 1:100,000

0 2 4 MILES

0 2 4 KILOMETERS

EXPLANATION

ARNOLD ENGINEERING DEVELOPMENT CENTER

— 20 — LINE OF EQUAL THICKNESS OF BEDROCK—Contour interval 20 feet

HYDROLOGIC BOUNDARY—Delineation of regional ground-water flow system underlying Arnold Air Force Base

HIGHLAND RIM ESCARPMENT

BOUNDARY OF ARNOLD AIR FORCE BASE

Figure 6. Thickness of bedrock above the Chattanooga Shale in the Arnold Air Force Base area.

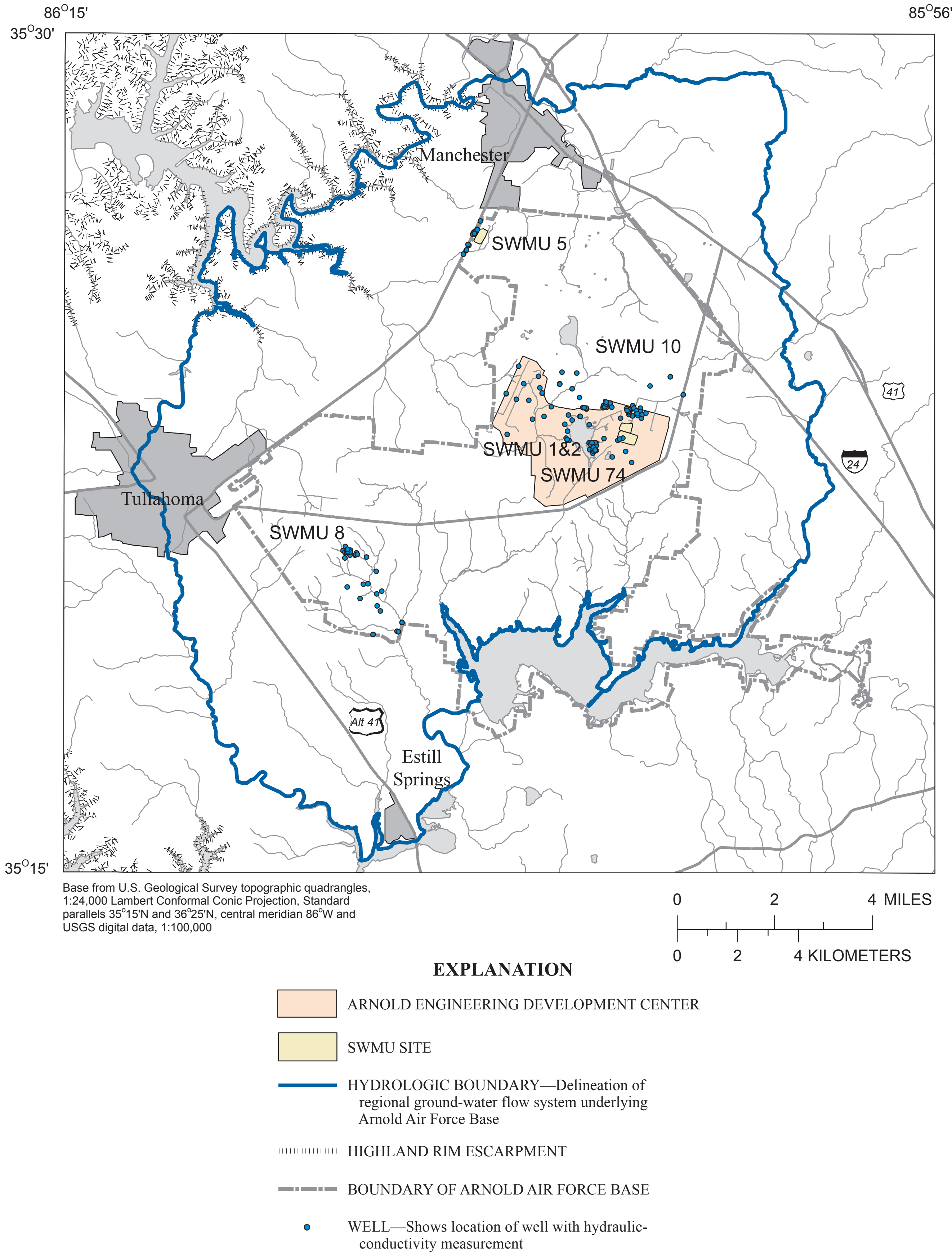


Figure 7. Location of wells with hydraulic-conductivity measurements at Arnold Air Force Base.

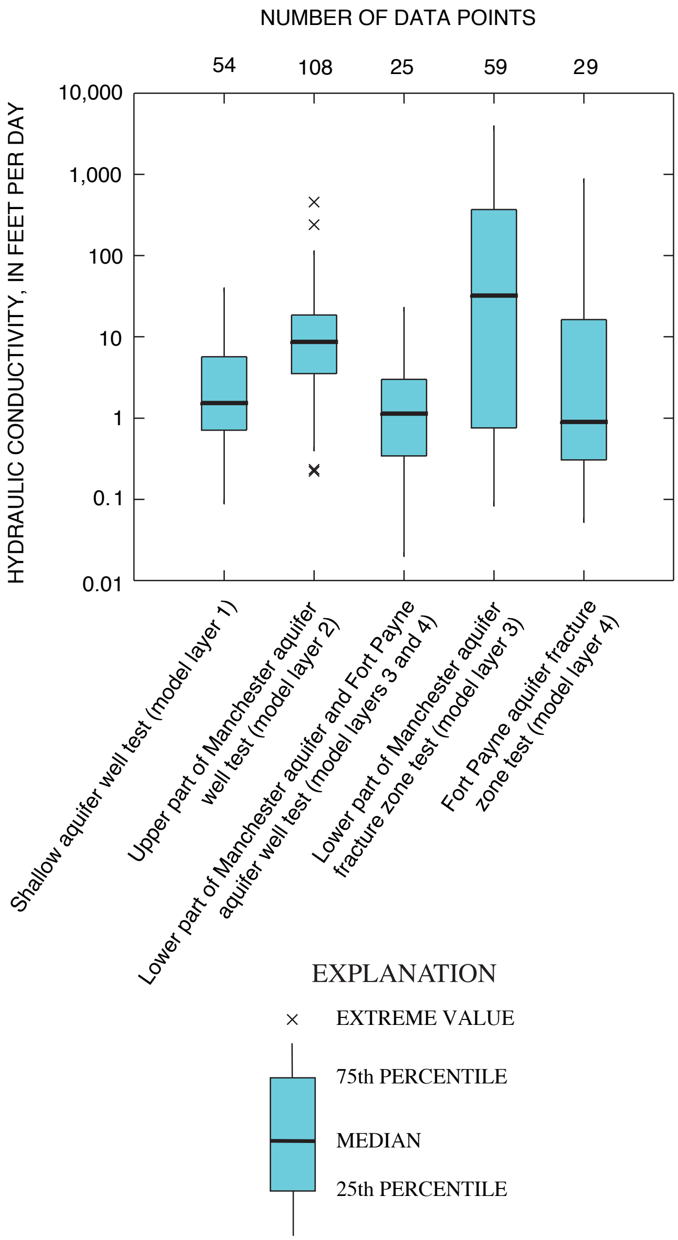


Figure 8. Ranges of hydraulic conductivity from wells and fracture zones at Arnold Air Force Base.

Manchester aquifer, consisting of chert gravels at the base of the regolith, is designated as the intermediate aquifer by AEDC. The lower part of the Manchester aquifer, consisting of solution openings in the top of bedrock, is included in the deep aquifer as designated by AEDC and is sometimes referred to as the upper part of the deep aquifer (fig. 3). Ground water in the Manchester aquifer occurs under confined conditions in areas where fine-grained materials in the shallow aquifer serve as a leaky confining unit. Based on 108 well tests, hydraulic conductivity within the upper part of the Manchester aquifer ranges from 0.22 to 450 ft/d with a median value of 8.7 ft/d (fig. 8). The upper part of the Manchester aquifer is typically about 10 ft thick. The lower part of the Manchester aquifer is typically 1 to 30 ft thick in the southern half of the study area and 40 to 170 ft thick in the northeastern part of the study area. Well tests for hydraulic conductivity for the lower part of the Manchester aquifer are discussed with the Fort Payne aquifer because many of the wells tested screen both the lower part of the Manchester aquifer and the Fort Payne aquifer. Hydraulic conductivity for 59 fracture zones in the lower part of the Manchester aquifer ranges from 0.08 to 3,980 ft/d with a median of 32 ft/d (fig. 8).

The Fort Payne aquifer is included in the deep aquifer as designated by AEDC and is sometimes referred to as the lower part of the deep aquifer (fig. 3). The Fort Payne aquifer consists of dense limestone in the lower part of the bedrock where fractures and solution openings are less developed. Fractures appear to be less common in the Fort Payne aquifer with the exception of the contact with the Chattanooga Shale where water-bearing fractures have been observed (COLOG, 2002). The Fort Payne aquifer typically is 1 to 15 ft thick in the southern half of the study area and 20 to 85 ft thick in the northeastern part of the study area. Hydraulic conductivity for 29 fracture zones in the Fort Payne aquifer ranges from 0.05 to 882 ft/d with a median of 0.9 ft/d (fig. 8). Hydraulic conductivity from well tests in 25 wells screened in both the lower part of the Manchester aquifer and the Fort Payne aquifer, ranges from 0.02 to 23 ft/d with a median value of 1.1 ft/d (fig. 8). The base of the Fort Payne aquifer is the Chattanooga Shale (Haugh and Mahoney, 1994; Haugh, 1996a).

Well yields in the AAFB area range from less than 1 gallon per minute (gal/min) to more than 500 gal/min (Burchett, 1977; Haugh and Mahoney, 1994). This variability in well yields results from heterogeneities within the aquifers and can be observed over distances as short as 100 ft (Haugh, 1996a). In the lower part of the Manchester aquifer, wells that intercept a fracture or fracture zone produce more water than those that do not intercept fracture zones. Similarly, in the upper part of the Manchester aquifer, wells screened in a chert-gravel zone produce more water than those screened outside of a gravel zone. The presence of these high permeability features within the aquifer creates a system that is heterogeneous and anisotropic on a local scale (Haugh, 1996a). Since the 1992 regional study, several important pathways in the regional flow system have been identified. These pathways appear to be preferential regional flow zones of high permeability within the Manchester aquifer that share the following characteristics: a depression or trough in the bedrock surface, a trough in the ground-water surface, low gradients in the ground-water surface, and a large spring or group of springs at the downgradient end. The most studied of these pathways is in the Crumpton Creek Basin where surface-geophysical, geologic, water-quality, and water-level data have been analyzed to document the flow path of the "northwest plume," which discharges to Big Spring at Rutledge Falls (fig. 2) (CH2M Hill, 2001; Williams, 2003).

No measured values for vertical hydraulic conductivity exist in the study area, but in most settings, the vertical hydraulic conductivity is smaller than the horizontal hydraulic conductivity (Heath, 1989). Vertical anisotropy in settings similar to the study area typically ranges from 100:1 to 2:1 (Freeze and Cherry, 1979). Horizontal layering can increase the vertical anisotropy, but vertical fractures can decrease vertical anisotropy (Freeze and Cherry, 1979). Vertical hydraulic gradients at well clusters generally are small indicating small vertical anisotropy over most of the study area. In some local areas, water levels in the shallow aquifer appear to be perched, creating large vertical hydraulic gradients between the shallow and Manchester aquifers. In these areas, the vertical anisotropy in the shallow aquifer may be greater than in the rest of the study area. Also, geophysical logging and hydraulic testing of bedrock wells indicate that in most wells tested, fractures in the upper and lower parts of the bedrock are not interconnected (COLOG, 2002). This indicates greater vertical anisotropy in the Fort Payne aquifer compared with the Manchester aquifer.

Ground-Water Withdrawals

Ground water is withdrawn at numerous locations at AAFB for two primary reasons: ground-water withdrawal associated with ground-water contamination and dewatering activities around below-grade testing facilities. Ground-water withdrawal wells are currently operating at SWMU 1&2, SWMU 5, SWMU 8, and SMWU 10 (figs. 2 and 9). Pumping rates from the withdrawal wells range from less than 1 gal/min to about 27 gal/min. Dewatering activities also occur at more than 20 facilities at AEDC (fig. 9). Dewatering at these facilities typically occurs through a gravity drain system whereby water flows to a sump and then is pumped to the surface. The deepest and most important of the dewatering systems is at the J4 test cell, which extends approximately 250 ft below land surface and dewaters at an average rate of about 105 gal/min (Haugh, 1996a, 1996b). The other dewatering facilities range in depth from about 5 to 80 ft below land surface with estimated average ground-water flow rates ranging between less than 1 and 40 gal/min (CH2M Hill, written commun., 2005).

Ground- and Surface-Water Interactions

Ground water naturally discharges at streams and springs in the study area. Flow was measured at 109 stream and spring sites in and nearby the study area during high and low base-flow conditions in 2002 (Robinson and Haugh, 2004). Most of the ground-water discharge occurs in the lower reaches of streams within the study area and to streams and springs that form the boundaries of the study area (Robinson and Haugh, 2004, figs. 3 and 4). Values of flow per square mile for all sites measured by Robinson and Haugh (2004, table 8) were 0.55 cubic foot per second per square mile [$(ft^3/s)/mi^2$] during high base-flow conditions and 0.37 $(ft^3/s)/mi^2$ during low base-flow conditions. Analyzing only those sites that have most of

Table 1. Sites used to calculate total flow per square mile in the Arnold Air Force Base model area.

[Data from Robinson and Haugh, 2004; mi^2, square mile; ft^3/s, cubic foot per second; $(ft^3/s)/mi^2$, cubic foot per second per square mile]

Basin	Station number	Basin area (mi^2)	June 2002		October 2002	
			Stream discharge, instantaneous (ft^3/s)	Flow per square mile [$(ft^3/s)/mi^2$]	Stream discharge, instantaneous (ft^3/s)	Flow per square mile [$(ft^3/s)/mi^2$]
Bradley Creek	03578502	45.49	34.5	0.76	13	0.29
Possum Branch	03578515	1.90	0.32	0.17	0.19	0.10
Brumalow Creek	03578700	4.13	1.36	0.33	0.28	0.07
Brumalow Creek	03578716	1.06	0	0	0	0
Hardaway Branch	03578725	0.75	0	0	0	0
Rowland Creek	03578988	1.02	0	0	0	0
Spring Creek	03579040	9.29	10.4	1.12	8.32	0.90
Spring Creek	03579050	0.28	0.36	1.29	0.16	0.57
Taylor Creek	03579502	2.92	5.42	1.86	0.71	0.24
Dry Creek	035795035	4.75	7.09	1.49	7.45	1.57
Rock Creek	03579680	36.5	19.0	0.52	13.5	0.37
Cat Creek	03596023	1.24	0.36	0.29	0.41	0.33
Bates Spring Branch	03596025	1.30	0.59	0.45	0.48	0.37
Crumpton Creek	03596120	27.04	12.7	0.47	7.62	0.28
Ovoca Lake	03596201	3.68	1.43	0.39	1.13	0.31
Bobo Creek	03596298	8.32	1.19	0.14	1.21	0.15
Machine Falls Branch	03596298	1.43	0.61	0.43	0.41	0.29
Bobo Creek (Short Spring)	03596300	0	9.22	0	5.16	0
All sites		151.2	104	0.69	59.9	0.40

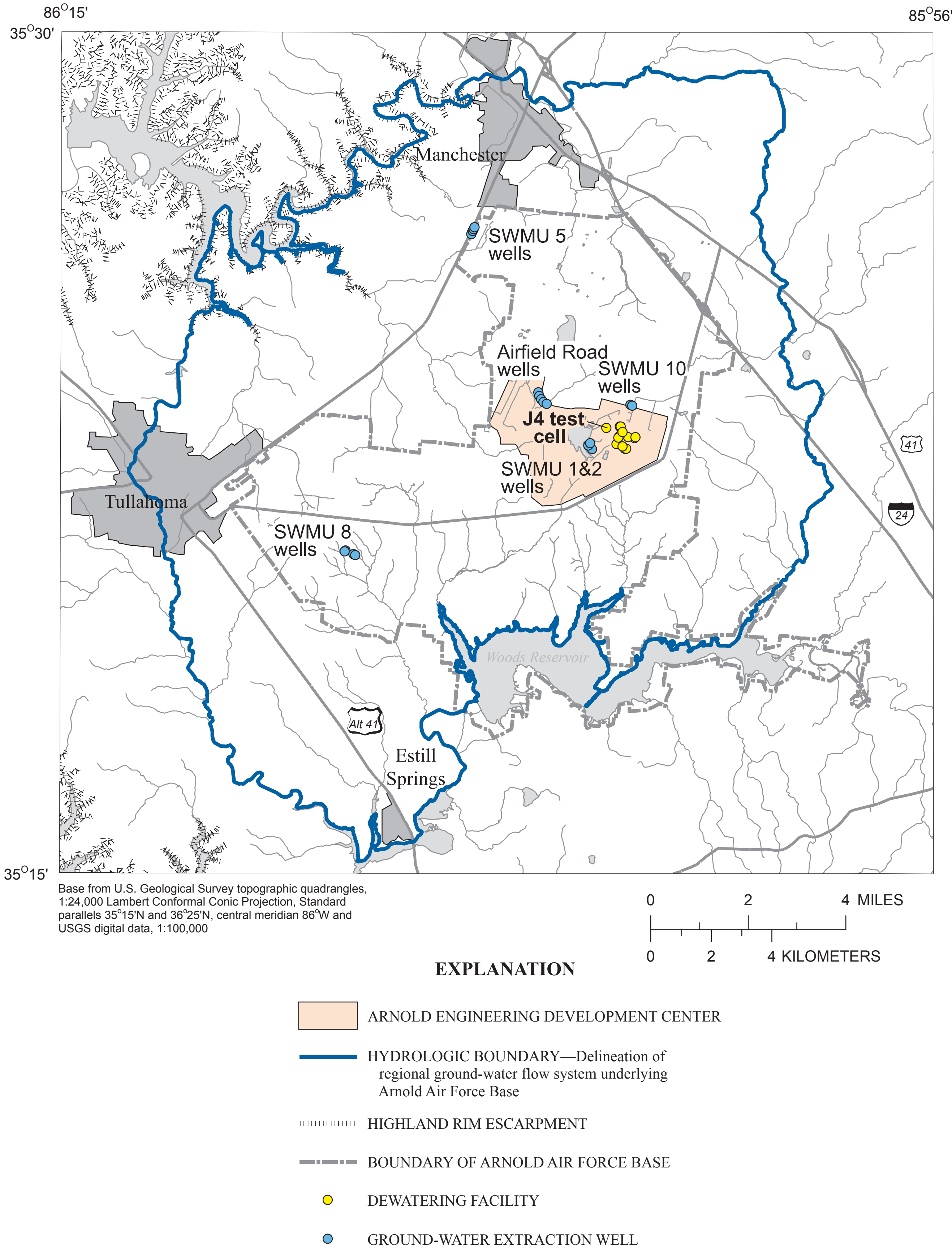


Figure 9. Location of ground-water withdrawal wells and dewatering facilities in the Arnold Air Force Base area.

their drainage areas within the study area results in average flow values of 0.69 $(ft^3/s)/mi^2$ in high base-flow conditions and 0.40 $(ft^3/s)/mi^2$ during low base-flow conditions (table 1).

An aerial thermography study conducted in 2000 identified 481 potential springs in and around the AAFB area (JAVA Corporation, 2000; CH2M Hill, 2001); 114 of these potential springs were field verified (fig. 10) (CH2M Hill, written commun, 2002). Most of these springs are located near the boundaries of the study area (fig. 10).

Flow Boundaries

A ground-water divide, approximately coinciding with the Duck River-Elk River surface-water divide, underlies AAFB and extends from southwest to northeast. Ground water flows from the divide area to the discharge areas, which are the major streams, springs, lakes, and reservoirs around the base. The regional discharge areas define the lateral extent of the ground-water flow system at AAFB. The boundaries of the flow system for this study are the same as defined by the 1992 regional study (Haugh and Mahoney, 1994). Moving counterclockwise from the northeastern corner of the study area (fig. 11), the lateral boundaries of the system are:

1. Roan Buck Branch, from the head to the confluence with Wolf Creek;
2. Wolf Creek, from the confluence with Roan Buck Branch to the confluence with Little Duck River;
3. Little Duck River, from the confluence with Wolf Creek to the Chattanooga Shale outcrop at Little Falls;
4. the Highland Rim escarpment from the Little Falls in the Little Duck River to Ovoca Falls on Carroll Creek;
5. Carroll Creek, from the Chattanooga Shale outcrop at Ovoca Falls to the head;
6. an imaginary flow line from the head of Carroll Creek to the Duck River-Elk River drainage divide, normal to the divide;
7. another imaginary flow line from the Duck River-Elk River drainage divide, normal to the divide to the head of an unnamed creek;
8. the unnamed creek, from the head to the confluence with North Fork Rock Creek;
9. North Fork Rock Creek, from the confluence with the unnamed creek to the confluence with Rock Creek;
10. Rock Creek, from the confluence with North Fork Rock Creek to the mouth at Tims Ford Lake;
11. Tims Ford Lake, from the mouth of Rock Creek to the mouth of the Elk River;
12. Elk River, from the mouth at Tims Ford Lake to Woods Reservoir;
13. Woods Reservoir, from the outlet point to the Elk River to the mouth of Bradley Creek;
14. Bradley Creek, from the mouth at Woods Reservoir to the confluence with Blue Spring Creek;
15. Blue Spring Creek, from the confluence with Bradley Creek to the head;
16. an imaginary flow line from the head of Blue Spring Creek to the Duck River-Elk River drainage divide, normal to the divide; and
17. a final imaginary flow line from the Duck River-Elk River drainage divide, normal to the divide to the head of Roan Buck Branch.

Water levels of Woods Reservoir and Tims Ford Lake remain relatively constant throughout the year (Flohr and others, 2003). At the northwestern boundary, numerous seeps and springs drain the ground-water system where the Chattanooga Shale crops out along the Highland Rim escarpment.

Recharge

In the study area, recharge occurs from direct infiltration of precipitation throughout the study area. The 1992 regional ground-water model (Haugh and Mahoney, 1994) used two recharge zones with recharge rates of 10 inches per year (in/yr) along the regional drainage divide and 6 in/yr throughout the remaining area. These rates were based on a regional study by Hoos (1990) in which recharge rates for drainage basins across Tennessee were estimated using a hydrograph-separation technique. Hoos (1990) reported annual recharge rates during years of average streamflow for drainage basins in the Highland Rim Physiographic Province of Tennessee ranging from 4.9 to 9.8 inches (in.).

To improve estimates of recharge, the current study also used a water-budget method to estimate ground-water recharge and to examine the variations in recharge annually. A simple water budget, assuming ground-water withdrawals are insignificant, can be described by the following equations:

$$\text{If } PR = ET + SM + SF$$
$$\text{and } SF = DR + GWD$$
$$\text{and assuming } GWD = GWR,$$
$$\text{then } PR = ET + SM + DR + GWR$$

where

PR	is	the mean precipitation,
ET	is	the mean evapotranspiration,
SM	is	soil moisture storage,
SF	is	the mean streamflow,
DR	is	mean direct runoff,
GWD	is	mean ground-water discharge, and
GWR	is	mean ground-water recharge.

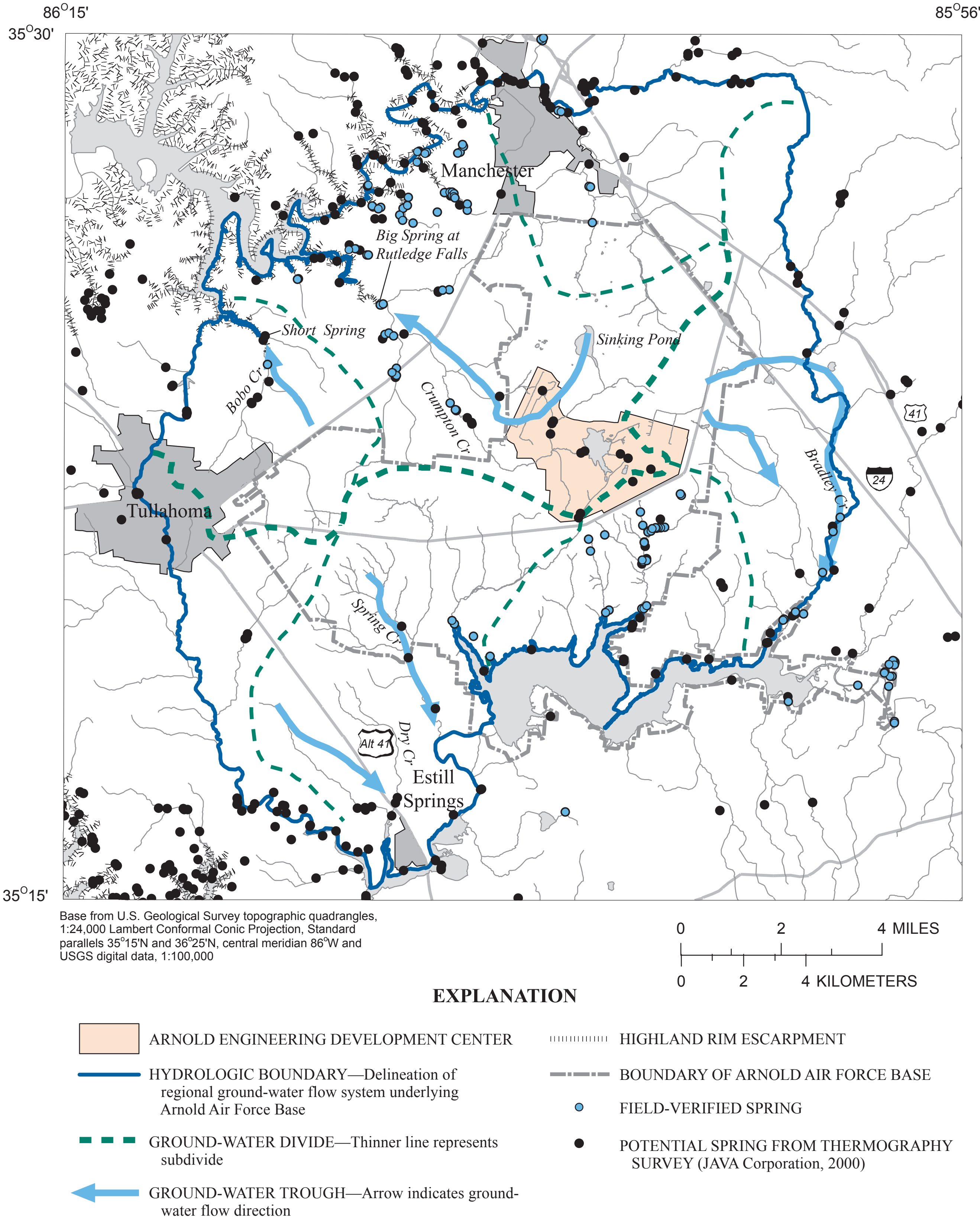


Figure 10. Location of springs in the Arnold Air Force Base area.

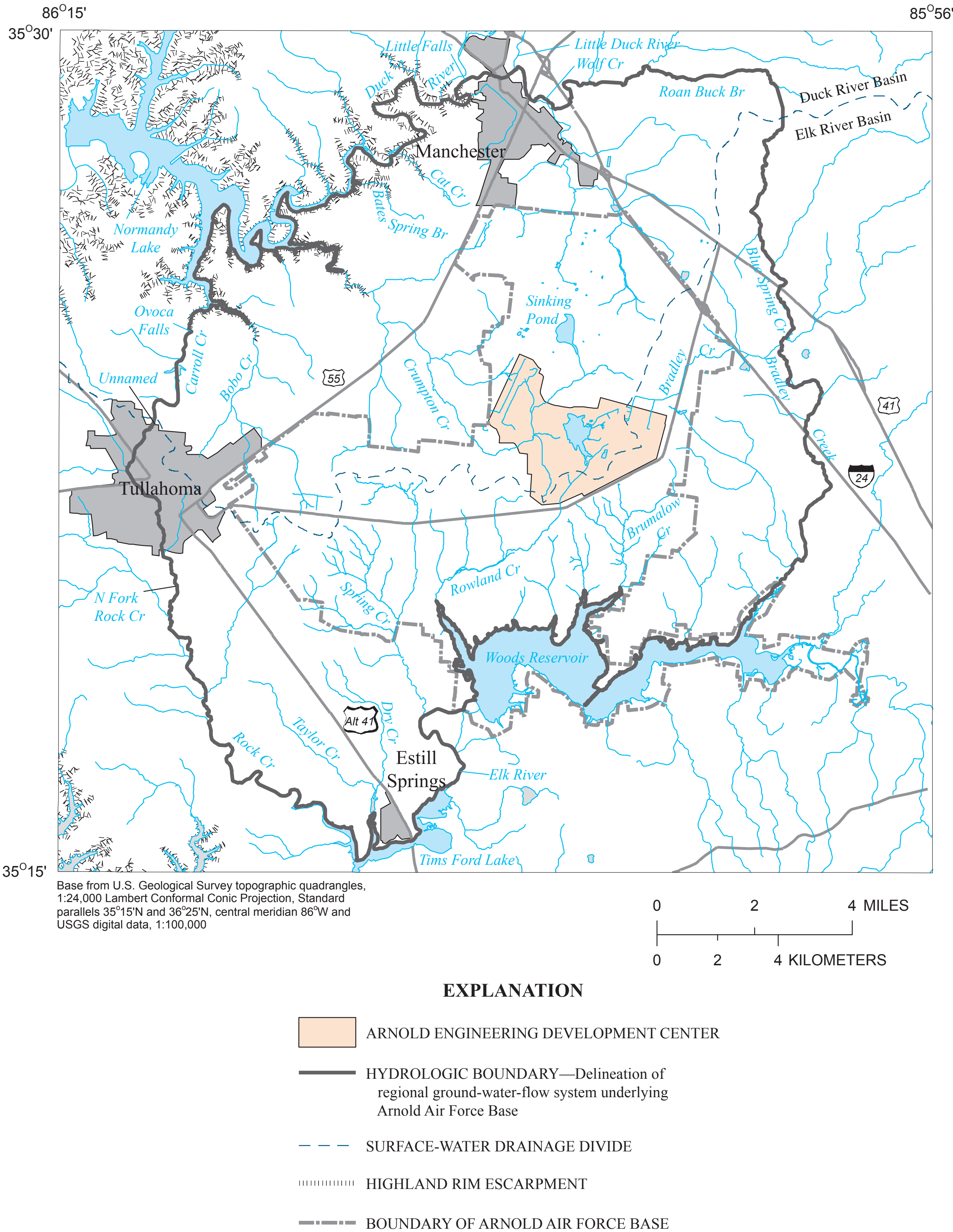


Figure 11. Regional flow boundaries for the Arnold Air Force Base area.

Using monthly mean precipitation and temperature data archived by the National Climatic Data Center (NCDC) for Tullahoma, Tennessee (NCDC station 409155), a Thornwaite water-budget method was used for this investigation to estimate the amount of precipitation that is lost to evapotranspiration in the study area (McCabe and others, 1985). If the evapotranspiration demand is greater than precipitation, then soil moisture storage is used to make up the deficit. If precipitation is greater than evapotranspiration, the surplus water first replenishes soil moisture storage then supports streamflow either by direct runoff or by recharging the ground-water system, which then discharges, supplying base flow to streams. Total streamflow is proportioned into direct runoff and ground-water discharge using a stream base-flow index, which estimates the portion of mean annual streamflow attributed to base flow. A national study by Wolock (2003a) estimates a base-flow index for the AAFB study area of 32 to 34 percent. The base-flow index at individual streamgages within the AAFB study area ranged from 22.4 to 40.9 percent (Wolock, 2003b). Using monthly mean precipitation and temperature data from Tullahoma and assuming a base-flow index of 30 percent, an annual water budget for the study area was estimated for the period from 1960 to 2005 (table 2, fig. 12). The average annual recharge from this method is 8.1 in/yr with a median of 8.4 in/yr. Annual estimates ranged from 1.3 in. for 1981 to 13.0 in. for 1994.

Wolfe and others (2004) in a study of the Sinking Pond Basin on AAFB developed a hydrologic model based on a water-balance approach. Sinking Pond is a seasonally ponded karst depression located in The Barrens along the regional drainage divide (fig. 1). During much of the year, Sinking Pond is filled with water and provides a constant rate of recharge to the ground-water system. For the period 1990–2002, the Sinking Pond hydrologic model produces an average basin recharge rate of 9.09 in/yr and an average pond recharge rate of 110 in/yr (W.J. Wolfe, U.S. Geological Survey, written commun., 2004). The basin recharge rate represents rainfall that occurs in the basin and infiltrates through the soil to recharge the ground water. The Sinking Pond Basin average recharge rate of 9.09 in/yr compares favorably with the 1992 regional ground-water model rate of 10 in/yr for areas along the drainage divide. The pond recharge rate represents water that drains through the bottom of the pond to recharge the ground water and is a concentrated source of recharge that is unique to Sinking Pond.

The distribution of recharge throughout the study area was further investigated by conducting a detailed stream base-flow study in 2002 (Robinson and Haugh, 2004). Stream base flows were measured in June and October 2002 at 109 sites. The average flow per square mile for all sites that have most of their drainage area within the modeled area was 0.69 $(ft^3/s)/mi^2$ in June 2002 and 0.40 $(ft^3/s)/mi^2$ in October 2002 (table 1). Expressing these flows in typical recharge units of inches per year would result in 9.2 and 5.4 in/yr, respectively. Data presented by Robinson and Haugh (2004) show that a group of drainage basins located in the southwestern part of the study area have higher base flows (two times or more) compared to other basins throughout the study area. These basins include Spring Creek, Dry Creek (near Estill Springs), and Taylor Creek with average flows of 1.35 $(ft^3/s)/mi^2$ or 18.3 in/yr in June 2002 and 0.96 $(ft^3/s)/mi^2$ or 13.1 in/yr in October 2002. The higher base flows imply conditions in these basins allow for greater recharge rates compared to other basins in the study area. A visual inspection of a stream discharge hydrograph for three sites in the study

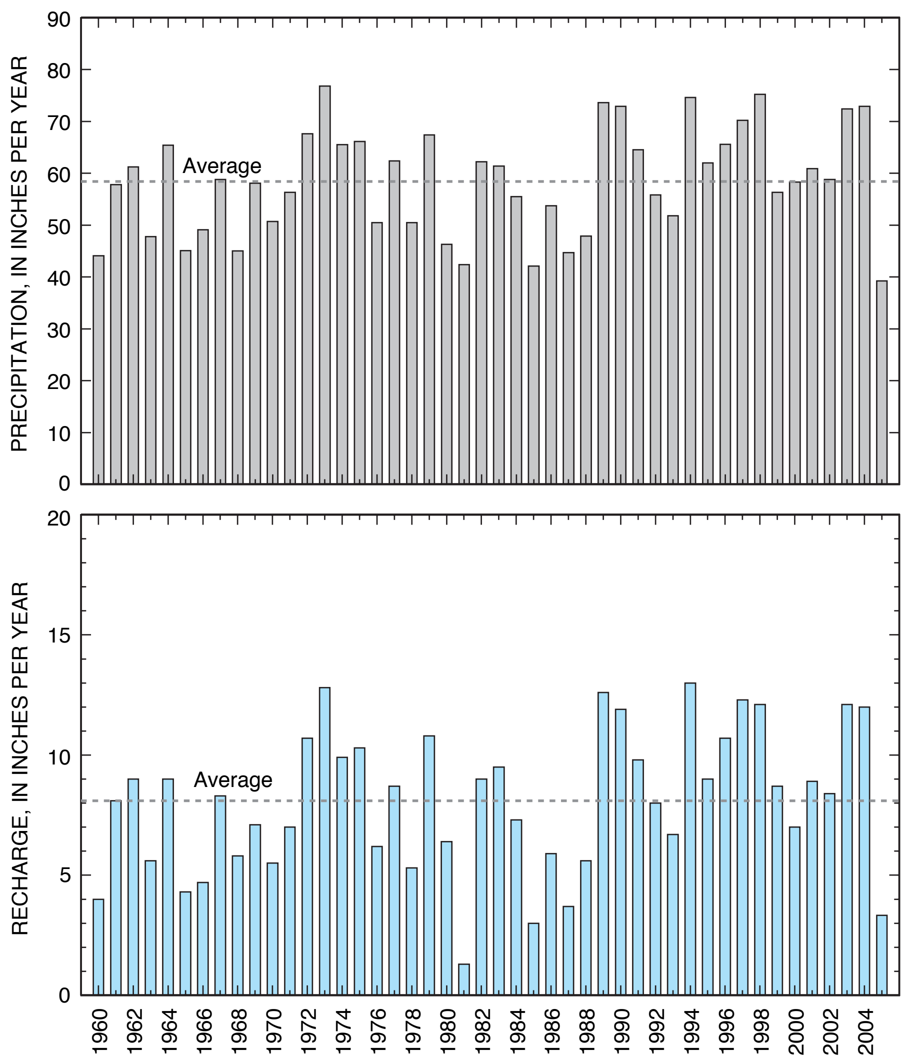


Figure 12. Precipitation and estimated recharge for the Arnold Air Force Base area, from 1960 to 2005.

Table 2. Estimated annual water budget for the Arnold Air Force Base area from 1960 to 2005.

[All values are in inches per year]

Year	Precipitation	Evapotranspiration	Streamflow	Direct runoff	Recharge	Soil moisture storage
1960	44.1	30.7	13.4	9.4	4.0	0.0
1961	57.8	30.8	27.0	18.9	8.1	0.0
1962	61.2	31.1	30.1	21.1	9.0	0.0
1963	47.8	31.6	18.5	13.0	5.6	–2.3
1964	65.4	33.2	29.8	20.9	9.0	2.3
1965	45.1	33.0	14.3	10.0	4.3	–2.2
1966	49.1	31.3	15.5	10.9	4.7	2.2
1967	58.8	31.1	27.6	19.3	8.3	0.0
1968	45.0	29.4	19.3	13.5	5.8	–3.7
1969	58.1	30.7	23.7	16.6	7.1	3.7
1970	50.7	32.3	18.4	12.9	5.5	0.0
1971	56.3	33.1	23.2	16.2	7.0	0.0
1972	67.6	32.1	35.5	24.9	10.7	0.0
1973	76.8	34.0	42.8	30.0	12.8	0.0
1974	65.5	32.6	32.9	23.0	9.9	0.0
1975	66.1	31.7	34.4	24.1	10.3	0.0
1976	50.5	29.9	20.6	14.4	6.2	0.0
1977	62.4	33.5	28.9	20.3	8.7	0.0
1978	50.5	32.9	17.7	12.4	5.3	0.0
1979	67.4	31.5	35.9	25.1	10.8	0.0
1980	46.3	31.1	21.4	15.0	6.4	–6.2
1981	42.4	31.8	4.4	3.1	1.3	6.2
1982	62.2	32.1	30.1	21.1	9.0	0.0
1983	61.4	29.7	31.7	22.2	9.5	0.0
1984	55.5	31.3	24.2	16.9	7.3	0.0
1985	42.1	32.7	9.9	6.9	3.0	–0.5
1986	53.7	33.4	19.7	13.8	5.9	0.5
1987	44.7	32.3	12.4	8.7	3.7	0.0
1988	47.9	29.2	18.6	13.0	5.6	0.0
1989	73.6	31.7	41.9	29.3	12.6	0.0
1990	72.9	33.1	39.8	27.9	11.9	0.0
1991	64.5	31.9	32.6	22.8	9.8	0.0
1992	55.8	29.0	26.8	18.8	8.0	0.0
1993	51.8	29.4	22.3	15.6	6.7	0.0
1994	74.6	31.4	43.3	30.3	13.0	0.0
1995	62.0	31.9	30.1	21.1	9.0	0.0
1996	65.6	29.9	35.7	25.0	10.7	0.0
1997	70.2	29.3	41.0	28.7	12.3	0.0
1998	75.2	34.8	40.4	28.3	12.1	0.0
1999	56.3	31.2	29.1	20.3	8.7	–3.9
2000	58.3	31.2	23.2	16.3	7.0	3.9
2001	60.9	31.3	29.6	20.7	8.9	0.0
2002	58.8	30.9	27.9	19.5	8.4	0.0
2003	72.4	31.9	40.5	28.3	12.1	0.0
2004	72.9	32.9	40.0	28.0	12.0	0.0
2005	39.2	30.7	11.1	7.8	3.3	–2.61
Average	58.4	32.7	26.9	18.8	8.1	–0.1

area show that Spring Creek has fewer peaks and higher base flows than the other sites, Little Duck River and Crumpton Creek (Robinson and Haugh, 2004, fig. 2). This further supports the concept that in the Spring Creek Basin more recharge occurs, which results in less runoff and higher base flows.

Based on this information, the AAFB study area can be divided into four areas with different recharge rates. The four areas are: The Barrens area along the regional drainage divide; the Spring Creek, Dry Creek (at Estill Springs), and Taylor Creek Basins in the southwestern part of the study area; Sinking Pond; and the rest of the study area.

Ground-Water Flow

Regional potentiometric surface maps of the Manchester aquifer for May and October 2002 (Robinson and others, 2005) show that the topography and surface drainage patterns influence ground-water flow in the AAFB area (fig. 13). The AEDC facility is on the regional ground-water divide, which runs southwest to northeast and generally coincides with the Duck River-Elk River surface-water divide. A broad saddle in the main ground-water divide separates a ground-water high southwest of AEDC from a larger, broader ground-water high north of AEDC. Ground water generally flows from the regional ground-water divide area toward the northwest or toward the south or southeast, and discharges to the principal streams and reservoirs (Mahoney and Robinson, 1993; Haugh and Mahoney, 1994; Robinson and others, 2005).

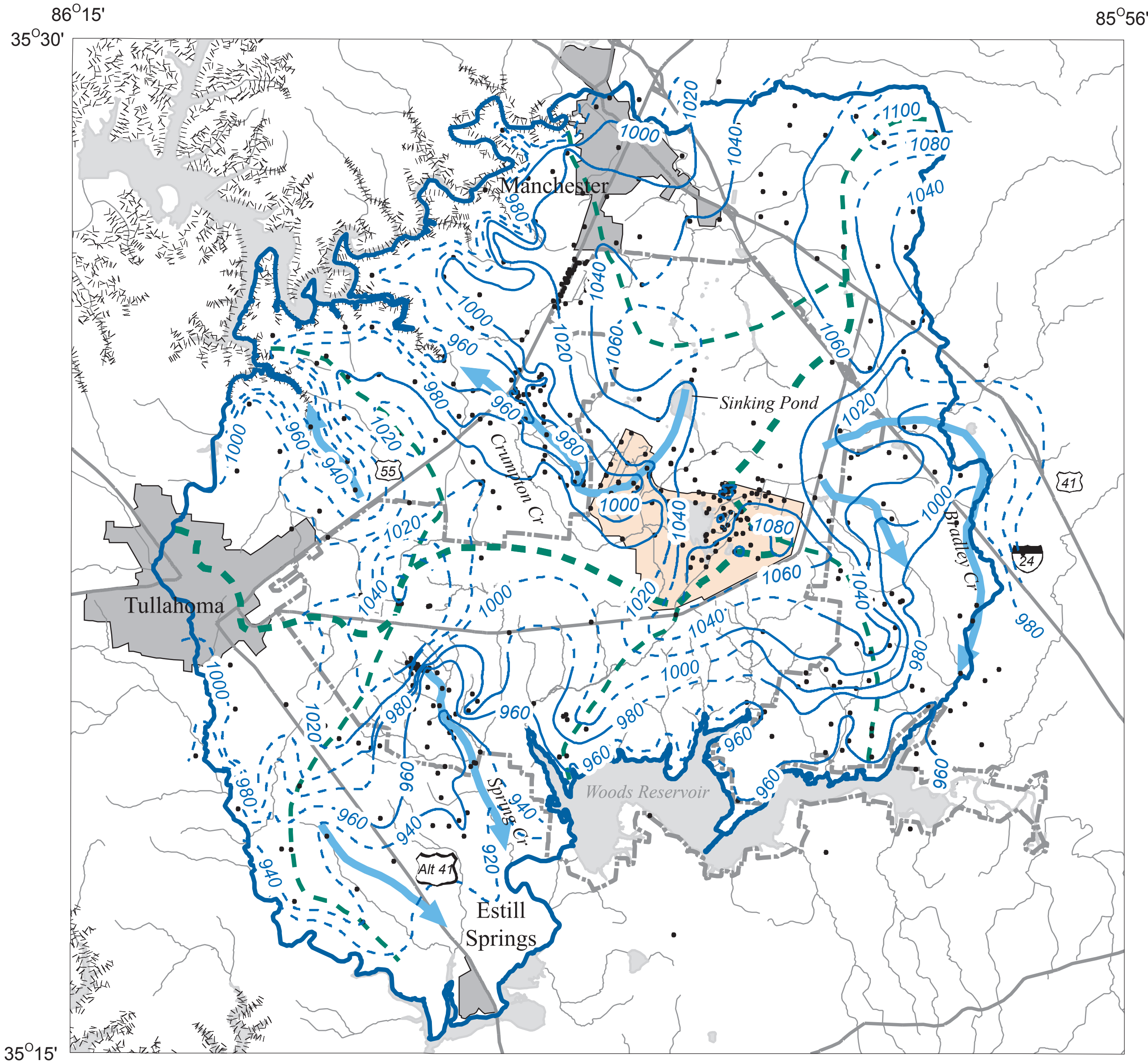
Several troughs are present in the potentiometric surface. The most prominent trough trends northwest to southeast in the Crumpton Creek Basin (fig. 13) (Robinson and others, 2005, figs. 2 and 4). This trough parallels the main axis of Crumpton Creek, but generally is not coincident with Crumpton Creek, but is aligned with a trough in the bedrock surface (fig. 5). During seasonal water-level lows in October 2002, this trough extended upgradient and toward the northeast to the Sinking Pond area (fig. 13) (Robinson and others, 2005, fig. 4). At the downgradient end of this trough is Big Spring at Rutledge Falls which has a steady discharge of about 3.3 ft^3/s (Williams and Farmer, 2003). Similar troughs in the potentiometric surface exist in the Bradley Creek Basin and discharge to several springs along the lower reach of Bradley Creek, in the Spring Creek Basin and discharge to several springs along the lower reach of Spring Creek, in the Dry Creek Basin and discharge to Estill Springs, and in the Bobo Creek Basin and discharge to Short Springs (fig. 13) (Robinson and others, 2005, figs. 2 and 4; Robinson and Haugh, 2004, tables 3 and 5). These troughs in the potentiometric surface are believed to be associated with zones of high permeability within the aquifer that are important regional flow paths (Haugh, 1996a; CH2M Hill, 1999, 2001; ACS, 2002).

Water Levels

Natural seasonal fluctuations of the water table are related to seasonal changes in precipitation and evapotranspiration and, thus, to changes in ground-water recharge. Ground-water levels normally are highest during the spring months following the winter period of high precipitation and low evapotranspiration. Water levels recede during the summer in response to diminishing precipitation and higher evapotranspiration and are lowest in the fall. Hydrographs of wells at AAFB exhibit these characteristic seasonal variations (figs. 14, 15, and 16) (Haugh and others, 1992, figs. 4–6; Haugh and Mahoney, 1994, figs. 15–22; Haugh, 1996a, figs. 14–16; and Robinson and others, 2005, fig. 5). Seasonal water-level fluctuations range from about 5 ft to greater than 25 ft. In general, water-level fluctuations are 10 to 15 ft (AEDC-135, -146, -185, -305, -551). The smallest water-level fluctuations occur near the regional discharge areas (AEDC-189, figs. 14 and 15). The largest water-level fluctuations occur in the northern half of the study area (AEDC-177, -353, -359, -488, figs. 14, 15, and 16).

The larger seasonal water-level fluctuations in the northern half of the study area result in seasonal water-level gradient reversals locally between the area just north of the retention pond (as represented by wells AEDC-551 and -305) and the area around Sinking Pond (as represented by wells AEDC-359, -201, and 353) (figs. 14 and 16). This gradient change coincides with the draining and filling of Sinking Pond (fig. 16). The seasonal change in water-level gradients in this area may explain the broad spreading observed in the “northwest plume” in the area north of the retention pond (fig. 2). This gradient change existed for about 4 months during average rainfall years of 2001 and 2002, 6 months during the lower than average rainfall year of 2005, and less than 1 month during the higher than average rainfall year of 2004 (figs. 12 and 16). Regionally, ground water throughout this area (as represented by wells AEDC-551, -305, -201, -359, and -353) flows toward the ground-water trough of the Crumpton Creek Basin (as represented by well AEDC-464) (figs. 14 and 16).

Natural vertical hydraulic gradients between aquifers are typically small (less than 3 ft). Large natural vertical gradients (greater than 5 ft) have been noted locally between the shallow and Manchester aquifers where ground water in the shallow aquifer appears to be perched, and between the lower part of the Manchester aquifer and the Fort Payne aquifer at a few well clusters in the northern part of the study area where the bedrock is thick (greater than 100 ft).



Base from U.S. Geological Survey topographic quadrangles, 1:24,000 Lambert Conformal Conic Projection, Standard parallels 35°15'N and 36°25'N, central meridian 86°W and USGS digital data, 1:100,000

0 2 4 MILES

0 2 4 KILOMETERS

EXPLANATION

ARNOLD ENGINEERING DEVELOPMENT CENTER

940 POTENTIOMETRIC-SURFACE CONTOUR—Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Hachures indicate depression. Contour interval 20 feet. Datum is NGVD 29

HYDROLOGIC BOUNDARY—Delineation of regional ground-water flow system underlying Arnold Air Force Base

GROUND-WATER DIVIDE—Thinner line represents subdivide

GROUND-WATER TROUGH—Arrow indicates ground-water flow direction

HIGHLAND RIM ESCARPMENT

BOUNDARY OF ARNOLD AIR FORCE BASE

WELL OR SPRING IN WHICH WATER-LEVEL MEASUREMENT WAS USED AS CONTROL

Figure 13. Altitude of the potentiometric surface of the Manchester aquifer in the Arnold Air Force Base area, October 2002. (Robinson and others, 2005.)

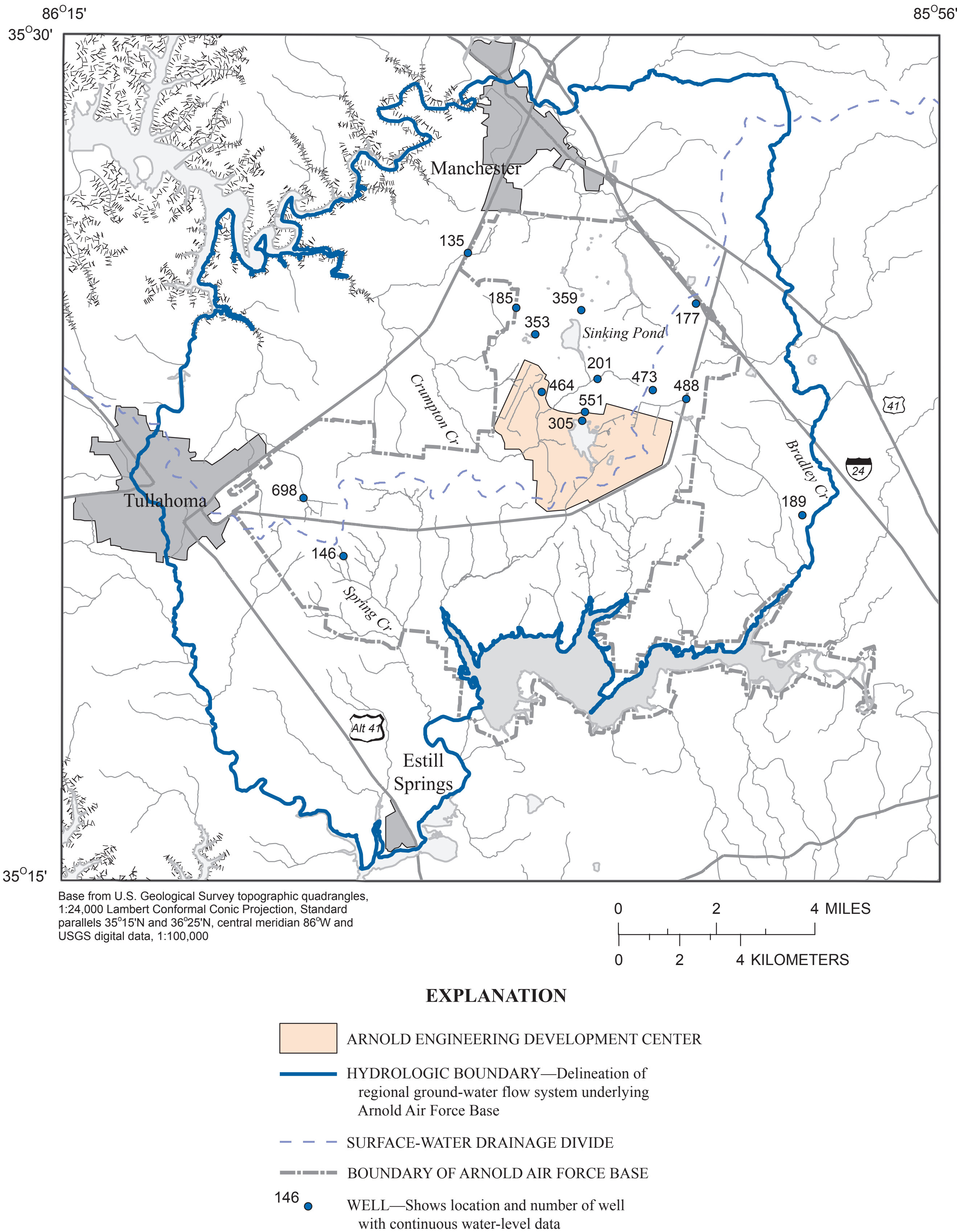


Figure 14. Location of selected wells with continuous water-level data in the Arnold Air Force Base area.

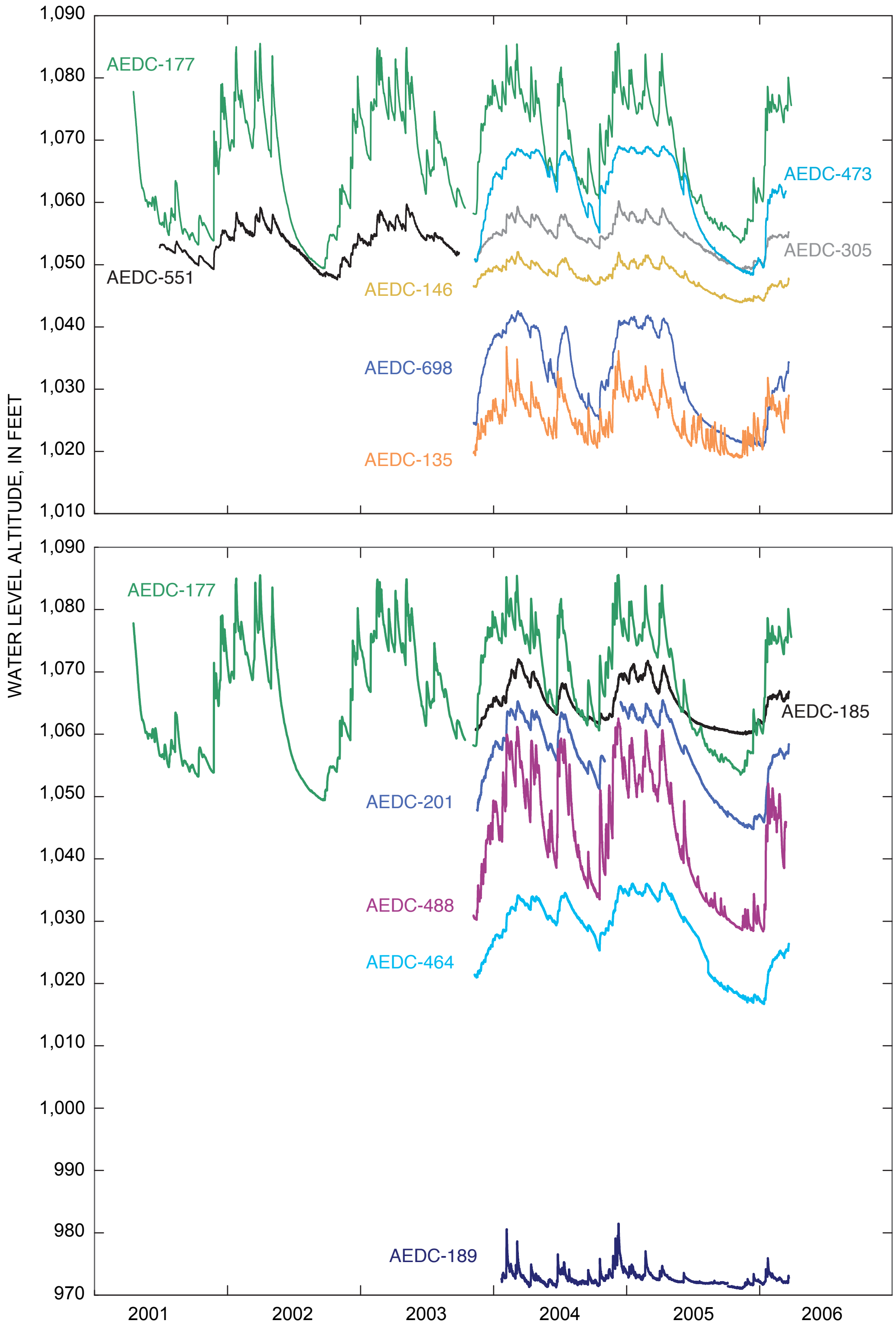


Figure 15. Water levels in selected wells in the Arnold Air Force Base area from 2001 to 2006.

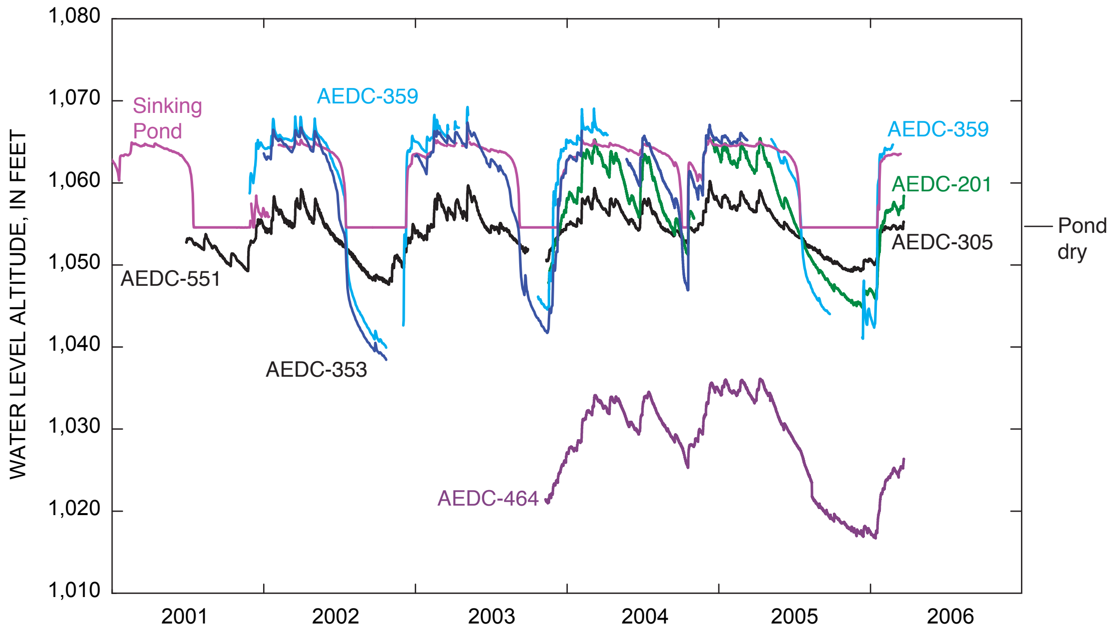


Figure 16. Water levels in wells 353, 359, 201, 551, 305, 464, and Sinking Pond from 2001 to 2006.

Simulation of Ground-Water Flow

The physical system described in the hydrogeology section of this report provides the framework for development of a ground-water flow model for AAFB. The resulting model provides a useful tool to test the understanding and concepts of the ground-water flow system. Although a model is necessarily a simplification of the physical system, the model should be consistent with all known hydrogeologic observations. The ground-water flow model code used in this study, MODFLOW-2000 (Harbaugh and others, 2000), uses finite-difference techniques to solve the ground-water flow equation for three-dimensional, steady or nonsteady flow in anisotropic, heterogeneous media. The model simulations presented in this report represent steady-state, average annual conditions.

Previous Ground-Water Flow Model

The 1992 ground-water flow model (Haugh and Mahoney, 1994) provides the foundation for the current updated flow model. The previous flow model was constructed using MODFLOW88 (McDonald and Harbaugh, 1988) and had 106 columns and 95 rows. Three layers, each of which varied in thickness but had a uniform value of hydraulic conductivity, represented the shallow, Manchester, and Fort Payne aquifers. Recharge was divided into two zones. The model was calibrated using manual methods to minimize the difference between simulated and observed water levels in 158 wells and streamflows at 7 sites. The updated 2002 model, described in this report, retains the same flow boundaries and basic concepts as the previous model, but is a more detailed representation of the flow system.

Conceptual Model

The Highland Rim aquifer system was divided into four layers to simulate ground-water flow (fig. 3). The layers were defined on the basis of differences in physical characteristics that affect hydrologic properties. Model layers are: layer 1 corresponds to the shallow aquifer, layer 2 corresponds to the upper part of the Manchester aquifer, layer 3 corresponds to the lower part of the Manchester aquifer, and layer 4 corresponds to the Fort Payne aquifer. Layers 2 and 3 are interconnected and support most of the regional ground-water flow as indicated by hydraulic-conductivity and geochemical data (Haugh and Mahoney, 1994). Layer 4, because of its lower hydraulic conductivity, supports much less of the regional ground-water flow. Geochemical and potentiometric data indicate that the Chattanooga Shale is an effective underlying confining unit for the Highland Rim aquifer system; therefore, the Chattanooga Shale is the base of the model (Haugh and Mahoney, 1994).

The streams draining the area are assumed to be hydraulically connected to layer 1 through leaky streambeds. Recharge by direct infiltration of precipitation occurs across the study area and is greater in The Barrens area north of AEDC and in the Spring, Taylor, and Dry Creek Basins. The system receives no subsurface recharge from outside the hydrologic boundaries. Ground-water discharge occurs as flow to streams, springs, Woods Reservoir, Tims Ford Lake, wells, and dewatering facilities.

Model Assumptions

The following assumptions were made in the development of the flow model of the hydrologic system in the Arnold Air Force Base area.

1. Fracture and dissolution zones are extensive enough in both aerial and vertical distribution that the hydrogeologic units can be simulated as porous media.
2. Over most of the model area, fracture and dissolution openings are small enough that flow is laminar.
3. The upper model boundary is assumed to be the water-table surface.
4. The lower model boundary is assumed to be a no-flow boundary corresponding to the Chattanooga Shale.
5. The hydraulic properties of hydrogeologic units are homogeneous within a block of the finite-difference grid.
6. Flow within a layer is horizontal; flow between layers is vertical.
7. The model grid is aligned with primary axes of fracture traces and any anisotropy is uniform within a layer.
8. The ground-water system is a closed system.
9. Use of steady-state, annual average conditions is representative of long-term flow conditions for simulation of advective transport with particle tracking.

Model Boundaries

The boundaries of the model correspond to natural boundaries wherever possible and are the same as defined by the 1992 regional study (Haugh and Mahoney, 1994) (fig. 11). Most of the lateral boundaries are streams and are simulated as head-dependent flow boundaries (river nodes) in layer 1 and as no-flow boundaries in layers 2, 3, and 4. The western and northern boundaries that are parts of the drainage divide are simulated as no-flow boundaries in all layers. Along the southern boundary, Woods Reservoir is simulated as a constant-head boundary in layers 1 and 2. Tims Ford Lake, being more deeply incised than Woods Reservoir, is simulated as a constant-head boundary in layers 3 and 4. Layers 1 and 2 crop out above the shoreline of Tims Ford Lake, therefore, water in layers 1 and 2 must drain vertically to layers 3 or 4 to discharge to Tims Ford Lake. The northwestern boundary, where all four layers crop out along the Highland Rim escarpment, is simulated as head-dependent flow (drain nodes) in layers 3 and 4. In these areas, water in layers 1 and 2 must drain vertically to layers 3 or 4 to discharge from the model. Vertically, the upper boundary of the model is the water table. The lower boundary of the model is the Chattanooga Shale, which serves as a no-flow boundary.

Model Construction

The model grid is approximately a 12- by 17-mile rectangle consisting of variably sized grid cells (fig. 17). The grid consists of 150 columns and 132 rows. About 142 square miles (mi^2) of the model grid is active. The smallest grid cells, located near the J4 test cell, are about 160 by 160 ft, and the largest grid cells, located near the model boundaries, are about 1,300 by 1,300 ft. The grid is oriented N. 55° E., N. 35° W. so that flow between model cells is parallel to the primary axes of fracture traces (Haugh and Mahoney, 1994, figs. 7 and 8).

Model parameters (Harbaugh and others, 2000) were defined for recharge and hydraulic-conductivity zones and vertical and horizontal anisotropy (table 3). Recharge to the model is from direct infiltration of precipitation. Based on the information in the recharge section of this report, the model was divided into four recharge zones representing the following areas: The Barrens area along the regional drainage divide (RCH_divide); the Spring Creek, Dry Creek (at Estill Springs), and Taylor Creek Basins (RCH_spcr); Sinking Pond (RCH_sp); and the rest of the study area (RCH_base) (fig. 18). The recharge rates for all zones were adjusted during model calibration using ranges estimated from previous work (described in the recharge section of this report) (table 3). Recharge rates input to the model are net recharge rates; therefore, evapotranspiration of ground water, typically less than 2 in/yr (Rutledge and Mesko, 1996), is not explicitly included in the model.

Hydraulic-conductivity zones were determined by integrating information from several data sets. The spatial distribution of the hydraulic-conductivity data set is highly biased to the SWMU sites, so the distribution of values is not adequate to define regional conductivity zones (fig. 7). Also, the hydraulic-conductivity values represent point measurements and are highly variable at a small local scale. Which of the point values are most appropriate to use in a model zone is dependent on how the local heterogeneities are connected on a regional scale. Therefore, the shapes of the hydraulic-conductivity zones within the model layer are based more on geology, lithology, top-of-rock surface, potentiometric data, locations of important springs and discharge points, conceptual models of the flow system, and trial and error during model calibration than the distribution of the hydraulic-conductivity data. The hydraulic-conductivity data set is used to define a reasonable range of values for each layer (fig. 8).

Layer 1 consists of a uniform hydraulic-conductivity value defined by hydraulic-conductivity parameter (HK_1). Layer 2 consists of six hydraulic-conductivity zones (fig. 19). The HK_3 zone covers most of the model area where data indicate hydraulic conductivity is near the average of the unit. Three of the zones (HK_5, HK_7, and HK_9) cover areas where data indicate hydraulic conductivity is higher than the average of the unit based on the following characteristics: a depression or trough in the bedrock surface, a trough in the ground-water surface, low gradients in the ground-water surface, and a large spring or group of springs at the

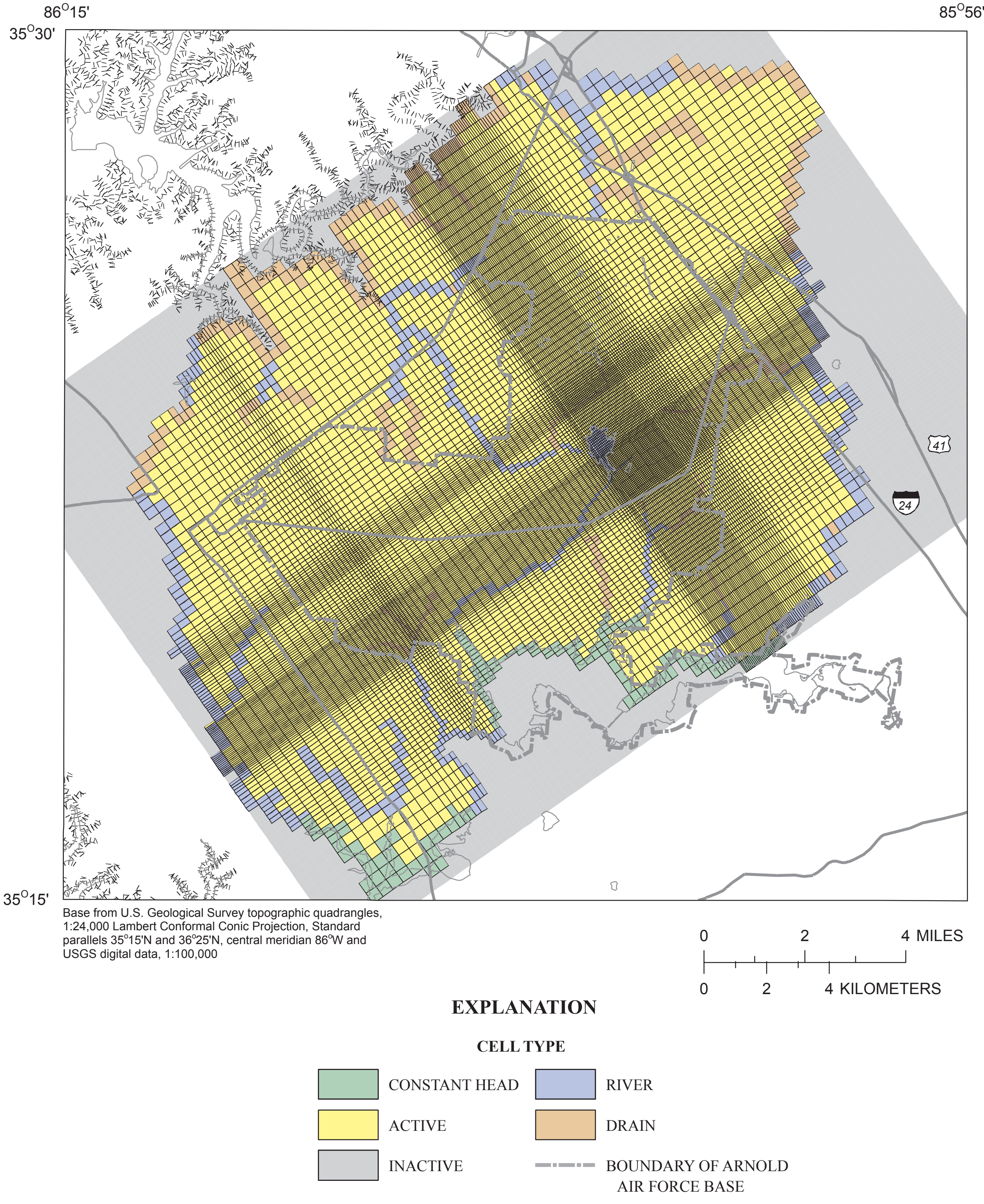


Figure 17. Model grid and cell types for the ground-water flow model of the Arnold Air Force Base area.

Table 3. Recharge and hydraulic-conductivity parameters defined in the Arnold Air Force Base area ground-water flow model.

Model parameter	Description	Initial estimates	Calibrated value
RCH_base	Recharge rate from direct infiltration of precipitation for most of the study area.	5 to 8 inches per year	4.2 inches per year
RCH_divide	Recharge rate from direct infiltration of precipitation in The Barrens area of the divide.	7 to 10 inches per year	7.8 inches per year
RCH_spcr	Recharge rate from direct infiltration of precipitation for Spring, Taylor, and Dry Creek drainage areas.	13 to 18 inches per year	17.7 inches per year
RCH_sp	Recharge rate from water that drains through the bottom of Sinking Pond.	110 inches per year	110 inches per year
HK_1	Hydraulic conductivity for all of layers 1 and 4 and a small part of layers 2 and 3.	0.3 to 6 feet per day	1.5 feet per day
HK_2	Hydraulic conductivity for parts of layers 2 and 3 where data suggest hydraulic conductivity is lower than average of the layer.	0.08 to 4 feet per day	0.2 foot per day
HK_3	Hydraulic conductivity for most of layers 2 and 3.	1 to 390 feet per day	21 feet per day
HK_4	Hydraulic conductivity for part of layer 3 near the J4 test cell.	500 to 1,000 feet per day	1,000 feet per day
HK_5	Hydraulic conductivity for parts of layers 2 and 3 where data suggest hydraulic conductivity is higher than average of the layer.	20 to 2,000 feet per day	1,900 feet per day
HK_7	Hydraulic conductivity for layers 2 and 3 in the area of the Crumpton Creek ground-water trough.	500 to 5,000 feet per day	6,500 feet per day
HK_9	Hydraulic conductivity for layers 2 and 3 in the areas of the Spring Creek and Short Springs ground-water troughs.	500 to 5,000 feet per day	5,900 feet per day
VANI_1	Ratio of horizontal to vertical hydraulic conductivity for most of layer 1.	10:1 to 100:1	21:1
VANI_1a	Ratio of horizontal to vertical hydraulic conductivity for part of layer 1 where water-level data show vertical gradient greater than 5 feet.	100:1 to 1,000:1	440:1
VANI_2	Ratio of horizontal to vertical hydraulic conductivity in layer 2.	10:1	10:1
VANI_3	Ratio of horizontal to vertical hydraulic conductivity in layer 3.	10:1	10:1
VANI_4	Ratio of horizontal to vertical hydraulic conductivity in layer 4.	1,000:1	1,000:1
Horizontal anisotropy (layers 1 and 2)	Ratio of hydraulic conductivity along column to hydraulic conductivity along row.	1:1	1:1
Horizontal anisotropy (layers 3 and 4)	Ratio of hydraulic conductivity along column to hydraulic conductivity along row.	1:1 to 2:1	1.5:1

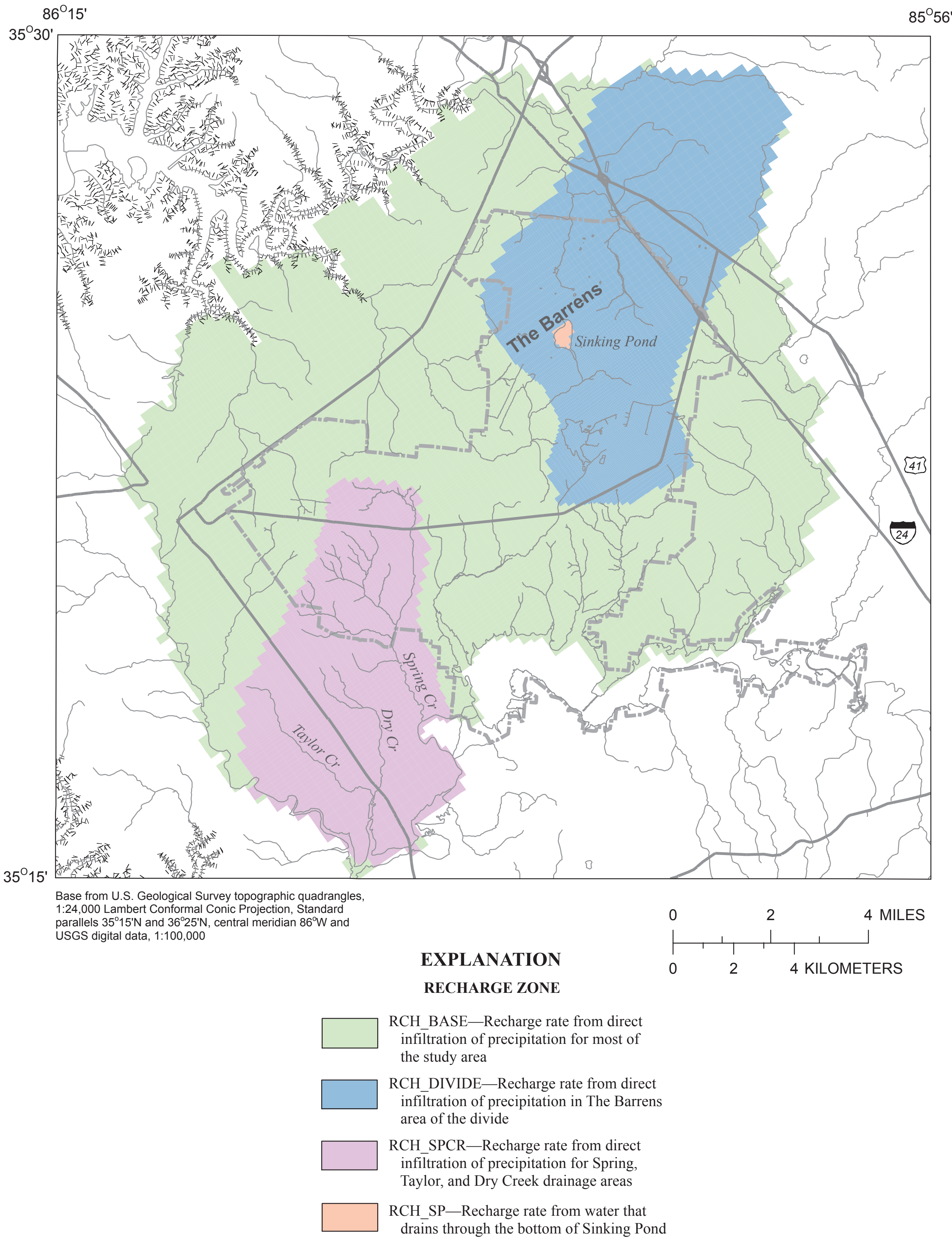


Figure 18. Distribution of simulated recharge zones for the ground-water flow model of the Arnold Air Force Base area.

Figure 19. Hydraulic-conductivity zones for model layer 2 of the Arnold Air Force Base area.

downgradient end of the zone. The other zones (HK_1 and HK_2) are present where data indicate hydraulic conductivity is lower than the average of the unit. Layer 3 consists of seven hydraulic-conductivity zones (fig. 20). The distribution of hydraulic-conductivity zones in layer 3 is identical to layer 2 with the exception of an additional zone (HK_4) near the J4 test cell. The HK_4 zone is present where fractures create higher permeability as indicated by elongated water-level depressions around the J4 test cell (Haugh, 1996a). Layer 4 consists of a uniform hydraulic-conductivity value defined by parameter (HK_1). Horizontal anisotropy is not simulated within layers 1 and 2, which represent the regolith, but is simulated as a uniform value within layers 3 and 4, which represent the bedrock. Vertical anisotropy is assumed to be uniform within each layer except layer 1 where vertical anisotropy is divided into two zones. In layer 1, a second zone (VANI_1a) is present where water-level data indicate the difference in water levels is greater than 5 ft between the shallow aquifer and upper part of the Manchester aquifer (fig. 21).

Stream reaches with perennial flow were simulated as river nodes in layer 1 (fig. 17). Stream reaches that were dry under both high and low base-flow conditions measured in 2002 were not simulated (Robinson and Haugh, 2004). The remaining stream reaches, which had flow under high base-flow conditions but were dry under low base-flow conditions, were simulated as drain nodes in layer 1. Large regional springs were simulated as drain nodes. Woods Reservoir and Tims Ford Lake were simulated by constant-head cells using water-level altitudes of 960 and 888 ft, respectively (Flohr and others, 2003).

Model Calibration

The process of adjusting the model input variables to produce the best match between simulated and observed water levels and flows is referred to as calibration. The digital model developed for this study was calibrated to steady-state conditions as defined by averaging water-level and flow measurements from the spring and fall 2002 (Robinson and Haugh, 2004; Robinson and others, 2005). Precipitation during 2002 was near average, so these data should be representative of average annual conditions (table 2). The model was calibrated using a combination of parameter estimation and manual methods to minimize the difference between simulated and observed water levels, streamflows, and spring flows. Initial calibration was done by fixing recharge to initial estimates and using parameter estimation procedures to estimate the hydraulic conductivity. Additional parameter estimation calibrations were then used to further refine the recharge parameters. Final calibration runs estimated the recharge and hydraulic-conductivity parameters together. Vertical anisotropy parameters for layers 2, 3, and 4 (VANI_2, VANI_3, and VANI_4) were fixed during the calibration process because low sensitivities made them difficult to estimate.

Overall, simulated water levels agree reasonably well with observed water levels (appendix; figs. 22, 23, 24, 25, 26, and 27). Water-level data at 615 wells were available for comparison to simulated conditions (appendix). The root mean square error (RMSE) was calculated to compare simulated and measured water levels. The RMSE, in feet, is calculated by

$$RMSE = \sqrt{\left(\sum_{i=1}^{N}\left\langle h_i^m - h_i^c\right\rangle^2\right)/N},$$

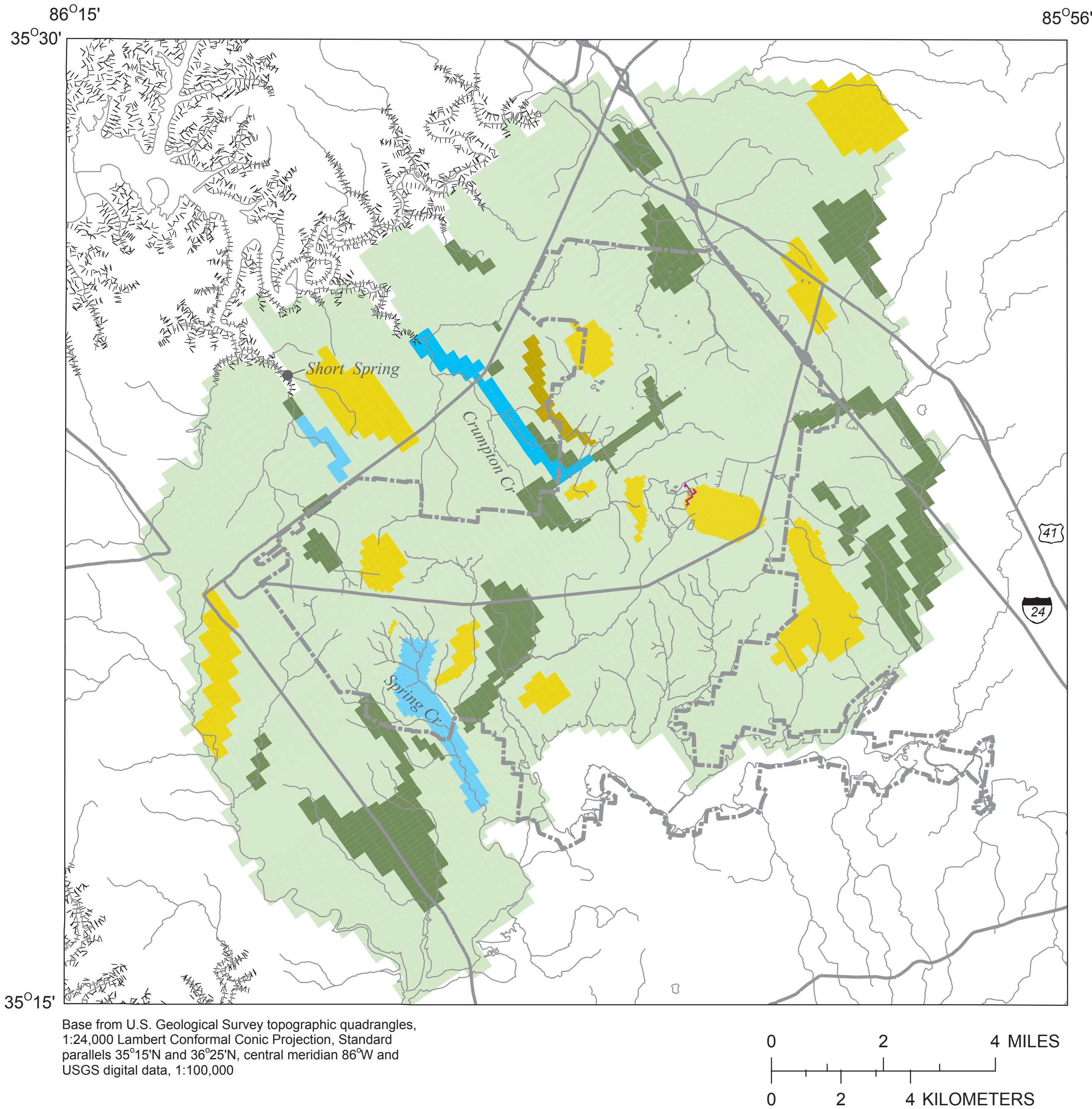
where:

N is the number of observations;
h_i^m is the measured water level, in feet; and
h_i^c is the simulated water level, in feet.

The RMSE for water levels is 9.8 ft. The average residual or difference between measured and simulated water levels is –0.47 ft. Seventy percent of the simulated water levels are within 10 ft of observed water levels, and 95 percent are within 20 ft. The range of residuals is similar in each layer. The residuals show a small positive bias in layer 1 and a small negative bias in layers 3 and 4 (fig. 27, appendix). The residuals show no significant spatial patterns (figs. 22, 23, 24, and 25). Simulated discharge fluxes to springs and streams are within ranges of base flow measured in spring and fall 2002 (table 4).

Table 4. Comparison of simulated and measured flows for the Arnold Air Force Base area ground-water flow model.

	Model-simulated streamflow, in cubic feet per second	Range of measured stream base flow from June and October 2002 (Robinson and Haugh, 2004), in cubic feet per second
Crumpton and Wiley Creeks	7.1	4.3 – 9.4
Big Spring at Rutledge Falls	3.3	3.1 – 3.5
Little Duck River	7.1	6.6 – 7.4
Bradley Creek	11.4	6.5 – 17.2
Spring Creek	10.3	8.5 – 10.8
Taylor and Dry Creeks	9.9	8.2 – 11.6
Rock Creek	5.3	6.7 – 9.5
J4	0.22	0.2 – 0.26

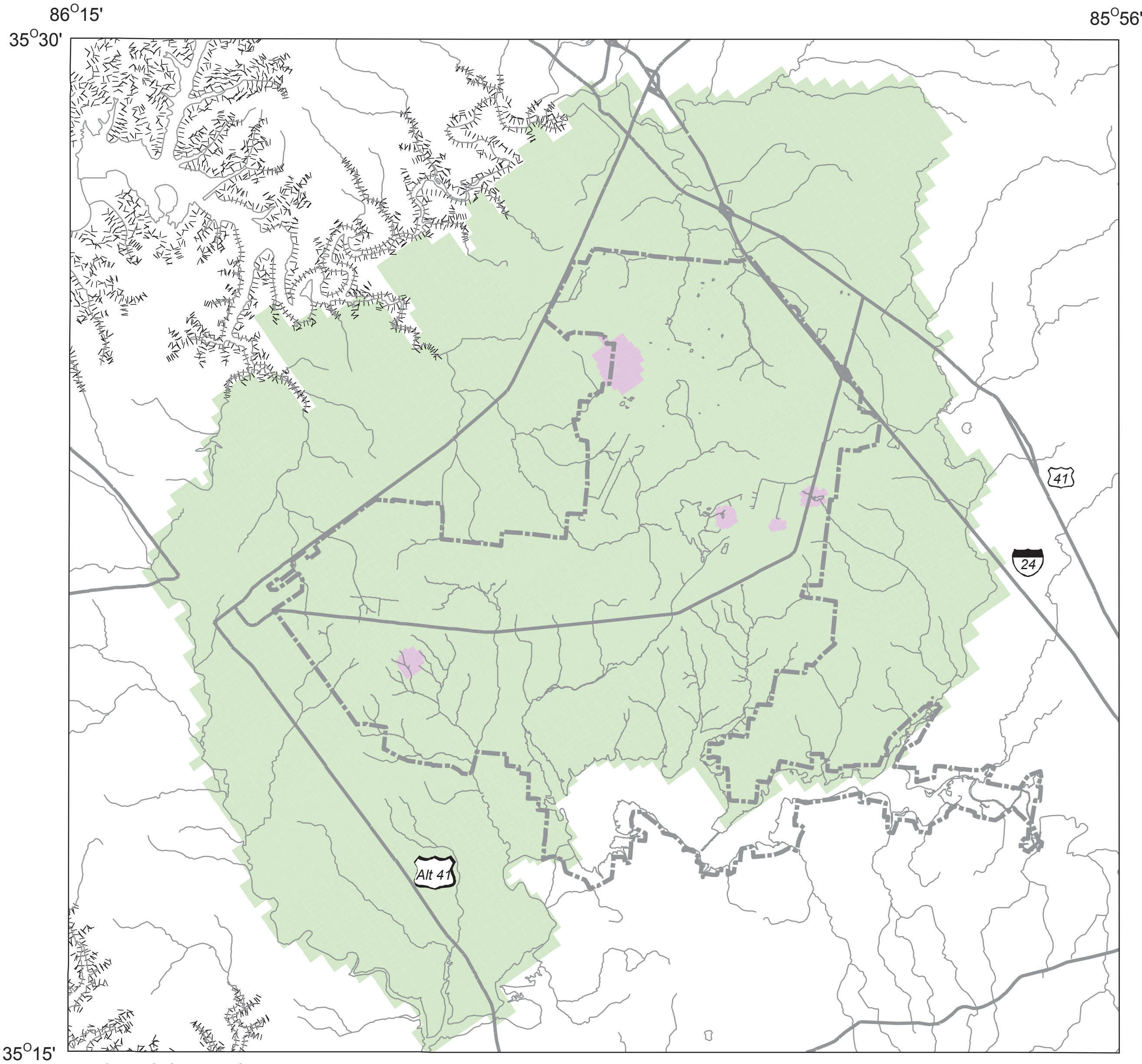


EXPLANATION

HYDRAULIC CONDUCTIVITY ZONE

- HK_1—Hydraulic conductivity for all of layers 1 and 4 and a small part of layers 2 and 3
- HK_2—Hydraulic conductivity for parts of layers 2 and 3 where data suggest hydraulic conductivity is lower than average of the layer
- HK_3—Hydraulic conductivity for most of layers 2 and 3
- HK_4—Hydraulic conductivity for part of layer 3 near the J4 test cell
- HK_5—Hydraulic conductivity for parts of layers 2 and 3 where data suggest hydraulic conductivity is higher than average of the layer
- HK_7—Hydraulic conductivity for layers 2 and 3 in the area of the Crumpton Creek ground-water trough
- HK_9—Hydraulic conductivity for layers 2 and 3 in the areas of Spring Creek and Short Springs ground-water trough

Figure 20. Hydraulic-conductivity zones for model layer 3 of the Arnold Air Force Base area.



Base from U.S. Geological Survey topographic quadrangles, 1:24,000 Lambert Conformal Conic Projection, Standard parallels 35°15'N and 36°25'N, central meridian 86°W and USGS digital data, 1:100,000

0 2 4 MILES

0 2 4 KILOMETERS

EXPLANATION

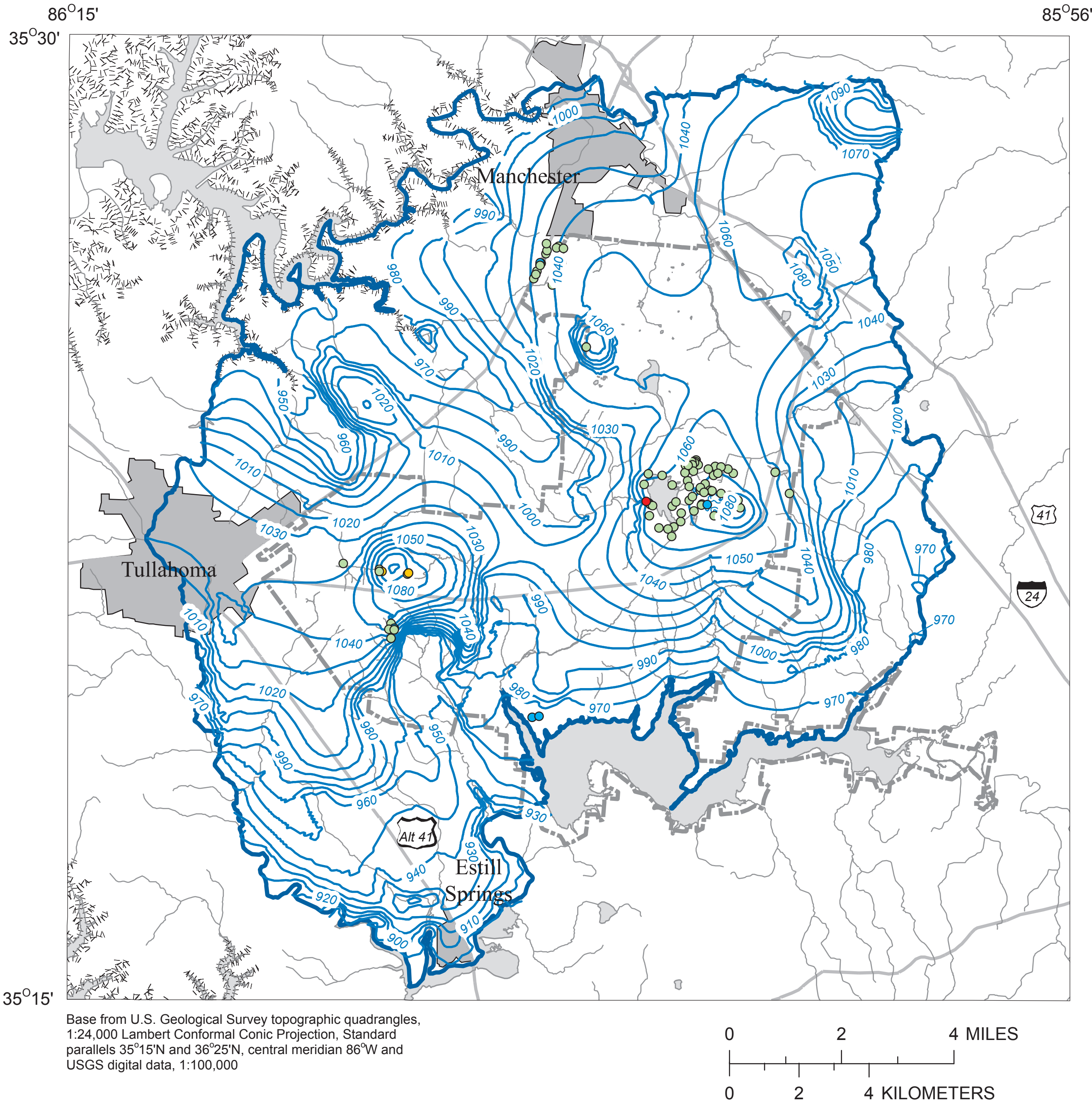
VERTICAL ANISOTROPY

VANI_1—Ratio of horizontal to vertical hydraulic conductivity for most of layer 1

VANI_1A—Ratio of horizontal to vertical conductivity for part of layer 1 where water-level data show vertical gradient greater than 5 feet

BOUNDARY OF ARNOLD AIR FORCE BASE

Figure 21. Vertical anisotropy zones for model layer 1 of the Arnold Air Force Base area.



Base from U.S. Geological Survey topographic quadrangles, 1:24,000 Lambert Conformal Conic Projection, Standard parallels 35°15'N and 36°25'N, central meridian 86°W and USGS digital data, 1:100,000

EXPLANATION

— 900 — POTENTIOMETRIC CONTOUR—Shows simulated altitude of water level. Hachures indicate depression. Contour interval 10 feet. Datum is NGVD 29

HYDROLOGIC BOUNDARY—Delineation of regional ground-water flow system underlying Arnold Air Force Base

HIGHLAND RIM ESCARPMENT

BOUNDARY OF ARNOLD AIR FORCE BASE

RESIDUAL, IN FEET

- LESS THAN –20
- –20 to –10
- –10 to 10
- 10 to 20
- GREATER THAN 20

Figure 22. Simulated steady-state water levels for layer 1 of the Arnold Air Force Base area ground-water flow model.

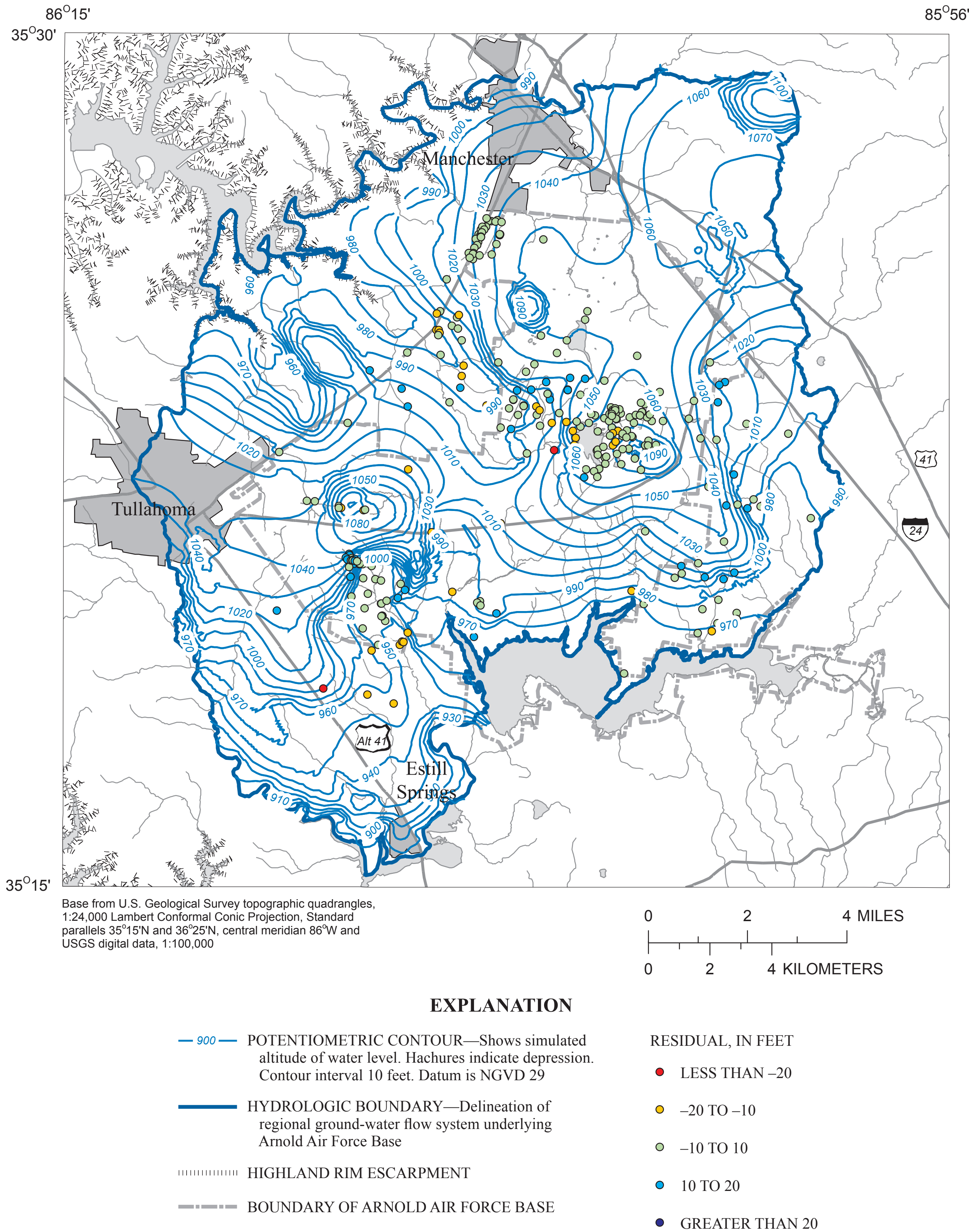


Figure 23. Simulated steady-state water levels for layer 2 of the Arnold Air Force Base area ground-water flow model.

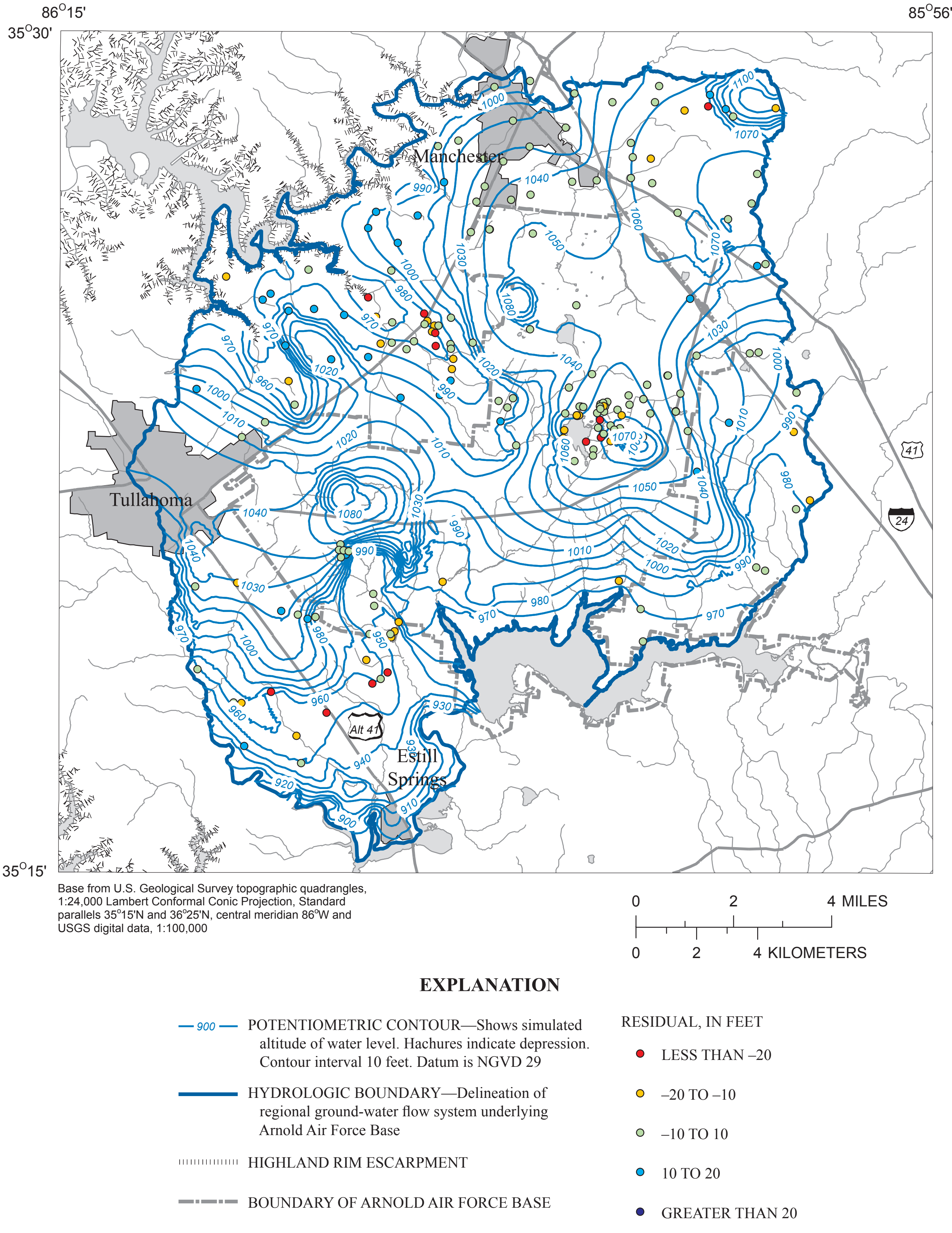


Figure 24. Simulated steady-state water levels for layer 3 of the Arnold Air Force Base area ground-water flow model.

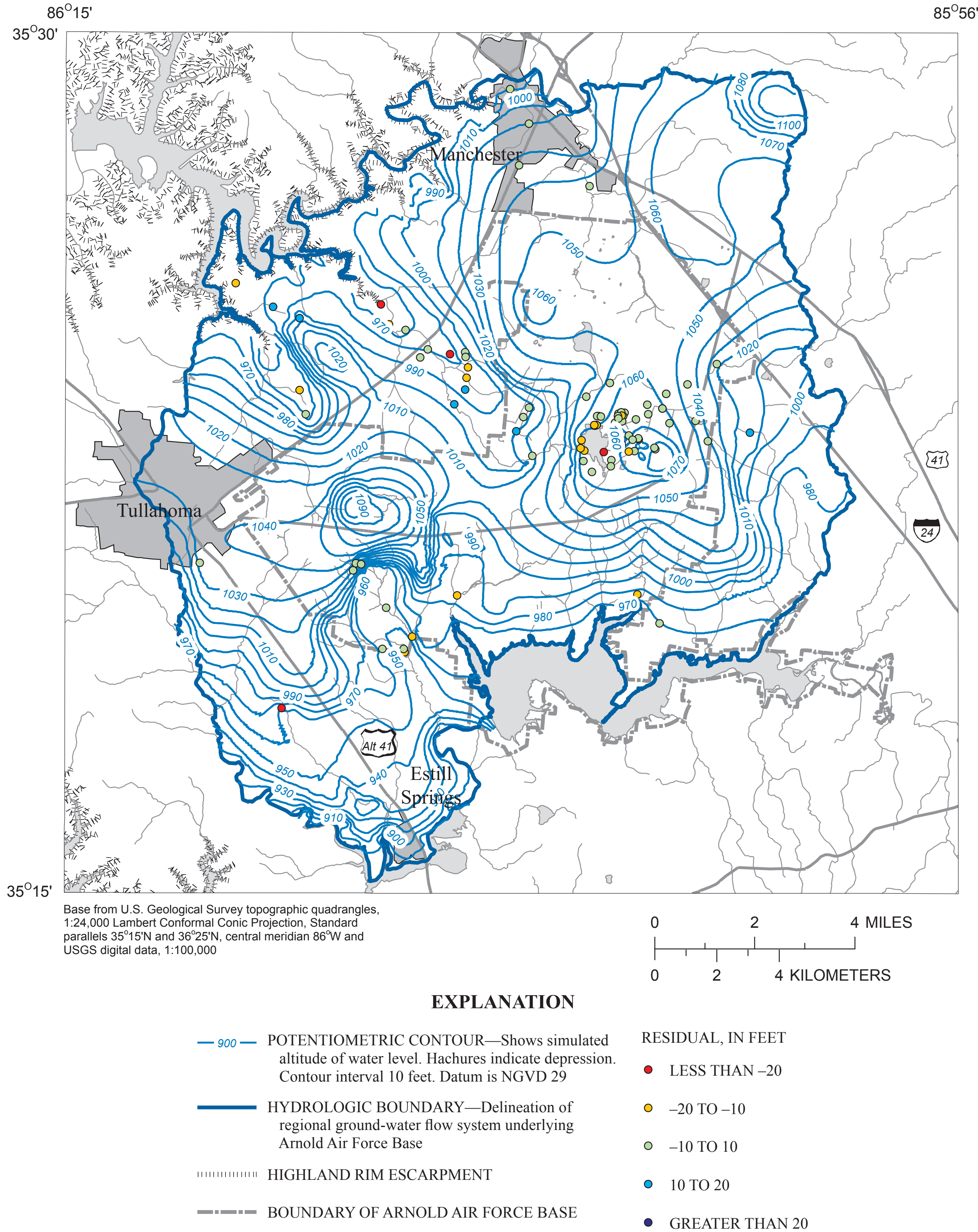


Figure 25. Simulated steady-state water levels for layer 4 of the Arnold Air Force Base area ground-water flow model.

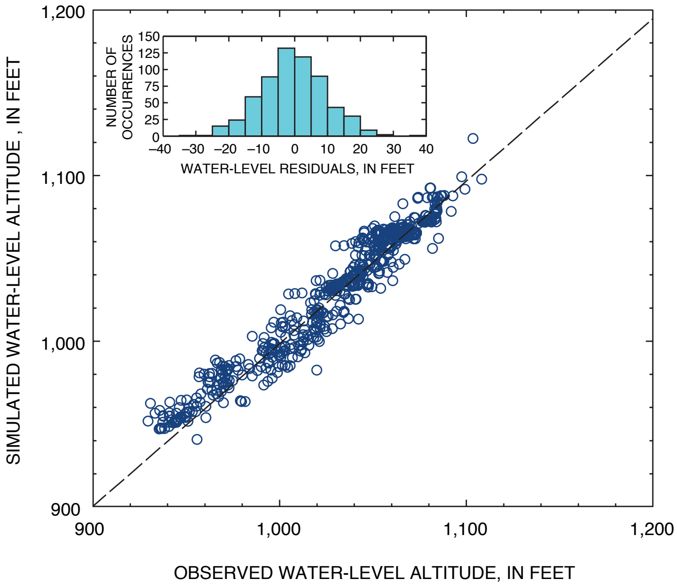


Figure 26. Simulated and observed water levels and distribution of residuals for the Arnold Air Force Base area ground-water flow model.

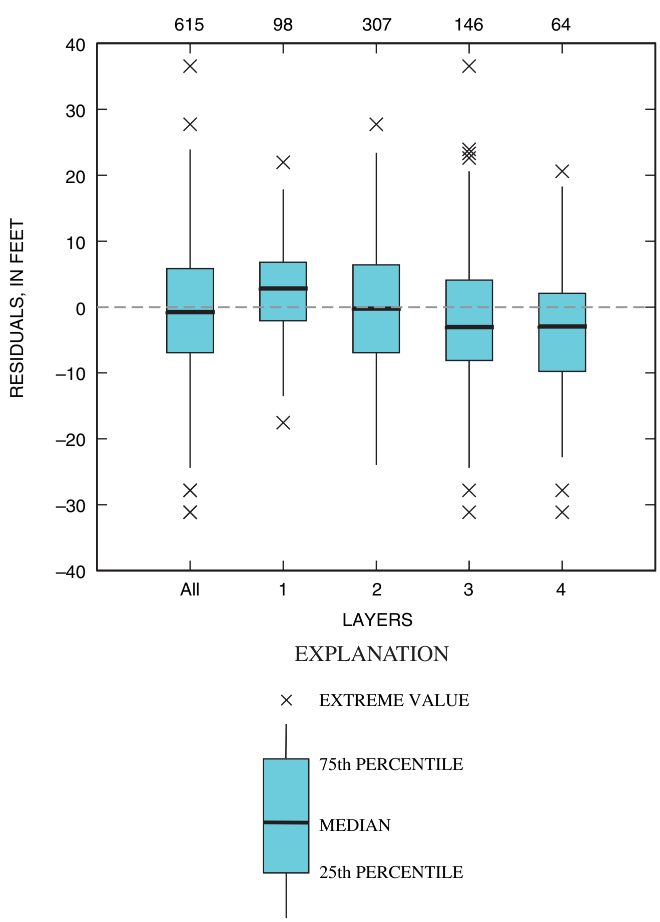


Figure 27. Distribution of residuals by layer for the Arnold Air Force Base area ground-water flow model.

The final values of hydraulic-conductivity parameters generally were within the range of initial estimates with the exception of parameters HK_7 and HK_9 where the calibrated values were slightly higher than the upper range of the initial estimates (table 3). The calibrated recharge rates generally were within the range of initial estimates. The calibrated recharge rates correspond to an average recharge rate over the entire model area of 7.6 in/yr.

Some of the estimated parameters for the calibrated flow model show high correlation coefficients (table 5). When parameters are correlated, the parameter-estimation process may not have enough information to estimate parameters individually and may estimate only the ratio or sums of parameters (Hill, 1998). To determine if the parameters were uniquely estimated, the parameter estimation was run from several different sets of starting parameter values. In each case, the regression converged to the same final values, indicating that the final values probably were estimated individually.

Components of the steady-state water budget of the simulated system are shown in figure 28. The primary source of water to the ground-water system is recharge (79.4 ft^3/s) to layer 1. Most of the water (70.0 ft^3/s) discharges from the ground-water system as seepage to rivers and drains. The remaining amount discharges to constant-head cells at Woods Reservoir and Tims Ford Lake (8.87 ft^3/s) or ground-water withdrawal wells and dewatering facilities (0.55 ft^3/s). Of the water entering layer 1, approximately 92 percent reaches layers 2 and 3, whereas only 5 percent reaches layer 4.

Sensitivity Analysis

Composite-scaled sensitivities were calculated for the calibrated model using the sensitivity process in MODFLOW-2000 for all the hydraulic-conductivity and recharge parameters (fig. 29) (Hill and others, 2000). Composite-scaled sensitivities can be used to compare the importance of different parameters to the calculation of model-simulated water levels and flows (Hill, 1998). Parameters with larger composite sensitivities have greater importance and greater influence on the model solution than parameters with smaller composite sensitivities. The most sensitive model parameter is RCH_divide, the recharge rate in The Barrens area. The next most sensitive parameter is HK_3. Three of the four most sensitive parameters were for recharge. The model is least sensitive to the parameters VANI_4, VANI_3, HK_4, and VANI_2.

Advective Flow Particle Tracking

A particle-tracking program, MODPATH (Pollock, 1994), used results from the flow model to depict ground-water flow paths under several different conditions to assess the effects of ground-water withdrawal wells and dewatering facilities. The only changes made to the model for the particle-tracking simulations were adding or removing ground-water withdrawals as

Table 5. Correlation coefficients between estimated parameters of the Arnold Air Force Base area ground-water flow model.

[See table 3 for parameter descriptions]

Estimated parameters	Correlation coefficients										
	HK_1	RCH_divide	VANI_1	HK_3	RCH_base	RCH_spcr	HK_9	HK_2	HK_7	HK_5	VANI_1a
HK_1	1.00										
RCH_divide	0.75	1.00									
VANI_1	0.03	–0.28	1.00								
HK_3	0.57	0.89	–0.28	1.00							
RCH_base	0.57	0.83	–0.47	0.90	1.00						
RCH_spcr	0.75	0.93	–0.21	0.92	0.81	1.00					
HK_9	0.58	0.58	0.23	0.58	0.43	0.73	1.00				
HK_2	–0.28	0.12	–0.18	0.18	0.15	0.07	–0.02	1.00			
HK_7	0.41	0.41	0.54	0.48	0.37	0.45	0.56	0.02	1.00		
HK_5	0.28	0.34	0.00	0.01	0.07	0.14	0.06	0.02	–0.09	1.00	
VANI_1a	0.24	0.02	0.09	–0.05	0.01	–0.04	0.02	–0.21	0.03	0.06	1.00

needed. In each simulation, particles were evenly distributed within each model cell in the appropriate starting locations. MODPATH is based on advective transport only and cannot be used to compute solute concentrations in ground water. In order to determine time-of-travel for the particles, porosities of 0.10 for layer 1, 0.20 for layers 2 and 3, and 0.05 for layer 4 were used. These porosity values are consistent with typical values for the lithologies of the layers (Freeze and Cherry, 1979; Heath, 1989).

Pre-Ground-Water Withdrawal Wells Particle Tracking

Particle-tracking analysis was done first under conditions before any ground-water withdrawal wells at SWMUs were operational. For these simulations, all dewatering at test facilities were active. Particles were tracked forward from four sites: SWMU 1&2, SWMU 5, SWMU 8, and SWMU 10 (fig. 30). These path lines should represent the historic flow paths from these sites. The flow paths indicated by the particle-tracking simulations agree reasonably well with maps of interpreted contaminant plumes (fig. 2).

From SWMU 1&2, most of the particles (70 percent) move to the northwest under the retention pond, then move west under the air field, then follow a prominent trough in the ground-water surface to discharge to Big Spring at Rutledge Falls. The estimate of travel times for ground water leaving SWMU 1&2 to reach the discharge point at Rutledge Falls ranges from 16 to 362 years with a mean travel time of 46 years and a median travel time of 43 years. Some of the particles (30 percent) from SWMU 1&2 curl around to the northeast to discharge to the J4 test cell. The estimate of travel times for ground water from SWMU 1&2 that is captured by dewatering operations at J4 ranges from 4 to 17 years with a mean travel time of 8 years and a median travel time of 7 years.

Pathlines from SWMU 5 show that particles generally move west and northwest to discharge to Cat Creek, Bates Spring Branch, or seeps and springs along the Highland Rim escarpment. The estimate of travel times for ground water from SWMU 5 to discharge locations ranges from 11 to 45 years with a mean travel time of 21 years and a median travel time of 20 years.

Pathlines from SWMU 8 show that particles move to the southeast to discharge along Spring Creek. The estimate of travel times for ground water from SWMU 8 to discharge locations along Spring Creek ranges from 1 to 8 years with a mean travel time of 3 years and a median travel time of 2 years.

Pathlines from SWMU 10 show that particles move to the northeast before turning south to discharge to springs along the lower reach of Bradley Creek. The estimate of travel times for ground water from SWMU 10 to discharge locations along Bradley Creek ranges from 33 to 244 years with a mean travel time of 78 years and a median travel time of 40 years.

Pathlines from SWMU 10 are sensitive to the extent of hydraulic-conductivity zone HK_5 in the Bradley Creek Basin. Under an alternate calibration of the flow model with a slight modification of the HK_5 zone, particles from SWMU 10 diverged to show two flow paths that both discharged to springs along the lower reach of Bradley Creek (fig. 31). Based on a detailed review of local water levels and water-quality data, these alternate flowpaths are believed to be less likely than the first scenario presented here, but may occur periodically or seasonally. SWMU 10 is located in an area near the regional divide where the horizontal ground-water gradients are flat and may vary locally in response to individual recharge events. Also, seasonal water levels vary over a greater range to the north of SWMU 10 when compared to areas south of SWMU 10. The flat gradient and greater range in water levels cause some additional uncertainty in modeling flow paths from SWMU 10.

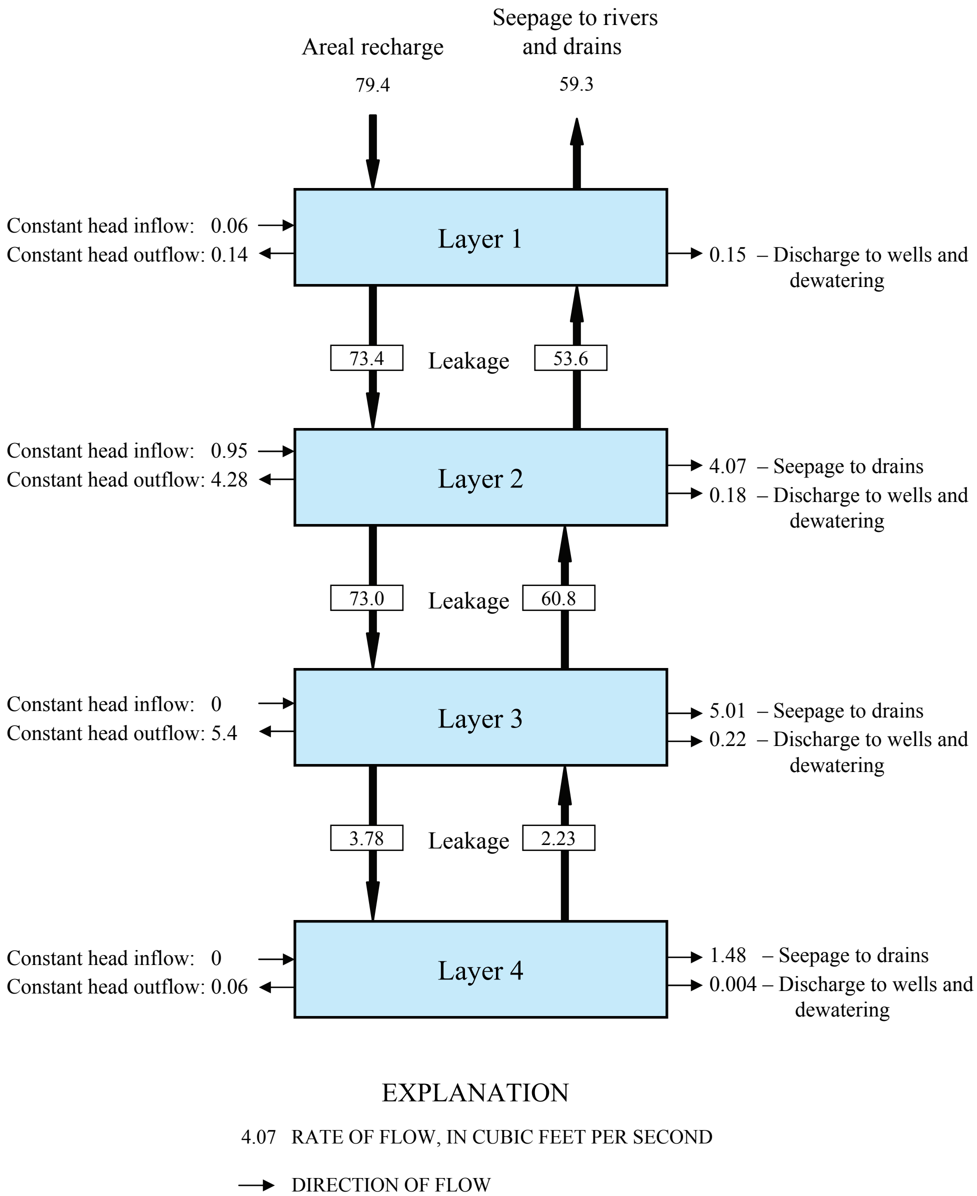


Figure 28. Distribution of water-budget components among the layers of the digital flow model for the Arnold Air Force Base area.

Ground-Water Withdrawal Wells Particle Tracking

Currently (2005), ground-water withdrawal wells are operating at SWMU 1&2, SWMU 5, SWMU 8, and SWMU 10. Particle-tracking results from these SWMUs under conditions with the ground-water withdrawal wells pumping show that no particles leave the SWMUs (fig. 32).

In 2005, five new ground-water withdrawal wells along the airfield road were scheduled to begin pumping. To analyze the effect of these new wells on the flowpaths from SWMU 1&2, a particle-tracking simulation was performed with the existing ground-water withdrawal wells at SWMU 1&2 turned off and the new wells along the airfield road turned on. The airfield road ground-water withdrawal wells and the J4 test cell capture about 89 percent of the particles from SWMU 1&2, with about 11 percent of the particles discharging near Rutledge Falls (fig. 33). To estimate the travel time of ground water from the area near the airfield road ground-water withdrawal wells to Big Spring at Rutledge Falls, a simulation was performed starting particles just downgradient of the capture area of the airfield road withdrawal wells. The estimate of travel time from the airfield road withdrawal wells area to Big Spring at Rutledge Falls ranges from 1 to 5 years with a mean travel time of 2 years and a median travel time of 2 years. This mean travel time of 2 years from the airfield road area to Big Spring at Rutledge Falls, compared with the mean travel time of 46 years from SWMU 1&2 to Big Spring at Rutledge Falls implies that the airfield road withdrawal wells should substantially reduce the time required to observe a change in contaminant discharge from the “northwest plume” at Big Spring at Rutledge Falls.

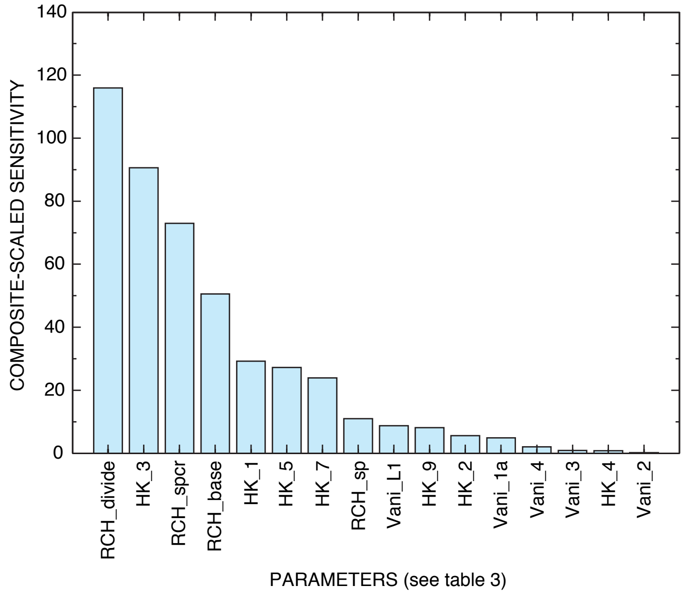


Figure 29. Composite-scaled sensitivities for model parameters.

Dewatering Facilities Particle Tracking

Three particle-tracking simulations were run to analyze the effects of dewatering facilities on flow paths in the Main Test Area (MTA). In the first simulation, particles were placed in the MTA (in a rectangular area bounded by Third and Fifth Streets and Avenues C and E) and tracked forward under conditions with all dewatering facilities turned on (fig. 34). In the second simulation, particles were placed in the MTA and tracked forward under conditions with all dewatering facilities turned off (fig. 35). In the third simulation, particles were placed at the location of the dewatering facilities and tracked backwards to their recharge locations (fig. 36). These simulations illustrate that the dewatering facilities have a substantial effect on flow paths that were simulated from the MTA and are effective in containing most of the ground water in this area.

Model Limitations

Models, by their very nature, are simplifications of the natural system. Factors that affect how well a model represents the natural system include the model scale; inaccuracies in estimating hydraulic properties; inaccurate or poorly defined boundary conditions; and the accuracy of pumping, water-level, and streamflow data. The model presented in this report is consistent with the conceptual model and hydrologic data of the area. The model uses a variably spaced grid so the model resolution is greatest near SWMUs, ground-water withdrawal wells, and dewatering facilities. The model will not provide accurate predictions on a scale smaller than the grid resolution.

The hydraulic-conductivity zones used in the model represent large-scale variations in hydraulic properties; the actual spatial variations of hydraulic properties of the aquifer system occur on a much smaller scale and are poorly defined. Additionally, the aquifer system, being karst in nature, has a wide range of measured hydraulic conductivity. Finally, evidence indicates that the aquifer system behaves anisotropically, but no measured values of the degree of anisotropy exist.

The model is calibrated to average annual conditions during 2002 and may not represent flow during seasonal extremes. Seasonal potentiometric maps (Robinson and others, 2005) and continuous water-level data (fig. 16) indicate some local seasonal shifts in flow directions in the upper part of the Crumpton Creek Basin. Similarly, ground-water gradients near the divide north of SWMU 10 may change seasonally.

The particle-tracking program, MODPATH, is based on advective transport of “water” particles and does not consider additional processes such as sorption, dispersion, and diffusion that would affect the travel times of a ground-water contaminant. Travel times also are directly related to assumptions about aquifer porosity. Since no measured values of porosity exist for the study area, the simulations use a uniform value of porosity for each layer as estimated from typical values for the lithologies of the layers. If porosity estimates are too high, travel times would be underestimated. If porosity estimates are too low, travel times would be overestimated.

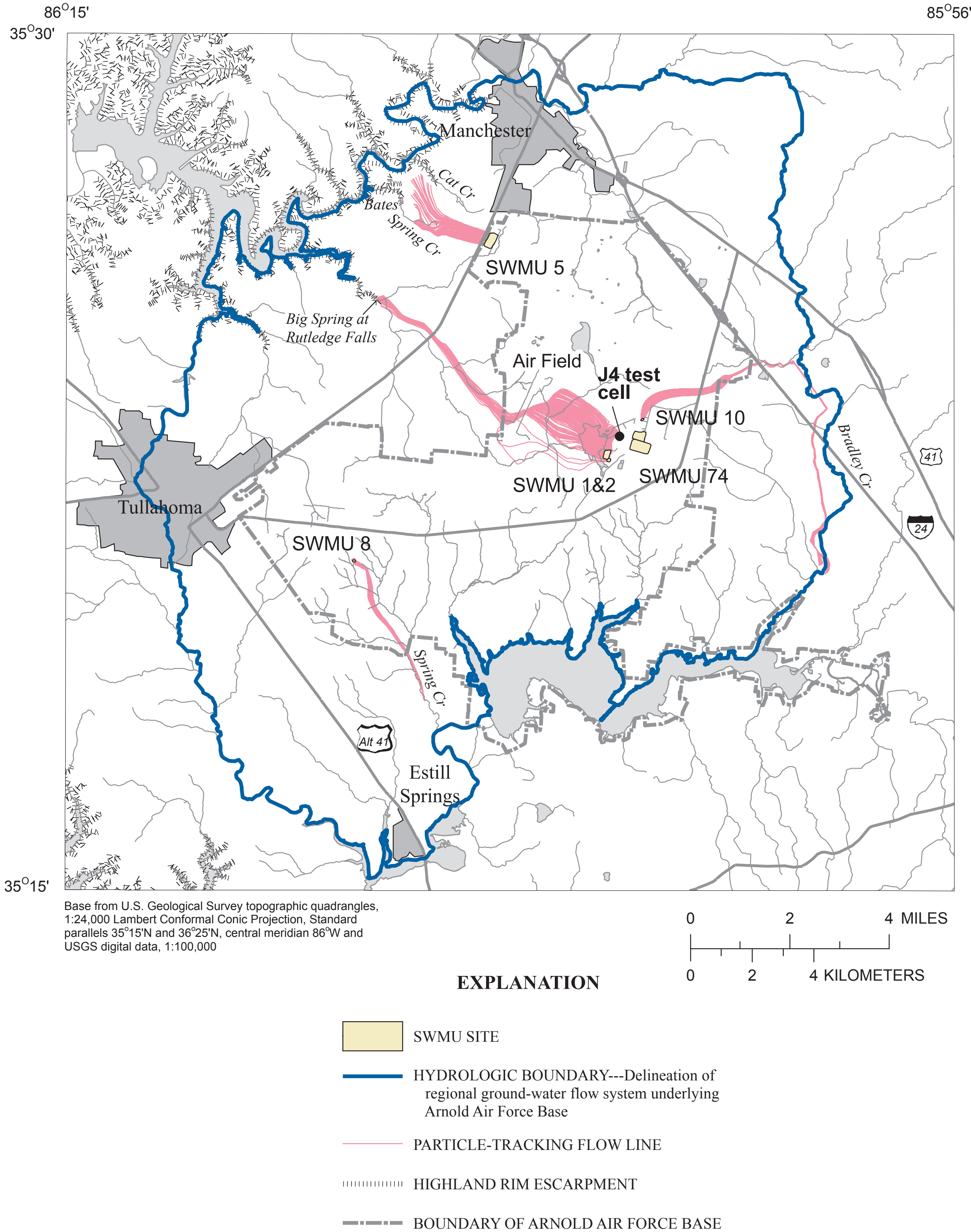


Figure 30. Forward particle tracking from SWMU 1&2, SWMU 5, SWMU 8, and SWMU 10 at Arnold Air Force Base with no ground-water withdrawal wells pumping.

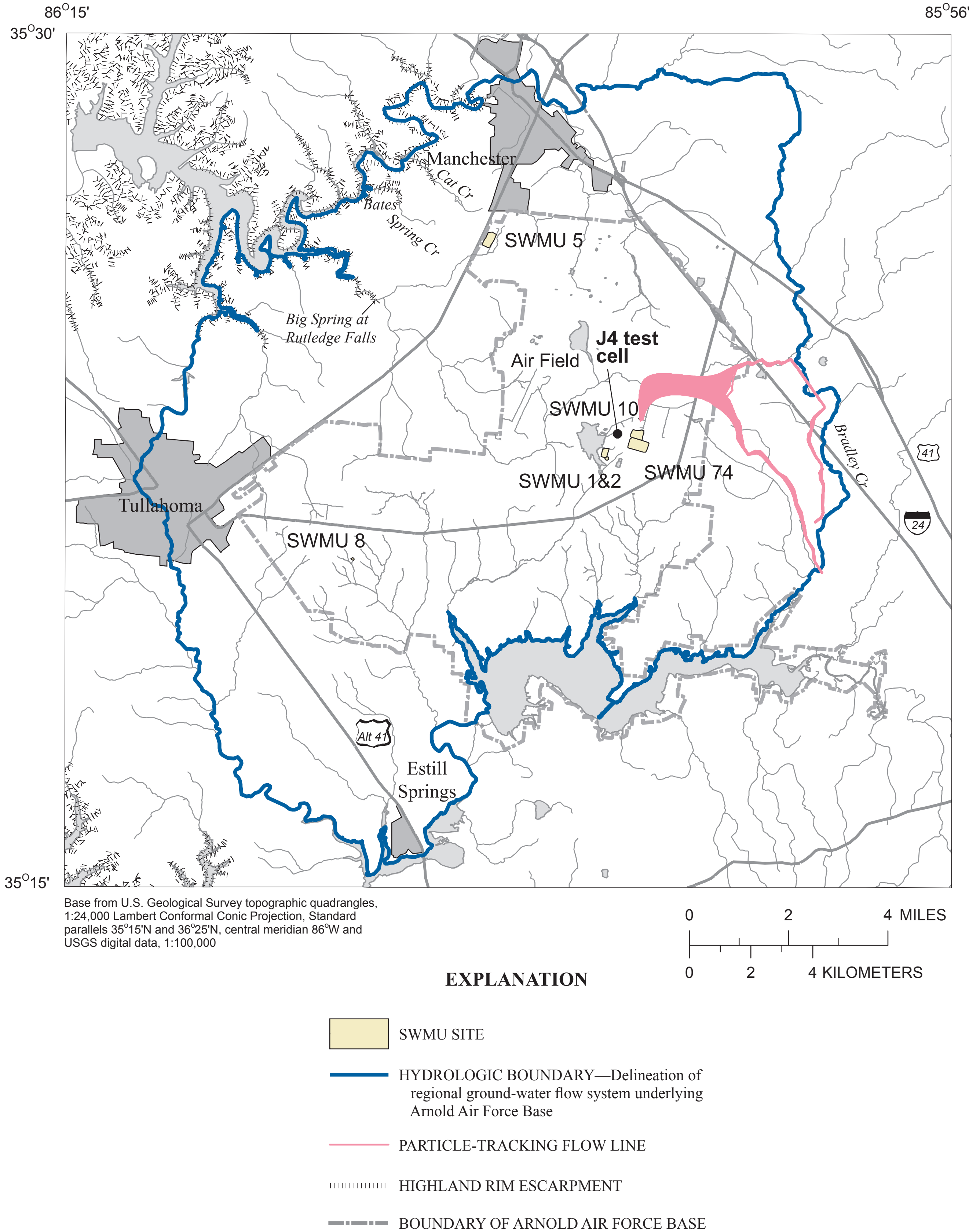


Figure 31. Forward particle tracking from SWMU 10 at Arnold Air Force Base under an alternative calibration of the flow model.

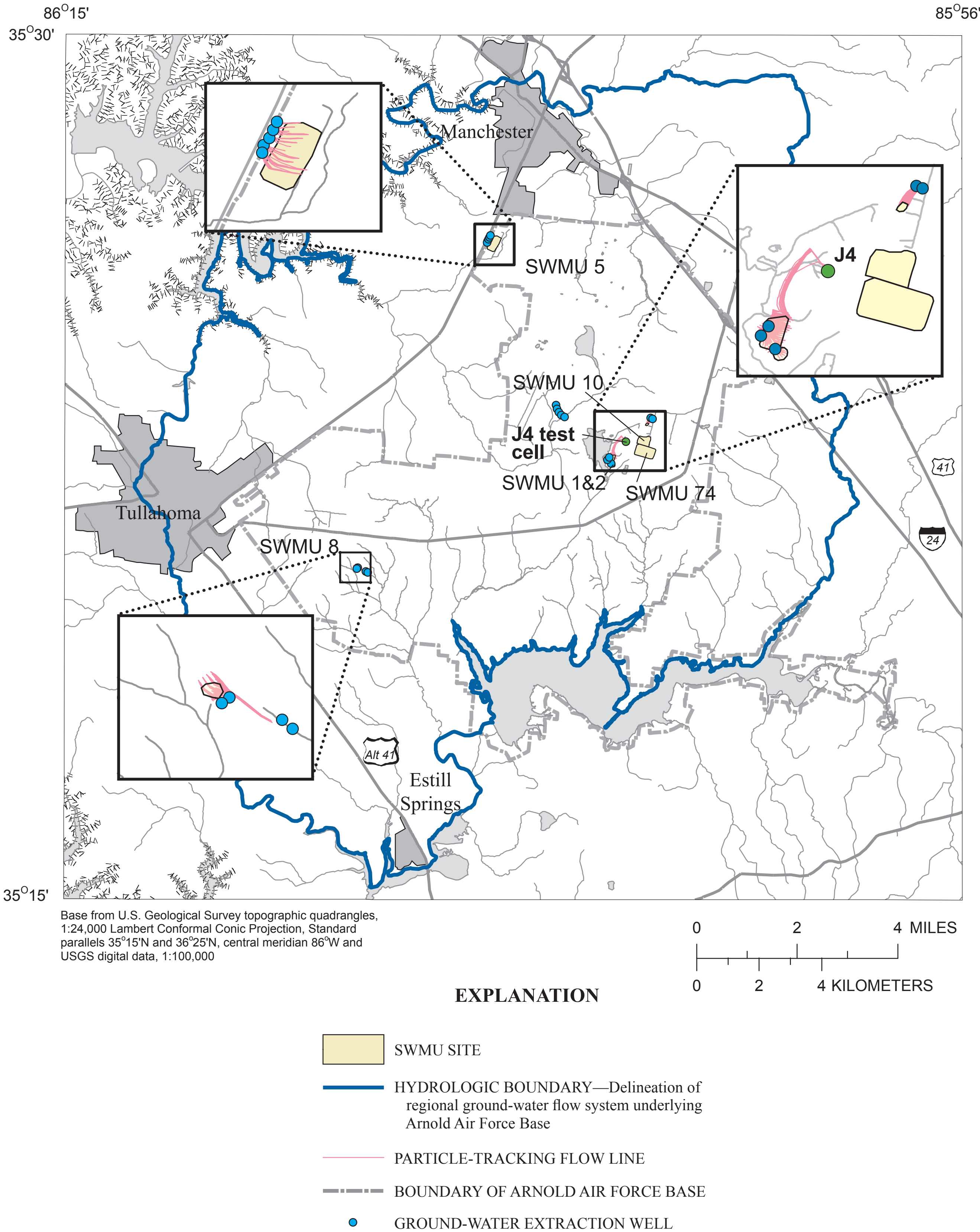


Figure 32. Forward particle tracking from SWMU 1&2, SWMU 5, SWMU 8, and SWMU 10 at Arnold Air Force Base with ground-water withdrawal wells pumping.

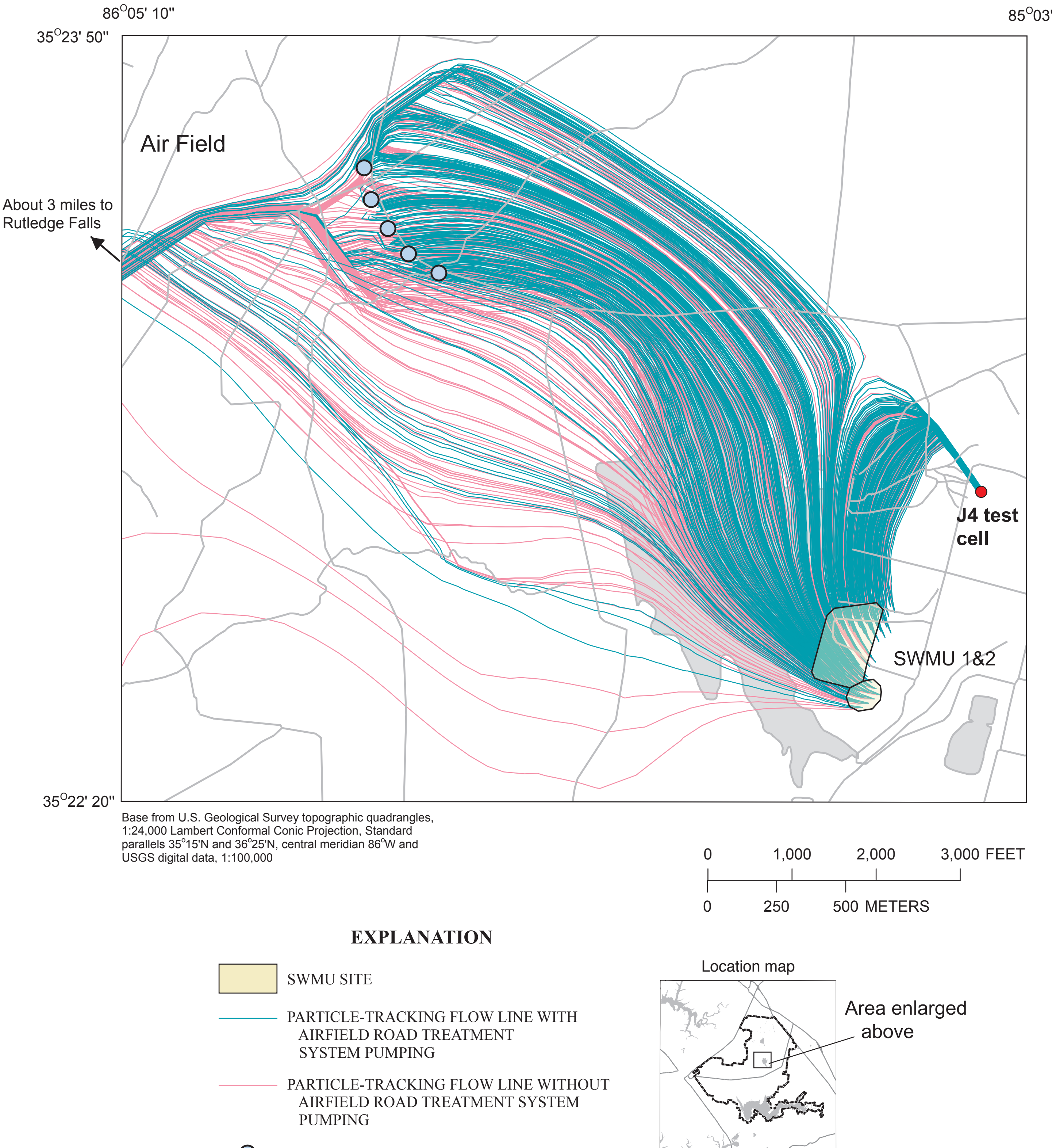


Figure 33. Forward particle tracking from SWMU 1&2 at Arnold Air Force Base with the airfield road ground-water withdrawal wells pumping.

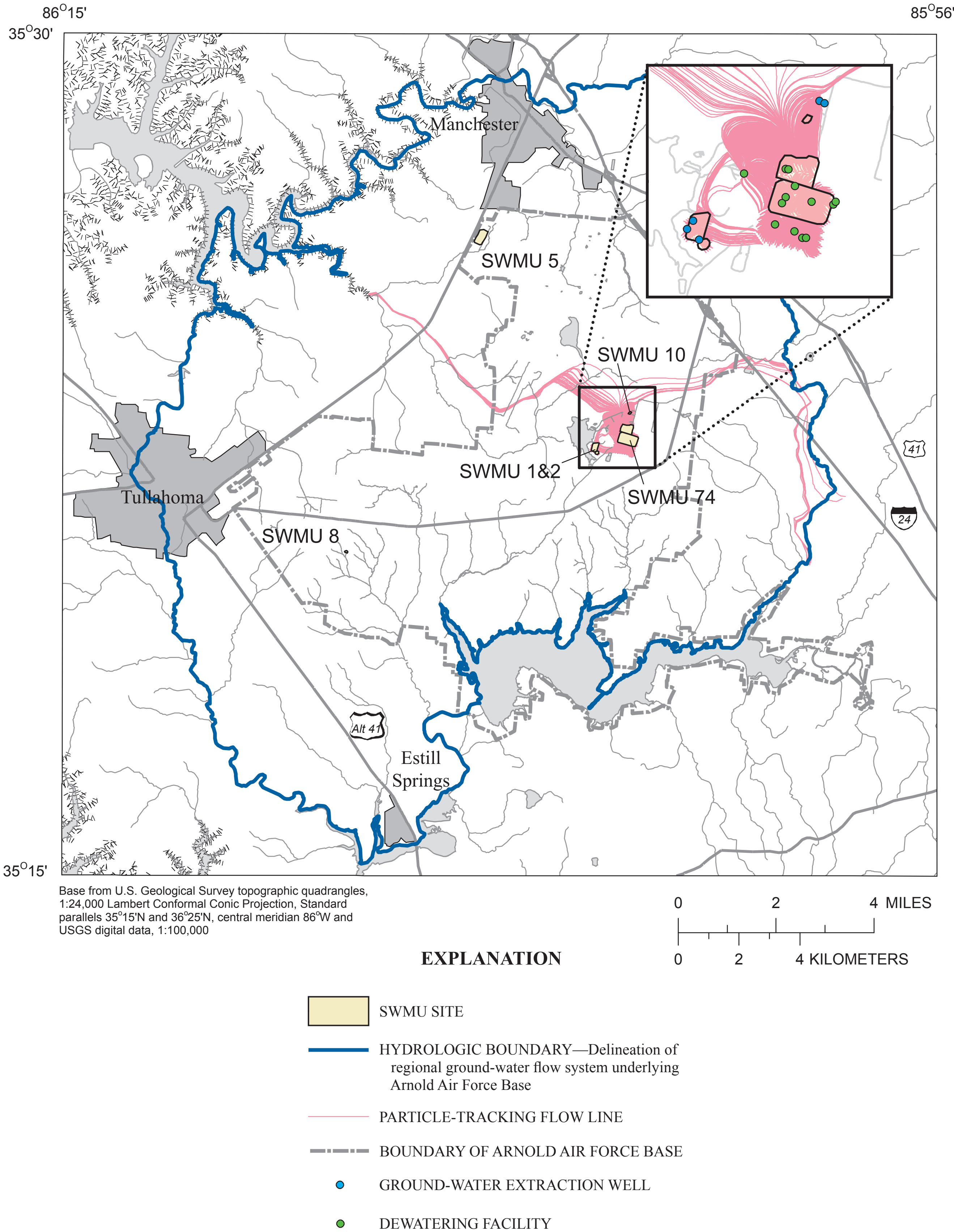


Figure 34. Forward particle tracking from the Main Test Area (SWMU 74) at Arnold Air Force Base with all dewatering facilities turned on.

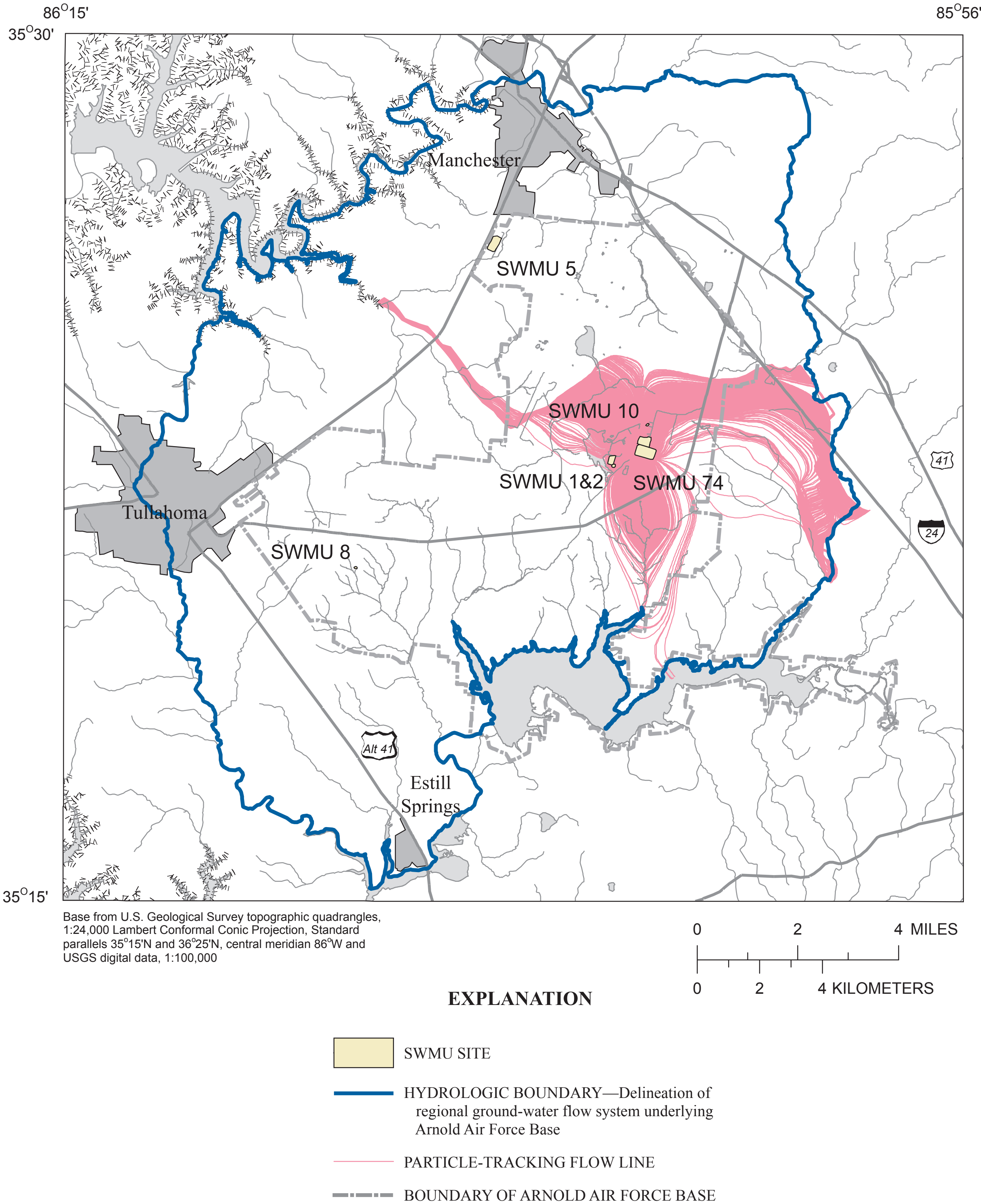


Figure 35. Forward particle tracking from the Main Test Area (SWMU 74) at Arnold Air Force Base with all dewatering facilities turned off.

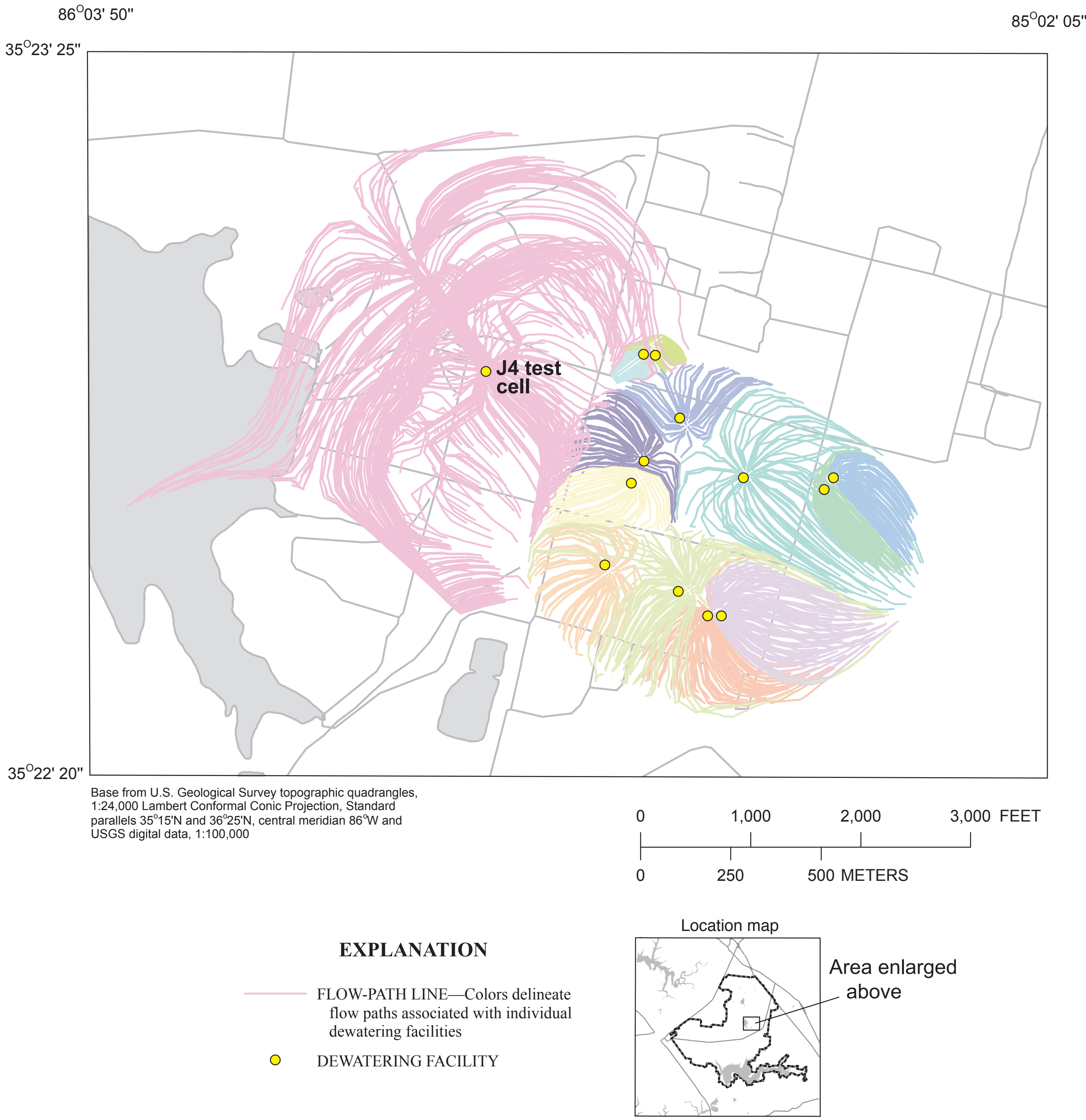


Figure 36. Backward particle tracking from dewatering facilities at the Main Test Area at Arnold Air Force Base.

Summary

Arnold Air Force Base (AAFB) occupies about 40,000 acres in Coffee and Franklin Counties, Tennessee. The primary mission of AAFB is to support the development of aerospace systems. Numerous site-specific ground-water contamination investigations have been conducted at designated Solid Waste Management Units (SWMUs) at AAFB. Several synthetic volatile organic compounds (VOCs), primarily chlorinated solvents, have been identified in the ground water at AAFB. Two ground-water contaminant plumes that originate at AAFB, the “SWMU 8 plume” and the “northwest plume,” have been shown to extend to regional discharge points outside the AAFB boundary.

The ground-water system at AAFB can be divided into several different zones or aquifers. The Manchester aquifer, the primary source of drinking water in the area, consists of chert gravels at the base of the regolith and solution openings in the upper part of the bedrock. A ground-water divide, approximately coinciding with the Duck River-Elk River surface-water divide, underlies AAFB and extends from southwest to northeast. Ground water flows from the divide area to the discharge areas, which are the major streams, springs, lakes, and reservoirs around the base. Several troughs are present in the potentiometric surface. The most prominent trough trends northwest to southeast in the Crumpton Creek Basin. The troughs in the potentiometric surface are believed to be associated with zones of high permeability within the aquifer that are important regional flow paths. These pathways share the following characteristics: a depression or trough in the bedrock surface, a trough in the ground-water surface, low gradients in the ground-water surface, and a large spring or group of springs at the downgradient end.

In the study area, recharge occurs from direct infiltration of precipitation throughout the study area. Based on water-budget and stream base-flow data, the AAFB study area can be divided into four areas with different recharge rates. The areas are: The Barrens area along the regional drainage divide; the Spring Creek, Dry Creek (at Estill Springs), and Taylor Creek Basins in the southwestern part of the study area; Sinking Pond; and the rest of the study area.

Ground water is withdrawn at numerous locations at AAFB for two primary reasons: ground-water withdrawal wells associated with ground-water contamination and dewatering activities around below-grade testing facilities. Ground-water withdrawal wells currently (2005) are operating at SWMU 1&2, SWMU 5, SWMU 8, and SMWU 10. Dewatering activities also occur at more than 20 facilities at AEDC.

The previous ground-water flow model (1992) was updated to incorporate new data and concepts about the ground-water flow system. For the computer flow model, the Highland Rim aquifer system was divided into four layers to simulate ground-water flow. The layers were defined on the basis of differences in physical characteristics that affect hydrologic properties. Model layer 1 corresponds to the shallow aquifer. Model layer 2 corresponds to the upper part of the Manchester aquifer. Model layer 3 corresponds to the lower part of the Manchester aquifer. Model layer 4 corresponds to the Fort Payne aquifer.

Model parameters (Harbaugh and others, 2000) were defined for recharge and hydraulic-conductivity zones. The digital model developed for this study was calibrated to steady-state conditions as defined by averaging measurements from spring and fall 2002. Overall, simulated water levels agree reasonably well with observed water levels. Water-level data at 615 wells were available for comparison to simulated conditions. The root mean square error for measured compared to simulated water levels was 9.8 feet. The average head difference between measured and simulated heads is –0.47 feet. The model has seven hydraulic-conductivity parameters with calibrated values that range from 0.2 to 6,500 feet per day. The model has four recharge parameters with calibrated rates of 4.2, 7.8, 17.7, and 110 inches per year (the high value represents focused recharge at Sinking Pond). The calibrated recharge rates correspond to an average recharge rate over the entire model area of 7.6 inches per year.

Particle-tracking flow paths were analyzed from selected SWMUs. From SWMU 1&2, most of the particles (70 percent) move to the northwest under the retention pond, then move west under the air field, then follow a prominent trough in the ground-water surface to discharge to Big Spring at Rutledge Falls. Pathlines from SWMU 5 show that particles generally move west and northwest to discharge to Cat Creek, Bates Spring Branch, or seeps and springs along the Highland Rim escarpment. Pathlines from SWMU 8 show that particles move to the southeast to discharge along Spring Creek. Pathlines from SWMU 10 show that particles move to the northeast before turning south to discharge to springs along the lower reach of Bradley Creek. Under an alternate calibration of the flow model, particles from SWMU 10 diverged to show two flow paths that both discharged to springs along the lower reach of Bradley Creek. Based on a detailed review of local water levels and water-quality data, this alternate scenario is believed to be less likely than the first one presented here, but may occur periodically or seasonally.

Currently (2005), ground-water withdrawal wells are operating at SWMU 1&2, SWMU 5, SWMU 8, and SWMU 10. Particle-tracking results from these SWMUs, under conditions with the ground-water withdrawal wells pumping, show that no particles leave the SWMUs. In 2005, five new ground-water withdrawal wells along the airfield road were scheduled to begin pumping to capture ground-water contamination that has already migrated beyond the SWMU 1&2 boundaries. The airfield road ground-water withdrawal wells and the J4 test cell capture about 89 percent of the particles from SWMU 1&2. About 11 percent of the particles under this simulation discharge near Rutledge Falls.

Three particle-tracking simulations were run to analyze the effects of dewatering facilities on flow paths in the Main Test Area (MTA). These simulations illustrate that the dewatering facilities have a substantial effect on flow paths

from the MTA and are effective in containing most of the ground water in this area.

The updated ground-water flow model is consistent with all current data on the ground-water system at AAFB. The model should provide a reliable tool to assist AAFB in managing the ground-water resources at the base.

Selected References

ACS, 2002, Changes in hydraulic parameters (determined from pumping tests) from source area to the head of the groundwater flow trough: FY 2002 Solid Waste Management Unit (SWMU 8) Site WP-6 Camp Forrest Water Treatment Plant Annual Interim Measure Operational and Effectiveness Monitoring Report for Arnold Air Force Base, TN, Draft Final, June 2002: Arnold Air Force Base, Tennessee, ACS.

ATA, 2004, Groundwater flow velocity estimate in bedrock based on correlation of GWTU down-times with well 577 contaminant trends: FY2004 Solid Waste Management Unit 8 (Site WP-6, former Camp Forrest Water Treatment Plant) Annual Interim Measure Operational and Effectiveness Monitoring Report for Arnold Air Force Base, Tennessee, Final, August 2004: Arnold Air Force Base, Tennessee, ATA.

Aycock, R.A., and Haugh, C.J., 2001, Ground-water hydrology and water-quality data for wells, springs, and surface-water sites in the Bradley-Brumalow Creeks area near Arnold Air Force Base, Tennessee, September to December 1999: U.S. Geological Survey Open-File Report 01-40, 49 p.

Battelle Columbus Division, 1988, Installation Restoration Program, Phase II-Conformation/Quantification, Stage 1, Final report, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee: Columbus, Ohio, Contract no. F33615–85–D–4507, Delivery order no. 12, July 1988, 7 sections.

Battelle Columbus Division, 1989a, Installation Restoration Program, RI/FS, Stage 2, Quality assurance project plan, Arnold Engineering Development Center, Arnold Air Force Base, Tennessee: Golden, Colorado, Contract no. F33615–85–D–4507, Task order no. 18, 2 sections.

Battelle Columbus Division, 1989b, Installation Restoration Program, RI/FS, Stage 2, Work plan, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee: Golden, Colorado, USAF Contract no. F33615–85–D–4507, Delivery order no. 18, 7 sections.

Battelle Denver Operations, 1989, Installation Restoration Program, RI/FS, Stage 2, Informal technical report—Field and analytical Data, Arnold Air Force Base, Tennessee: Golden, Colorado, Contract no. F33615–85–D–4507, Delivery order no. 26, 267 p.

Benham Group, 1989a, Base comprehensive plan, 65 Percent submittal, Arnold Air Force Base, Tennessee: Contract no. F40650–88–C0014, June 5, 1989, 16 plans.

Benham Group, 1989b, Executive summary—Plan overview, 65 Percent submittal, Arnold Air Force Base, Tennessee: Contract no. F40650–88–C0014, 6 sections, 1 appendix.

Brahana, J.V., and Bradley, M.W., 1986a, Preliminary delineation and description of the regional aquifers of Tennessee—The Highland Rim aquifer system: U.S. Geological Survey Water-Resources Investigations Report 82-4054, 38 p.

Brahana, J.V., and Bradley, M.W., 1986b, Preliminary delineation and description of the regional aquifers of Tennessee—The Central Basin aquifer system: U.S. Geological Survey Water-Resources Investigations Report 82-4002, 35 p.

Burchett, C.R., 1977, Water resources of the upper Duck River Basin, central Tennessee: Tennessee Division of Water Resources, Water Resources Series no. 12, 103 p.

Burchett, C.R., and Hollyday, E.F., 1974, Tennessee's newest aquifer [abs.]: Geological Society of America Abstracts with Programs, v. 6, no. 4, p. 338.

CH2M HILL, 1999, Resource conservation and recovery act facility investigation supplement for solid waste management unit 8 at Arnold Air Force Base: Oak Ridge, Tenn., CH2M HILL.

CH2M HILL, 2001, Resource conservation and recovery act facility investigation supplement for solid waste management unit 74 at Arnold Air Force Base: Oak Ridge, Tenn., CH2M HILL.

COLOG, 2002, HydroPhysical and geophysical logging results for solid waste management unit 10 at Arnold Air Force Base, Manchester, Tennessee: Golden, Colorado, COLOG.

Dames and Moore, 1975, Groundwater investigation and foundation study Aerospace-Jet Propulsion Systems Test Facility (ASTF): Technical report, unnumbered document, September 11, 1975, 40 p.

Engineering Science, 1984, Installation restoration program, Phase I: Records search, Arnold Engineering Development Center (AEDC), Tennessee: Atlanta, Georgia, Engineering Science, consultant engineer unnumbered document, October 1984, 6 sections.

Flohr, D.F., Garrett, J.W., Hamilton, J.T., and Phillips, T.D., 2003, Water resources data—Tennessee, water year 2002: U.S. Geological Survey Water-Data Report TN-02-1, 418 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, Prentice Hall, 604 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model—user guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Haugh, C.J., 1996a, Hydrogeology of the area near the J4 test cell, Arnold Air Force Base, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 96-4182, 43 p.

Haugh, C.J., 1996b, Well-construction, water-level, and water-quality data for ground-water monitoring wells for the J4 hydrogeologic study, Arnold Air Force Base, Tennessee: U.S. Geological Survey Open-File Report 95-763, 81 p.

Haugh, C.J., and Mahoney, E.N., 1994, Hydrogeology and simulation of ground-water flow at Arnold Air Force Base, Coffee and Franklin Counties, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 93-4207, 69 p.

Haugh, C.J., Mahoney, E.N., and Robinson, J.A., 1992, Well-construction, water-level, geophysical, and water-quality data for ground-water monitoring wells for Arnold Air Force Base, Tennessee: U.S. Geological Survey Open-File Report 92-135, 88 p.

Heath, R.C., 1989, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Hill, M.C., 1998, Methods and guidelines for effective model calibration: with application to UCODE, a computer code for universal inverse modeling, and MODFLOWP, a computer code for inverse modeling with MODFLOW: U.S. Geological Survey Water-Resources Investigations Report 98-4005, 90 p.

Hill, M.C., Banta, E.R., Harbaugh, A.W., and Anderman, E.R., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model—user guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs: U.S. Geological Survey Open-File Report 00-184, 209 p.

Hoos, A.B., 1990, Recharge rates and aquifer hydraulic characteristics for selected drainage basins in Middle and East Tennessee: U.S. Geological Survey Water-Resources Investigations Report 90-4015, 34 p.

JAVA Corporation, 2000, Aerial thermography surveying—identification of potential springs phases II and III: Huntsville, Alabama, JAVA Corporation.

Mahoney, E.N., and Robinson, J.A., 1993, Altitude of the potentiometric surface in the Manchester aquifer at Arnold Air Force Base, May 1991, Coffee and Franklin Counties, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 93-4059, 1 sheet, scale 1:97,000.

McCabe, G.J., McLaughlin, J.D., and Muller, R.A., 1985, Thornwaite continuous monthly water budget: Louisiana Office of State Climatology, Climate Paper 85-1, 19 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 576 p. (586 p.)

Miller, R.A., 1974, The geologic history of Tennessee: Tennessee Division of Geology Bulletin 74, 63 p.

National Oceanic and Atmospheric Administration, 1960–2004, Climatological data annual summary, Tennessee: Asheville, N.C., National Climate Data Center, published annually.

Oak Ridge National Laboratory, 1989a, U.S. Air Force installation restoration program, phase IV, remedial design for site 10, Arnold Engineering Development Center, Tullahoma, Tennessee, Task 2.7, Baseline analytical report: Oak Ridge National Laboratory, Tennessee, Hazardous Waste Remedial Actions Program, August 1989, 6 sections, 5 appendices.

Oak Ridge National Laboratory, 1989b, U.S. Air Force installation restoration program, draft risk assessment for site 10, Arnold Engineering Development Center, Arnold Air Force Base, Tennessee: Hazardous Waste Remedial Actions Program unnumbered document, second draft, December 1989, 103 p.

Pollock, D.W., 1994, User's guide for MODPATH/MODPATH-PLOT, version 3: A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water-flow model: U.S. Geological Survey Open-File Report 94-464, 249 p.

Post, Buckley, Schuh and Jernigan, Inc., 1989a, Installation restoration program, Phase IV-A, Site 1 remedial action plan, v. 1, Arnold Air Force Base, Tennessee: Nashville, Tenn., Consultant engineer report, 6 sections, 3 appendices.

Post, Buckley, Schuh and Jernigan, Inc., 1989b, Installation restoration program, Phase IV-A, Site 1 remedial action plan, v. 2, Arnold Air Force Base, Tennessee: Nashville, Tenn., Consulting engineer report, 7 sections.

Post, Buckley, Schuh and Jernigan, Inc., 1989c, Installation restoration program, Phase IV-A, Site 1 remedial action plan, v. 3 (support documentation), Arnold Air Force Base, Tennessee: Nashville, Tenn., Consultant engineer report, 10 appendices.

Post, Buckley, Schuh and Jernigan, Inc., 1989d, Installation restoration program, Phase IV-A, Site 1, environmental assessment, Arnold Air Force Base, Tennessee: Nashville, Tenn., Consulting engineer report, 4 sections.

Post, Buckley, Schuh and Jernigan, Inc., 1989e, Draft work management plan for groundwater extraction investigation for site 1, Arnold Engineering Development Center: Nashville, Tenn., Consulting engineer report, 6 sections.

Robinson, J.A., and Haugh, C.J., 2004, Base-flow data in the Arnold Air Force Base area, Tennessee, June and October 2002: U.S. Geological Survey Open-File Report 2004-1318, 26 p.

Robinson, J.A., Hileman, G.E., and Haugh, C.J., 2005, Potentiometric surface of the Manchester Aquifer, Arnold Air Force Base, Tennessee, 2002: U.S. Geological Survey Scientific Investigations Map 2005-2882, 1 plate.

Rutledge, A.T., and Mesko, T.O., 1996, Estimated hydrologic characteristics of shallow aquifer systems in the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces based on analysis of streamflow recession and base flow: U.S. Geological Survey Professional Paper 1422-B, 58 p.

Science Applications International Corporation, 1990, Installation restoration program, remedial investigation/feasibility study, stage 2, technical report draft, Arnold Air Force Base, Tennessee: Golden, Colo., Contract no. F33615–85–D–4543, task order no. 6, 3 v., 5 sections, 11 appendices.

U.S. Army Corps of Engineers, Mobile District, 1988a, Final foundation report, FY-89 PCD ANZY870198 Large Rocket Test Facility (J-6), Arnold Engineering Development Center, Air Force Systems Command, Arnold Air Force Station, Tennessee: U.S. Army Corps of Engineers, 94 p., 19 plates.

U.S. Army Corps of Engineers, Mobile District, 1988b, Final foundation report, FY-89 PCD ANZY870198 Large Rocket Test Facility (J-6), Appendix A, Arnold Engineering Development Center, Air Force Systems Command, Arnold Air Force Station, Tennessee: U.S. Army Corps of Engineers, 309 p.

Williams, S.D., 2003, Ground-water levels and water-quality data for wells in the Crumpton Creek area near Arnold Air Force Base, Tennessee, November 2001 to January 2002: U.S. Geological Survey Water-Resources Investigations Report 03-4175, 28 p.

Williams, S.D., and Aycock, R.A., 2001, Ground-water levels and water-quality data for wells in the Spring Creek area near Arnold Air Force Base, Tennessee, April and May 2000: U.S. Geological Survey Open-File Report 01-150, 16 p.

Williams, S.D., and Farmer, J.J., 2003, Volatile organic compound data from three karst springs in Middle Tennessee, February 2000 to May 2001: U.S. Geological Survey Open-File Report 03-355, 69 p.

Wilson, C.W., Jr., 1976, Geologic map and mineral resources summary of the Manchester quadrangle, Tennessee: Tennessee Division of Geology, MRS 86-NE, scale 1:24,000.

Wolfe, W.J., 1996, Hydrology and tree-distribution patterns of karst wetlands at Arnold Engineering Development Center, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 96-4277, 46 p.

Wolfe, W.J., Evans, J.P., McCarthy, Sarah, Gain, W.S., and Bryan, B.A., 2004, Tree-regeneration and mortality patterns and hydrologic change in a forested karst wetland—Sinking Pond, Arnold Air Force Base, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 03-4217, 53 p.

Wolfe, W.J., and League, D.E., 1996, Water-surface elevations of wetlands and nearby wells at Arnold Air Force Base, near Manchester, Tennessee: U.S. Geological Survey Open-File Report 95-753, 19 p.

Wolock, D.M., 2003a, Base-flow index grid for the conterminous United States: U.S. Geological Survey Open-File Report 03-263, digital dataset, accessed May 22, 2006, at *http://water.usgs.gov/lookup/getspatial?bfi48grd*

Wolock, D.M., 2003b, Flow characteristics at U.S. Geological Survey streamgages in the conterminous United States: U.S. Geological Survey Open-File Report 03-146, digital dataset, accessed May 22, 2006, at *http://water.usgs.gov/lookup/getspatial?qsitesdd*

Wolock, D.M., 2003c, Estimated mean annual natural groundwater recharge in the conterminous United States: U.S. Geological Survey Open-File Report 03-111, digital dataset, accessed May 22, 2006, at *http://water.usgs.gov/lookup/getspatial?rech48grd*

Woodward-Clyde Consultants, 1990, Ground water extraction investigation report, Hazardous waste site No. 1, Arnold Engineering Development Center, Arnold Air Force Base, Tullahoma, Tennessee: Consulting engineer report, September 28, 1990, 7 sections, 7 appendices.

Appendix

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
MW-1	1076.41	1072.43	1074.42	1071.11	3.31
MW-2	1070.48	1066.47	1068.47	1067.20	1.27
MW-9	1084.39	1083.62	1084.01	1079.76	4.25
MW-10	1085.05	1081.04	1083.05	1079.65	3.40
MW-22	1067.08	1055.05	1061.07	1065.05	–3.98
MW-24	1075.00	1063.50	1069.25	1065.75	3.50
MW-25	1064.01	1055.51	1059.76	1066.05	–6.29
MW-27	1073.14	1064.58	1068.86	1063.75	5.12
MW-28	1073.18	1067.89	1070.54	1063.79	6.75
MW-29	1069.25	1049.64	1059.44	1063.17	–3.73
MW-30	1062.89	1060.11	1061.50	1067.85	–6.35
MW-31	1035.59	1033.39	1034.49	1057.69	–23.20
MW-32	1065.00	1055.13	1060.07	1065.00	–4.93
MW-64	1040.28	1037.13	1038.70	1059.06	–20.36
MW-72	1060.69	1055.12	1057.91	1051.86	6.05
MW-75	1057.71	1052.15	1054.93	1047.84	7.09
MW-76	1036.52	1024.87	1030.69	1030.32	0.37
MW-78	1045.30	1034.55	1039.93	1033.48	6.45
MW-80	1032.53	1023.67	1028.10	1031.66	–3.56
MW-81	1064.59	1067.11	1065.85	1067.88	–2.03
MW-82	1078.65	1078.09	1078.37	1075.74	2.63
MW-83	1084.68	1081.70	1083.19	1073.38	9.81
MW-84	1081.23	1079.95	1080.59	1072.35	8.24
MW-85	1084.28	1083.60	1083.94	1072.10	11.84
MW-86	1097.50	1087.99	1092.74	1087.65	5.09
MW-91	1047.51	1043.25	1045.38	1065.44	–20.06
MW-92	1061.63	1054.43	1058.03	1065.51	–7.48
MW-93	1067.78	1060.81	1064.30	1066.34	–2.04
MW-96	1071.27	1065.20	1068.23	1066.00	2.24
MW-97	1067.98	1060.51	1064.24	1066.01	–1.77
MW-98	1059.48	1049.41	1054.44	1058.99	–4.55
MW-99	1055.84	1046.19	1051.02	1061.50	–10.48
MW-102	1074.09	1064.96	1069.53	1064.14	5.39
MW-103	1077.54	1066.24	1071.89	1064.71	7.18

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
MW-104	1076.27	1065.28	1070.78	1064.73	6.05
MW-105	1071.87	1059.69	1065.78	1064.10	1.68
MW-106	1075.91	1067.27	1071.59	1064.98	6.61
MW-107	1078.76	1067.85	1073.31	1065.48	7.83
MW-108	1077.44	1067.55	1072.49	1064.86	7.63
MW-109	1074.44	1064.15	1069.30	1064.87	4.43
MW-110	1058.24	1047.47	1052.86	1064.22	–11.36
MW-111	1072.17	1063.93	1068.05	1063.60	4.45
MW-112	1072.69	1064.03	1068.36	1063.62	4.74
MW-113	1069.86	1058.89	1064.38	1062.98	1.40
MW-114	1071.87	1063.25	1067.56	1062.90	4.66
MW-116	1072.69	1063.08	1067.89	1063.82	4.08
MW-117	1073.50	1064.30	1068.90	1063.94	4.96
MW-118	1069.02	1058.26	1063.64	1064.60	–0.96
MW-119	1069.24	1057.74	1063.49	1062.86	0.63
MW-120	1072.16	1060.95	1066.56	1064.88	1.68
MW-121	1073.59	1064.78	1069.18	1063.47	5.71
MW-122	1069.88	1060.28	1065.08	1063.11	1.97
MW-132	1065.80	1056.30	1061.05	1061.12	–0.07
MW-134	1033.24	1021.98	1027.61	1030.42	–2.81
MW-135	1031.14	1020.18	1025.66	1030.47	–4.81
MW-137	1038.76	1032.14	1035.45	1036.53	–1.08
MW-138	1052.38	1037.04	1044.71	1039.38	5.33
MW-139	1056.90	1050.08	1053.49	1042.32	11.17
MW-140	1050.11	1036.52	1043.32	1042.08	1.24
MW-141	1050.14	1036.52	1043.33	1042.14	1.19
MW-143	1062.43	1057.00	1059.71	1047.85	11.87
MW-144	1058.08	1051.35	1054.71	1048.02	6.69
MW-145	1055.07	1055.21	1055.14	1048.48	6.66
MW-146	1049.30	1044.46	1046.88	1034.29	12.59
MW-147	1044.56	1039.33	1041.94	1033.57	8.37
MW-148	1038.27	1032.65	1035.46	1037.76	–2.30
MW-149	1023.77	1019.31	1021.54	1036.78	–15.24
MW-150	1022.72	1018.04	1020.38	1014.41	5.97

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
MW-151	1036.66	1027.81	1032.23	1030.03	2.20
MW-152	1022.64	1017.89	1020.27	1017.23	3.04
MW-153	1021.79	1016.75	1019.27	1016.53	2.74
MW-154	1046.68	1043.68	1045.18	1066.39	–21.21
MW-155	1063.82	1060.34	1062.08	1061.88	0.20
MW-156	1079.06	1077.25	1078.16	1075.95	2.21
MW-157	1063.33	1060.09	1061.71	1075.25	–13.54
MW-158	1079.63	1077.33	1078.48	1072.95	5.53
MW-159	1077.85	1074.50	1076.18	1072.38	3.81
MW-160	1079.12	1077.71	1078.42	1072.16	6.26
MW-161	1079.02	1077.61	1078.32	1072.36	5.96
MW-162	1079.65	1078.03	1078.84	1072.46	6.38
MW-163	1077.87	1075.84	1076.86	1072.22	4.64
MW-164	1086.90	1081.91	1084.41	1087.12	–2.71
MW-165	1087.90	1082.94	1085.42	1085.94	–0.52
MW-171	1072.73	1060.57	1066.65	1069.05	–2.40
MW-173	972.02	969.03	970.53	984.59	–14.07
MW-174	968.59	964.60	966.60	986.76	–20.16
MW-177	1078.74	1055.38	1067.06	1049.40	17.66
MW-179	1046.76	1035.78	1041.27	1042.36	–1.09
MW-181	1005.89	997.29	1001.59	1008.90	–7.30
MW-182	1006.05	996.67	1001.36	1008.67	–7.31
MW-183	1007.70	997.91	1002.80	1008.92	–6.12
MW-185	1071.02	1060.92	1065.97	1082.98	–17.01
MW-186	1095.99	1080.52	1088.26	1087.97	0.29
MW-188	972.94	971.14	972.04	977.43	–5.39
MW-189	973.72	971.05	972.39	973.57	–1.19
MW-190	948.06	942.08	945.07	952.43	–7.36
MW-191	949.34	935.25	942.30	952.72	–10.43
MW-194	1005.29	998.34	1001.82	1011.60	–9.78
MW-195	1018.98	1007.40	1013.19	1006.94	6.25
MW-196	1045.66	1045.36	1045.51	1051.66	–6.14
MW-197	1055.62	1040.37	1047.99	1051.79	–3.80
MW-198	1045.33	1029.96	1037.65	1041.94	–4.29

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
MW-199	1045.48	1030.67	1038.08	1042.41	–4.33
MW-200	1064.23	1045.14	1054.68	1053.88	0.80
MW-201	1064.31	1045.14	1054.72	1054.03	0.69
MW-202	963.51	960.33	961.92	975.12	–13.20
MW-203	963.65	959.81	961.73	975.25	–13.52
MW-213	1050.94	1029.26	1040.10	1037.78	2.32
MW-214	996.28	986.48	991.38	994.24	–2.86
MW-215	1068.87	1047.94	1058.41	1058.60	–0.19
MW-216	1031.98	1014.21	1023.10	1017.20	5.90
MW-217	1046.17	1043.88	1045.03	1061.69	–16.66
MW-218	1078.02	1067.18	1072.60	1061.76	10.84
MW-219	1051.87	1035.59	1043.73	1040.38	3.35
MW-221	1016.00	1007.54	1011.77	995.11	16.66
MW-222	989.61	981.05	985.33	1002.99	–17.66
MW-223	1000.97	992.75	996.86	1011.38	–14.52
MW-224	1064.00	1057.05	1060.53	1036.65	23.88
MW-225	1001.35	998.24	999.80	991.51	8.29
MW-226	1027.11	1020.00	1023.55	1017.11	6.44
MW-227	1027.12	1016.07	1021.60	1009.77	11.83
MW-228	966.98	964.14	965.56	988.52	–22.96
MW-230	1015.57	1010.16	1012.87	1012.36	0.51
MW-231	1027.31	1011.86	1019.59	1036.62	–17.03
MW-232	1031.08	1025.82	1028.45	1040.97	–12.52
MW-236	953.08	946.45	949.77	953.93	–4.17
MW-238	1033.45	1025.71	1029.58	1033.66	–4.08
MW-241	1033.30	1025.45	1029.38	1033.23	–3.85
MW-243	1034.52	1026.95	1030.73	1033.83	–3.10
MW-244	1034.70	1026.29	1030.49	1033.80	–3.31
MW-245	1031.02	1022.90	1026.96	1031.24	–4.28
MW-247	1022.55	1015.78	1019.17	1028.69	–9.52
MW-248	1007.43	1008.89	1008.16	1028.72	–20.56
MW-249	1050.29	1036.78	1043.54	1042.26	1.28
MW-250	1050.51	1036.92	1043.71	1042.28	1.43
MW-251	1050.50	1036.91	1043.70	1042.23	1.47

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
MW-252	1052.87	1041.02	1046.94	1042.54	4.40
MW-253	1050.52	1036.90	1043.71	1042.21	1.50
MW-258	1030.01	1022.59	1026.30	1033.75	–7.45
MW-259	1028.07	1027.27	1027.67	1033.90	–6.23
MW-260	1034.51	1027.41	1030.96	1033.88	–2.92
MW-261	1033.83	1025.22	1029.53	1033.79	–4.26
MW-262	1039.88	1038.75	1039.32	1033.96	5.36
MW-263	1042.20	1042.22	1042.21	1034.48	7.73
MW-269	1047.34	1043.00	1045.17	1060.52	–15.35
MW-270	1066.06	1059.70	1062.88	1062.49	0.39
MW-271	1071.90	1064.78	1068.34	1063.62	4.72
MW-272	1045.24	1038.78	1042.01	1056.92	–14.91
MW-273	1033.04	1026.97	1030.01	1057.59	–27.58
MW-274	1054.29	1046.95	1050.62	1057.56	–6.94
MW-275	1072.37	1062.90	1067.64	1061.81	5.83
MW-276	1079.92	1075.73	1077.83	1071.72	6.11
MW-278	1064.56	1058.26	1061.41	1065.59	–4.18
MW-279	1059.21	1054.22	1056.71	1067.28	–10.57
MW-280	1070.71	1065.89	1068.30	1070.31	–2.01
MW-282	1055.94	1049.24	1052.59	1061.09	–8.50
MW-283	1066.78	1059.27	1063.03	1061.12	1.91
MW-284	1075.16	1068.32	1071.74	1061.80	9.94
MW-285	1068.59	1057.18	1062.89	1063.79	–0.90
MW-286	1072.98	1062.26	1067.62	1063.91	3.71
MW-287	1077.94	1067.93	1072.93	1064.63	8.30
MW-288	1072.18	1058.59	1065.39	1068.25	–2.86
MW-289	1072.29	1058.52	1065.41	1068.30	–2.89
MW-290	1075.25	1066.37	1070.81	1069.07	1.74
MW-291	1064.95	1036.94	1050.94	1069.64	–18.70
MW-292	1072.44	1058.94	1065.69	1070.47	–4.78
MW-293	1074.17	1064.48	1069.33	1070.45	–1.12
MW-299	1058.21	1049.99	1054.10	1066.18	–12.08
MW-300	1057.38	1048.78	1053.08	1066.08	–13.00
MW-301	1056.43	1046.83	1051.63	1055.45	–3.82

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
MW-302	1055.79	1046.49	1051.14	1054.75	–3.61
MW-303	1062.86	1053.35	1058.11	1055.83	2.28
MW-304	1058.33	1048.82	1053.58	1059.53	–5.95
MW-305	1058.32	1048.78	1053.55	1059.49	–5.94
MW-306	1065.59	1060.17	1062.88	1060.30	2.58
MW-307	1063.46	1059.99	1061.72	1063.76	–2.04
MW-308	1064.78	1059.24	1062.01	1066.47	–4.46
MW-310	1070.50	1067.06	1068.78	1067.61	1.17
MW-311	1074.72	1068.83	1071.78	1064.86	6.92
MW-312	1034.20	1025.74	1029.97	1027.67	2.30
MW-314	1050.78	1048.05	1049.42	1063.39	–13.97
MW-315	1055.01	1047.73	1051.37	1065.99	–14.62
MW-316	1054.21	1050.64	1052.43	1065.78	–13.35
MW-317	1059.47	1051.82	1055.65	1067.55	–11.90
MW-319	1044.28	1043.98	1044.13	1062.13	–18.00
MW-321	1066.26	1061.31	1063.79	1068.27	–4.48
MW-322	1069.31	1051.90	1060.61	1068.27	–7.66
MW-324	1082.96	1079.78	1081.37	1071.86	9.51
MW-325	1084.93	1082.45	1083.69	1073.98	9.71
MW-327	1085.08	1082.05	1083.57	1076.65	6.92
MW-330	1071.94	1059.68	1065.81	1065.26	0.55
MW-331	1072.27	1060.97	1066.62	1065.26	1.36
MW-332	1073.91	1060.49	1067.20	1064.06	3.14
MW-333	1070.62	1059.30	1064.96	1063.16	1.80
MW-334	1070.86	1059.14	1065.00	1063.54	1.46
MW-335	1070.23	1058.52	1064.38	1063.56	0.82
MW-336	1079.95	1065.57	1072.76	1065.80	6.96
MW-342	1019.84	1010.33	1015.09	1003.79	11.30
MW-343	1062.11	1046.21	1054.16	1031.79	22.37
MW-344	1032.68	1024.37	1028.53	1031.74	–3.21
MW-345	1022.94	1015.61	1019.28	1028.37	–9.09
MW-347	1046.71	1046.41	1046.56	1033.91	12.65
MW-353	1068.06	1040.76	1054.41	1048.20	6.21
MW-354	1066.47	1045.45	1055.96	1048.23	7.73

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
MW-355	1064.60	1037.40	1051.00	1049.44	1.56
MW-356	1066.15	1040.57	1053.36	1055.82	–2.46
MW-357	1055.44	1046.08	1050.76	1052.15	–1.39
MW-358	1070.86	1047.45	1059.16	1057.60	1.56
MW-359	1066.67	1040.22	1053.44	1057.60	–4.16
MW-364	1069.53	1061.17	1065.35	1066.43	–1.08
MW-365	1062.41	1055.44	1058.93	1065.78	–6.85
MW-366	1061.46	1054.11	1057.79	1065.72	–7.92
MW-367	1064.97	1058.11	1061.54	1066.04	–4.50
MW-368	1069.79	1059.91	1064.85	1062.30	2.55
MW-369	1069.15	1054.54	1061.85	1062.50	–0.65
MW-370	1069.12	1057.94	1063.53	1063.77	–0.24
MW-371	1037.71	1030.25	1033.98	1035.99	–2.01
MW-372	1043.03	1043.79	1043.41	1036.08	7.33
MW-373	1033.70	1024.51	1029.11	1032.55	–3.44
MW-374	1029.79	1020.14	1024.96	1032.40	–7.44
MW-375	1033.42	1023.35	1028.39	1030.64	–2.25
MW-381	1063.69	1058.04	1060.87	1054.81	6.06
MW-382	1060.42	1054.92	1057.67	1041.51	16.17
MW-384	1059.38	1057.47	1058.43	1052.45	5.98
MW-387	1037.34	1031.98	1034.66	1028.44	6.22
MW-388	1021.38	1016.93	1019.16	1005.57	13.59
MW-389	1023.78	1019.17	1021.48	1027.79	–6.31
MW-390	1004.60	1000.77	1002.68	994.38	8.30
MW-391	996.64	994.73	995.69	995.31	0.37
MW-392	1022.16	1017.16	1019.66	1002.42	17.24
MW-393	1023.15	1017.95	1020.55	1001.11	19.44
MW-395	970.43	964.63	967.53	973.66	–6.13
MW-397	950.70	943.88	947.29	953.90	–6.61
MW-398	971.78	968.06	969.92	962.79	7.13
MW-403	1072.07	1059.23	1065.65	1068.74	–3.09
MW-404	1071.05	1059.38	1065.21	1070.12	–4.91
MW-411	1071.13	1056.74	1063.93	1068.07	–4.14
MW-412	1069.41	1051.75	1060.58	1067.41	–6.83

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
MW-413	1069.23	1051.34	1060.29	1068.35	–8.06
MW-419	1072.25	1058.51	1065.38	1067.93	–2.55
MW-420	1069.61	1052.73	1061.17	1067.19	–6.02
MW-421	1068.99	1050.92	1059.95	1068.15	–8.20
MW-422	1080.07	1079.29	1079.68	1075.16	4.52
MW-428	1054.51	1031.16	1042.84	1046.19	–3.35
MW-429	947.73	941.13	944.43	951.94	–7.51
MW-430	953.13	945.56	949.35	954.60	–5.25
MW-431	949.92	943.13	946.53	953.94	–7.42
MW-432	962.60	958.36	960.48	953.81	6.67
MW-435	943.90	937.98	940.94	954.83	–13.89
MW-436	944.07	938.13	941.10	954.73	–13.63
MW-437	949.31	942.55	945.93	952.99	–7.06
MW-438	946.64	939.71	943.18	950.64	–7.46
MW-439	957.98	952.96	955.47	960.78	–5.31
MW-440	953.18	948.58	950.88	951.73	–0.85
MW-441	1022.03	1017.69	1019.86	1010.79	9.07
MW-442	948.56	942.01	945.29	952.21	–6.93
MW-443	959.39	947.06	953.23	957.39	–4.17
MW-444	961.99	948.30	955.15	957.53	–2.38
MW-445	947.98	941.39	944.69	951.10	–6.42
MW-446	941.41	939.81	940.61	951.09	–10.48
MW-447	948.04	939.85	943.95	951.10	–7.15
MW-448	948.08	941.33	944.71	951.10	–6.40
MW-449	937.12	937.65	937.39	951.11	–13.72
MW-450	1042.78	1025.97	1034.38	1017.36	17.02
MW-451	1045.05	1026.19	1035.62	1033.94	1.68
MW-452	1069.24	1050.81	1060.03	1067.10	–7.07
MW-453	1058.48	1048.76	1053.62	1056.62	–3.00
MW-454	1074.15	1059.17	1066.66	1065.90	0.76
MW-455	1069.26	1051.06	1060.16	1065.92	–5.76
MW-456	1045.35	1043.68	1044.52	1062.17	–17.65
MW-457	1057.88	1048.32	1053.10	1060.79	–7.69
MW-458	1059.77	1051.90	1055.84	1063.91	–8.07

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
MW-460	1056.36	1046.91	1051.64	1051.46	0.18
MW-461	1039.57	1021.40	1030.48	1018.09	12.39
MW-462	1000.90	990.19	995.55	1008.12	–12.58
MW-463	1058.21	1036.54	1047.38	1032.72	14.66
MW-464	1026.83	1010.56	1018.70	1017.75	0.95
MW-467	1006.28	994.77	1000.53	1019.16	–18.63
MW-468	1001.99	991.97	996.98	998.42	–1.44
MW-469	1001.97	991.46	996.72	998.42	–1.70
MW-470	1071.16	1068.14	1069.65	1072.19	–2.54
MW-471	1046.91	1026.71	1036.81	1025.90	10.91
MW-472	1012.50	998.78	1005.64	1015.35	–9.71
MW-473	1067.98	1048.52	1058.25	1056.51	1.74
MW-474	1001.95	991.39	996.67	998.45	–1.78
MW-475	1078.16	1059.44	1068.80	1066.62	2.18
MW-476	1080.04	1075.99	1078.02	1072.43	5.59
MW-481	1058.13	1047.86	1052.99	1057.23	–4.24
MW-487	1088.17	1078.89	1083.53	1074.92	8.61
MW-488	1053.69	1028.56	1041.13	1040.58	0.55
MW-490	937.77	935.86	936.82	947.43	–10.61
MW-491	937.44	935.37	936.41	947.52	–11.12
MW-492	936.47	935.69	936.08	947.43	–11.35
MW-494	1059.99	1049.13	1054.56	1058.13	–3.57
MW-495	1022.12	1017.20	1019.66	1008.62	11.04
MW-496	1022.23	1017.25	1019.74	1011.89	7.85
MW-497	1022.12	1017.88	1020.00	1018.55	1.45
MW-498	1082.55	1080.14	1081.35	1073.34	8.01
MW-499	1008.06	997.96	1003.01	996.56	6.45
MW-501	1057.43	1037.86	1047.65	1034.16	13.49
MW-502	1062.92	1043.14	1053.03	1040.83	12.20
MW-503	1007.68	998.21	1002.95	997.01	5.94
MW-504	1057.40	1047.08	1052.24	1044.92	7.32
MW-505	1055.86	1046.68	1051.27	1044.86	6.41
MW-506	1057.45	1037.81	1047.63	1034.17	13.46
MW-507	1057.44	1037.82	1047.63	1034.29	13.34

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
MW-508	1057.42	1037.82	1047.62	1034.32	13.30
MW-509	1057.41	1037.80	1047.61	1034.32	13.29
MW-510	1057.45	1037.66	1047.56	1034.80	12.76
MW-518	1069.14	1050.67	1059.91	1067.13	–7.22
MW-519	1069.16	1050.63	1059.90	1067.15	–7.25
MW-520	1069.16	1050.64	1059.90	1067.16	–7.26
MW-524	1001.59	991.07	996.33	998.31	–1.98
MW-525	1002.24	991.86	997.05	998.66	–1.61
MW-551	1057.58	1047.67	1052.63	1056.66	–4.03
MW-553	1033.93	1025.83	1029.88	1032.81	–2.93
MW-555	1035.47	1027.21	1031.34	1033.85	–2.51
MW-557	1036.64	1028.93	1032.79	1034.44	–1.65
MW-559	1000.11	990.88	995.50	994.50	1.00
MW-560	1016.85	1008.33	1012.59	1000.07	12.52
MW-561	1017.41	1007.79	1012.60	999.53	13.07
MW-562	996.53	987.01	991.77	996.27	–4.50
MW-563	997.66	989.90	993.78	996.22	–2.44
MW-564	1040.85	1033.06	1036.95	1037.78	–0.83
MW-567	1039.34	1031.71	1035.53	1036.76	–1.23
MW-569	1043.22	1034.73	1038.97	1039.56	–0.59
MW-570	1043.18	1035.45	1039.32	1039.77	–0.45
MW-571	1048.65	1036.89	1042.77	1041.78	0.99
MW-572	1049.36	1038.21	1043.79	1042.05	1.74
MW-573	1036.66	1029.62	1033.14	1035.41	–2.27
MW-574	1034.55	1026.18	1030.37	1033.65	–3.28
MW-575	1032.66	1022.81	1027.73	1032.83	–5.10
MW-576	1036.49	1035.53	1036.01	1032.93	3.08
MW-577	947.98	941.32	944.65	951.06	–6.41
MW-578	1034.97	1027.44	1031.20	1034.38	–3.18
MW-580	937.52	933.32	935.42	946.98	–11.56
MW-581	941.46	935.39	938.43	947.36	–8.94
MW-582	937.51	936.33	936.92	947.36	–10.44
MW-583	953.87	946.54	950.21	957.34	–7.13
MW-584	972.99	969.52	971.26	975.15	–3.90

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
MW-585	972.06	968.36	970.21	972.07	–1.86
MW-586	1023.68	1018.36	1021.02	1016.72	4.30
MW-588	959.74	955.20	957.47	963.42	–5.95
MW-589	1071.41	1061.48	1066.44	1066.77	–0.33
MW-591	1085.86	1082.81	1084.34	1078.57	5.77
MW-592	1084.55	1082.55	1083.55	1077.98	5.57
MW-594	1079.86	1078.82	1079.34	1072.65	6.69
MW-596	1080.31	1078.96	1079.64	1072.91	6.73
MW-597	1048.79	1046.85	1047.82	1061.62	–13.80
MW-598	1069.13	1057.74	1063.43	1063.25	0.18
MW-599	1056.31	1048.90	1052.61	1066.93	–14.32
MW-600	1056.47	1048.99	1052.73	1066.96	–14.23
MW-601	1006.29	996.41	1001.35	985.52	15.83
MW-602	1007.21	998.66	1002.93	985.41	17.52
MW-603	972.17	971.46	971.82	982.76	–10.94
MW-604	974.99	968.98	971.99	982.37	–10.39
MW-605	974.15	971.11	972.63	983.21	–10.58
MW-606	971.45	966.10	968.78	983.14	–14.37
MW-607	998.40	992.99	995.70	994.92	0.77
MW-608	982.08	975.29	978.69	989.31	–10.62
MW-609	1008.27	1007.01	1007.64	996.12	11.52
MW-610	1000.98	999.99	1000.49	996.14	4.35
MW-611	1026.44	1021.78	1024.11	1009.05	15.06
MW-612	979.38	973.83	976.61	988.30	–11.70
MW-613	995.22	990.08	992.65	983.80	8.85
MW-614	1022.55	1008.91	1015.73	997.56	18.17
MW-615	1044.04	1014.59	1029.32	1031.62	–2.30
MW-616	1051.73	1032.91	1042.32	1039.21	3.11
MW-617	1051.78	1034.34	1043.06	1041.17	1.89
MW-618	1086.51	1082.37	1084.44	1084.45	–0.01
MW-619	1086.10	1082.62	1084.36	1083.59	0.77
MW-620	1009.38	1000.06	1004.72	1028.54	–23.82
MW-621	987.78	982.80	985.29	979.08	6.21
MW-622	1031.27	1020.82	1026.05	1030.22	–4.17

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
MW-623	1077.69	1076.26	1076.97	1072.54	4.43
MW-624	1079.28	1077.51	1078.40	1072.83	5.57
MW-625	1086.04	1082.06	1084.05	1080.61	3.44
MW-626	1085.32	1082.08	1083.70	1078.84	4.86
MW-628	1043.50	1035.03	1039.27	1040.05	–0.78
MW-629	1044.05	1036.08	1040.07	1040.27	–0.20
MW-630	1043.97	1036.62	1040.30	1040.27	0.03
MW-632	1039.35	1032.01	1035.68	1035.73	–0.05
MW-633	1040.24	1037.05	1038.65	1035.86	2.80
MW-635	1061.49	1055.98	1058.73	1067.22	–8.49
MW-636	1052.59	1035.59	1044.09	1041.41	2.68
MW-642	1085.31	1082.20	1083.76	1077.33	6.43
MW-643LD	1051.03	1048.87	1049.95	1059.56	–9.61
MW-643UD	1058.42	1049.97	1054.19	1059.65	–5.46
MW-644LD	1045.45	1039.31	1042.38	1059.31	–16.93
MW-644UD	1057.91	1048.69	1053.30	1059.39	–6.09
MW-645LD	1044.88	1048.11	1046.49	1059.85	–13.36
MW-645UD	1058.45	1048.17	1053.31	1059.85	–6.54
MW-646LD	1043.47	1038.07	1040.77	1060.11	–19.34
MW-646UD	1056.72	1048.51	1052.62	1060.11	–7.49
MW-647	1030.76	1013.56	1022.16	1017.52	4.64
MW-648	1053.31	1028.57	1040.94	1040.59	0.35
MW-649	1054.88	1031.15	1043.02	1046.12	–3.10
MW-650	1050.47	1030.23	1040.35	1045.90	–5.55
MW-651	1070.22	1055.10	1062.66	1062.31	0.35
MW-652	1070.31	1055.16	1062.73	1062.53	0.20
MW-653	1057.72	1038.13	1047.93	1061.51	–13.58
MW-654	1069.01	1050.37	1059.69	1061.52	–1.83
MW-655	1052.75	1036.38	1044.57	1045.82	–1.25
MW-656			1059.46	1056.44	3.02
MW-656LD	1069.02	1049.73	1058.92	1056.46	2.46
MW-657	1069.15	1050.05	1059.60	1065.11	–5.51
MW-658	1069.10	1050.00	1059.55	1065.13	–5.58
MW-659	1030.59	1026.23	1028.41	1015.98	12.43

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
MW-559A	1000.18	990.37	995.28	994.50	0.78
MW-660	1062.50	1053.98	1058.24	1065.94	–7.70
MW-661	1065.25	1051.63	1058.44	1061.47	–3.03
MW-662	1062.33	1055.95	1059.14	1064.52	–5.38
MW-665	1069.10	1050.16	1059.63	1064.56	–4.93
MW-666	1070.81	1066.19	1068.50	1067.38	1.12
MW-667	1070.77	1066.16	1068.46	1067.40	1.06
MW-668	1070.87	1068.35	1069.61	1068.03	1.58
MW-669	1073.22	1064.70	1068.96	1065.77	3.19
MW-670	1075.25	1066.43	1070.84	1066.73	4.11
MW-671	1076.11	1069.13	1072.62	1064.13	8.49
MW-672	1071.74	1065.74	1068.74	1066.91	1.83
MW-674	1071.85	1062.90	1067.38	1065.07	2.31
MW-675	1071.47	1062.52	1066.99	1065.05	1.94
MW-676	1071.63	1062.19	1066.91	1065.84	1.07
MW-677	1050.55	1030.61	1040.58	1051.89	–11.31
MW-678	1050.54	1030.61	1040.58	1051.89	–11.31
MW-679	1074.03	1071.11	1072.57	1074.31	–1.74
MW-680	1073.43	1070.64	1072.04	1074.59	–2.55
MW-681	1091.57	1081.26	1086.42	1087.87	–1.45
MW-682	1092.01	1081.75	1086.88	1087.77	–0.89
MW-683	1090.22	1078.93	1084.58	1086.94	–2.36
MW-684	1087.58	1077.39	1082.48	1086.74	–4.26
MW-685	1084.64	1076.66	1080.65	1092.47	–11.82
MW-686	1084.81	1076.87	1080.84	1092.43	–11.59
MW-687	1077.76	1070.29	1074.03	1086.17	–12.14
MW-688	1078.10	1070.47	1074.29	1086.86	–12.57
MW-689	1085.06	1078.39	1081.72	1086.78	–5.06
MW-690	1077.79	1070.33	1074.06	1086.61	–12.55
MW-691	1081.87	1076.24	1079.06	1086.70	–7.64
MW-698	1039.29	1021.87	1030.58	1034.61	–4.03
MW-699	1045.88	1039.55	1042.71	1035.10	7.61
MW-700	1014.36	1001.18	1007.77	1009.97	–2.20
MW-701	1006.86	994.94	1000.90	1011.10	–10.20

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
MW-702	1056.77	1051.17	1053.97	1048.51	5.46
19_LF2_MW_01	969.37	965.38	967.38	966.53	0.84
19_LF2_MW_04	1005.85	986.10	995.98	977.70	18.27
19_LF2_MW_06	1000.79	990.07	995.43	982.53	12.90
JAR-002	1106.30	1092.21	1099.26	1091.69	7.57
JAR-003	1084.85	1081.82	1083.34	1082.57	0.77
PZ_22_1a	1006.08	997.78	1001.93	993.56	8.37
PZ_22_2	1005.22	995.59	1000.41	991.76	8.65
PZ_22_3	1003.61	994.74	999.18	993.55	5.62
PZ-BKG-1	1061.16	1039.64	1050.40	1044.31	6.09
SSB7-PZ	1061.07	1045.55	1053.31	1041.13	12.18
UTSI-3	982.31	975.82	979.07	964.15	14.92
UTSI-5	982.39	977.04	979.72	963.52	16.20
UTSI-6	983.48	979.58	981.53	963.75	17.78
A-002	992.09	986.19	989.14	989.54	–0.40
A-003	1011.28	1002.32	1006.80	989.95	16.85
A-010	1065.36	1056.33	1060.85	1044.49	16.36
A-013	972.97	962.74	967.86	987.09	–19.24
A-016	961.71	959.30	960.51	960.65	–0.14
A-021	970.29	967.48	968.89	969.56	–0.68
A-030	1017.64	1007.71	1012.68	1003.83	8.85
A-031	1039.58	1025.74	1032.66	1010.39	22.28
A-034	1040.90	1038.07	1039.48	1044.59	–5.11
B-001	1024.62	1018.18	1021.40	999.85	21.55
B-002	1023.60	991.91	1007.76	1006.42	1.34
B-005	1043.00	1026.04	1034.52	1018.03	16.49
B-006	1028.14	1019.30	1023.72	1028.50	–4.78
B-011	999.66	991.18	995.42	993.28	2.14
B-014	1031.50	1020.35	1025.93	1015.00	10.93
B-015	992.96	988.18	990.57	994.35	–3.78
B-018	1021.38	1015.11	1018.25	1007.33	10.93
B-019	965.20	962.41	963.81	980.66	–16.85
B-022	1012.49	988.50	1000.50	1005.41	–4.91
B-023	1011.91	1006.71	1009.31	1014.14	–4.83

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
B-031	1034.23	1022.10	1028.17	1007.52	20.65
B-034	1090.59	1073.30	1081.94	1056.05	25.89
B-038	1044.95	1036.80	1040.88	1025.32	15.56
B-039	964.00	961.43	962.72	975.44	–12.73
C-001	1010.92	1000.28	1005.60	985.22	20.38
C-002	1021.10	1015.39	1018.25	1002.18	16.07
C-003	1024.85	1015.46	1020.16	1019.15	1.01
C-009	1016.80	1006.05	1011.43	997.67	13.76
C-012	1047.90	1036.66	1042.28	1013.37	28.91
C-015	986.55	981.21	983.88	983.44	0.44
C-016	991.84	984.53	988.19	982.30	5.89
C-023	1030.55	1019.69	1025.12	1005.84	19.28
C-025	1023.62	1011.58	1017.60	1011.51	6.10
C-026	1056.46	1042.42	1049.44	1032.83	16.61
C-028	1072.40	1055.66	1064.03	1046.54	17.49
C-029	1062.47	1045.96	1054.21	1048.19	6.02
C-039	1049.73	1035.17	1042.45	1037.00	5.45
D-002	975.64	965.68	970.66	978.20	–7.54
D-008	972.39	967.09	969.74	975.27	–5.53
D-009	972.18	967.42	969.80	974.28	–4.48
D-011	958.96	956.84	957.90	968.10	–10.20
D-012	965.19	962.30	963.75	970.37	–6.63
D-013	968.62	963.85	966.24	968.17	–1.93
D-014	962.30	960.37	961.34	971.07	–9.74
D-016	970.45	962.31	966.38	970.37	–3.99
D-018	983.34	962.40	972.87	971.83	1.04
D-027	1010.80	1001.40	1006.10	997.78	8.32
D-030	971.69	964.72	968.21	977.55	–9.35
DW38	951.13	949.26	950.20	964.51	–14.31
E-001	1107.46	1099.75	1103.61	1122.38	–18.77
E-002	1106.55	1097.86	1108.20	1097.77	10.43
E-003	1051.74	1047.66	1049.70	1067.93	–18.23
E-004	1057.68	1051.70	1054.69	1065.39	–10.70
E-005	1048.53	1043.28	1045.91	1054.79	–8.88

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
E-006	1058.03	1047.55	1052.79	1058.49	–5.69
E-007	1025.34	1024.05	1024.69	1028.04	–3.35
E-008	1050.51	1045.50	1048.01	1045.99	2.02
E-009	1095.05	1088.86	1091.95	1078.24	13.71
E-010	1103.16	1091.86	1097.51	1099.23	–1.72
E-011	1050.79	1037.40	1044.10	1051.86	–7.76
E-012	1066.70	1058.02	1062.36	1058.74	3.63
E-013	1057.80	1045.58	1051.69	1064.65	–12.96
E-014	1061.51	1050.62	1056.07	1059.95	–3.88
E-015	1055.45	1046.27	1050.86	1060.27	–9.41
E-016	1050.58	1046.30	1048.44	1046.45	1.99
E-017	1091.35	1078.88	1085.12	1062.09	23.03
E-018	1078.65	1068.10	1073.38	1065.28	8.10
E-020	1064.70	1037.71	1051.20	1052.22	–1.02
E-021	1054.17	1042.94	1048.56	1052.12	–3.56
E-022	1063.82	1051.30	1057.56	1065.01	–7.45
F-001	998.30	993.75	996.03	990.35	5.68
F-002	1017.30	1015.90	1016.60	1023.15	–6.55
F-004	1041.41	1032.40	1036.91	1013.62	23.29
F-005	1020.50	1009.90	1015.20	1001.06	14.14
F-007	1020.00	1014.30	1017.15	1016.39	0.76
F-008	1043.00	1037.75	1040.38	1035.08	5.30
F-009	1051.20	1037.90	1044.55	1044.73	–0.18
F-010	1043.44	1036.76	1040.10	1034.44	5.66
F-011	1032.20	1016.20	1024.20	1007.42	16.78
F-012	1022.40	1021.20	1021.80	1010.27	11.53
F-013	1011.90	1007.70	1009.80	990.53	19.27
F-015	1002.10	999.00	1000.55	990.12	10.43
F-018	1009.50	1006.00	1007.75	1003.74	4.01
F-019	1025.50	1016.70	1021.10	1020.14	0.96
F-020	1043.90	1042.10	1043.00	1042.91	0.09
F-021	1024.60	1019.20	1021.90	1029.60	–7.70
F-022	1052.10	1039.10	1045.60	1043.86	1.74
F-023	1043.10	1035.10	1039.10	1033.08	6.02
F-024	1039.60	1030.85	1035.22	1028.52	6.70

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
F-025	1015.80	1004.50	1010.15	997.45	12.70
F-027	998.60	984.50	991.55	973.59	17.96
F-028	1003.50	994.10	998.80	981.16	17.64
F-029	1048.00	1033.30	1040.65	1025.38	15.27
F-030	1003.00	996.20	999.60	984.66	14.94
F-031	976.50	973.20	974.85	976.30	–1.45
F-032	950.70	948.30	949.50	956.37	–6.87
F-033	984.90	981.80	983.35	985.92	–2.57
F-034	938.20	937.50	937.85	954.68	–16.83
F-035	1009.10	997.00	1003.05	1002.40	0.65
F-036	1023.90	1010.60	1017.25	1018.90	–1.65
F-037	1026.00	1013.80	1019.90	982.69	37.21
F-038	1007.50	1001.00	1004.25	984.28	19.97
F-040	996.10	991.40	993.75	975.67	18.08
F-041	1002.40	989.20	995.80	995.23	0.57
F-042	1013.60	1013.50	1013.55	993.09	20.46
F-043	942.90	939.10	941.00	956.78	–15.78
F-044	931.10	928.10	929.60	951.81	–22.21
F-046	1038.40	1029.20	1033.80	1035.34	–1.54
F-047	1030.20	1006.90	1018.55	1024.39	–5.84
F-048	952.30	951.10	951.70	957.59	–5.89
F-049	957.00	954.60	955.80	940.78	15.02
F-050	954.70	953.10	953.90	961.93	–8.03
F-051	956.90	954.20	955.55	965.74	–10.19
F-052	941.50	940.00	940.75	948.49	–7.74
F-053	932.00	929.60	930.80	962.55	–31.75
F-059	1016.90	1007.30	1012.10	1029.02	–16.92
F-060	1021.10	1016.50	1018.80	1007.10	11.70
R-002	972.06	965.14	968.60	977.57	–8.97
R-003	973.93	967.40	970.67	977.92	–7.26
R-006	972.11	966.62	969.37	985.02	–15.66
R-007	997.18	990.21	993.70	987.06	6.63
R-016	966.66	958.36	962.51	980.44	–17.93
R-018	996.81	991.30	994.06	991.83	2.23
R-021	960.34	953.90	957.12	980.93	–23.81

Appendix. Comparison of measured and simulated water-level altitudes for the Arnold Air Force Base area ground-water flow model.—Continued

Well	Water-level elevation, in feet				
	May 2002	October 2002	Average	Simulated	Residual
R-024	999.10	992.19	995.65	999.28	–3.64
R-026	1003.95	998.26	1001.11	992.64	8.47
R-027	974.50	967.76	971.13	982.05	–10.92
R-028	972.03	965.50	968.77	982.63	–13.86
R-031	964.86	959.99	962.43	978.57	–16.14
R-033	961.98	956.93	959.46	980.11	–20.65
R-034	972.73	966.25	969.49	980.75	–11.26
R-035	995.08	988.41	991.75	1002.21	–10.47
R-040	994.25	987.65	990.95	998.49	–7.54
R-047	1016.34	1006.20	1011.27	994.05	17.22
R-048	974.38	971.36	972.87	985.39	–12.52
R-050	979.65	975.78	977.72	982.65	–4.93
R-062	1015.82	1009.31	1012.57	1002.61	9.96
R-065	998.17	987.29	992.73	993.08	–0.35
R-068	1025.67	1017.56	1021.62	1007.90	13.72
R-100	979.63	974.00	976.82	984.83	–8.02
R-101	983.47	976.47	979.97	979.53	0.44
R-102	966.61	962.25	964.43	967.48	–3.05
R-103	997.17	991.62	994.40	986.79	7.60
R-104	1034.49	1015.57	1025.03	1014.78	10.25
R-105	994.71	985.47	990.09	984.59	5.50
S-001	950.60	938.94	944.77	956.56	–11.79
S-009	949.36	943.11	946.24	959.87	–13.64
S-017	940.46	931.08	935.77	958.23	–22.46
S-019	951.04	943.28	947.16	964.36	–17.20
S-022	941.55	933.46	937.51	955.08	–17.58
S-027	938.74	927.85	933.30	956.56	–23.27
S-029	960.97	941.55	951.26	959.57	–8.31
S-030	1046.10	1028.95	1037.53	1025.18	12.35
S-031	1034.55	1030.31	1032.43	1021.75	10.68
S-032	1007.13	1004.22	1005.68	995.34	10.34
S-033	973.38	972.53	972.96	976.24	–3.29
S-034	1008.22	1004.81	1006.52	1012.49	–5.97
SH17	955.34	958.25	956.80	978.59	–21.80
SJO35	941.10	941.03	941.07	963.29	–22.22