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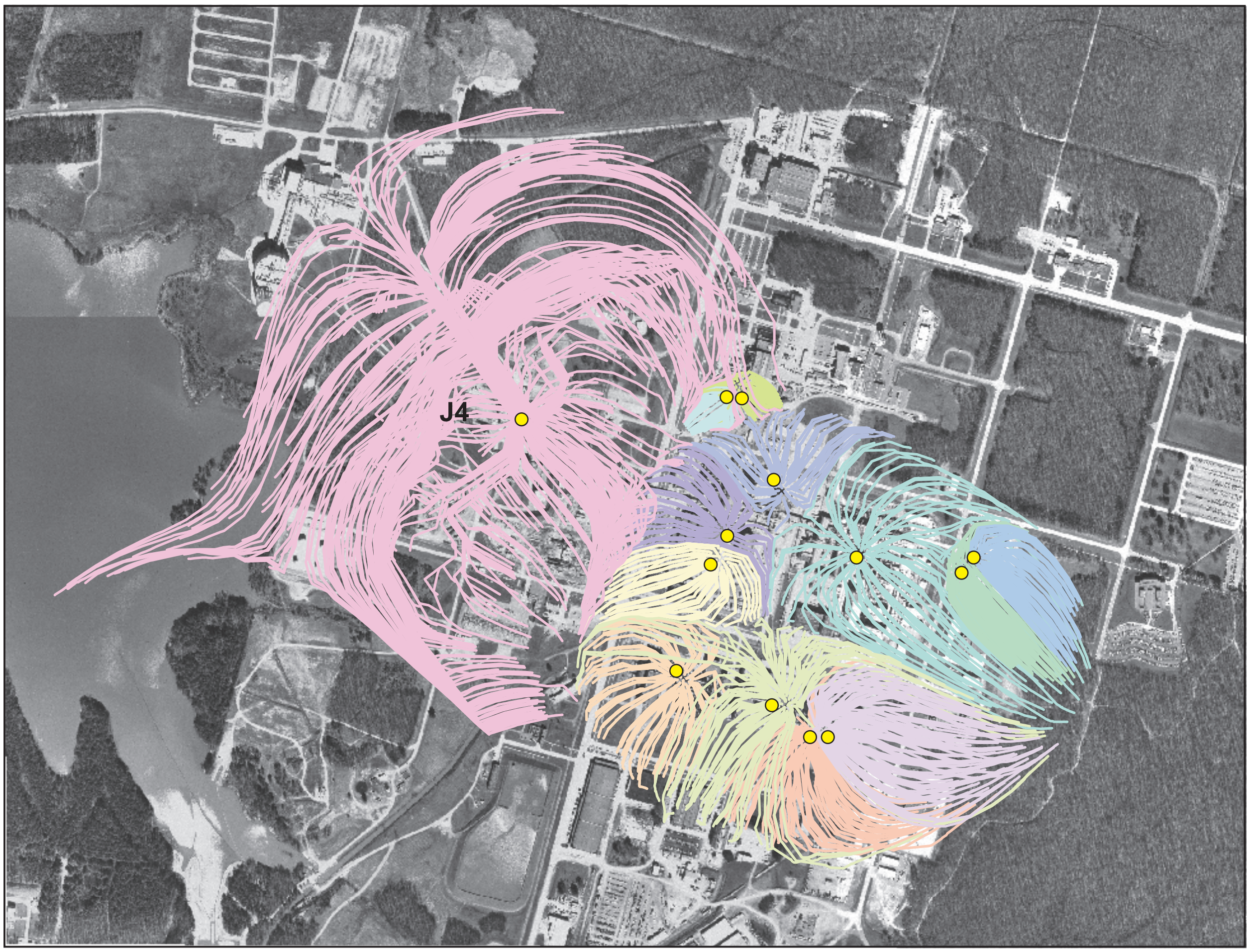
Hydrogeology and Simulation of Ground-Water Flow at Arnold Air Force Base, Coffee and Franklin Counties, Tennessee—2002 Update



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.)

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

By Connor J. Haugh

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Suggested citation:
Haugh, C.J., 2006, Hydrogeology and simulation of ground-water flow at Arnold Air Force Base, Coffee and Franklin Counties, Tennessee—2002 update: U.S. Geological Survey Scientific Investigations Report 2006–5157, 70 p.

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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

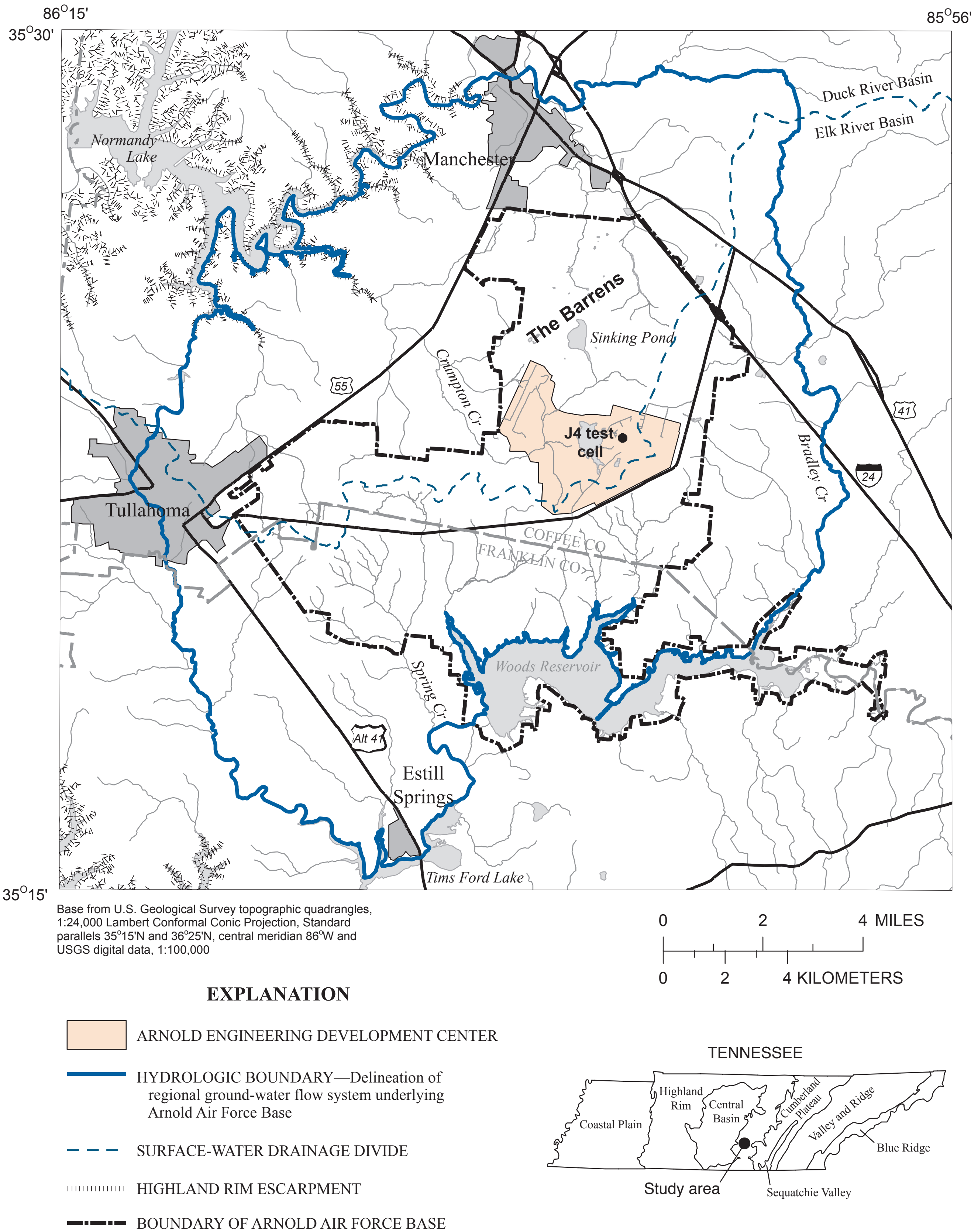


Figure 1. Location of study area at Arnold Air Force Base, Coffee and Franklin Counties, Tennessee.

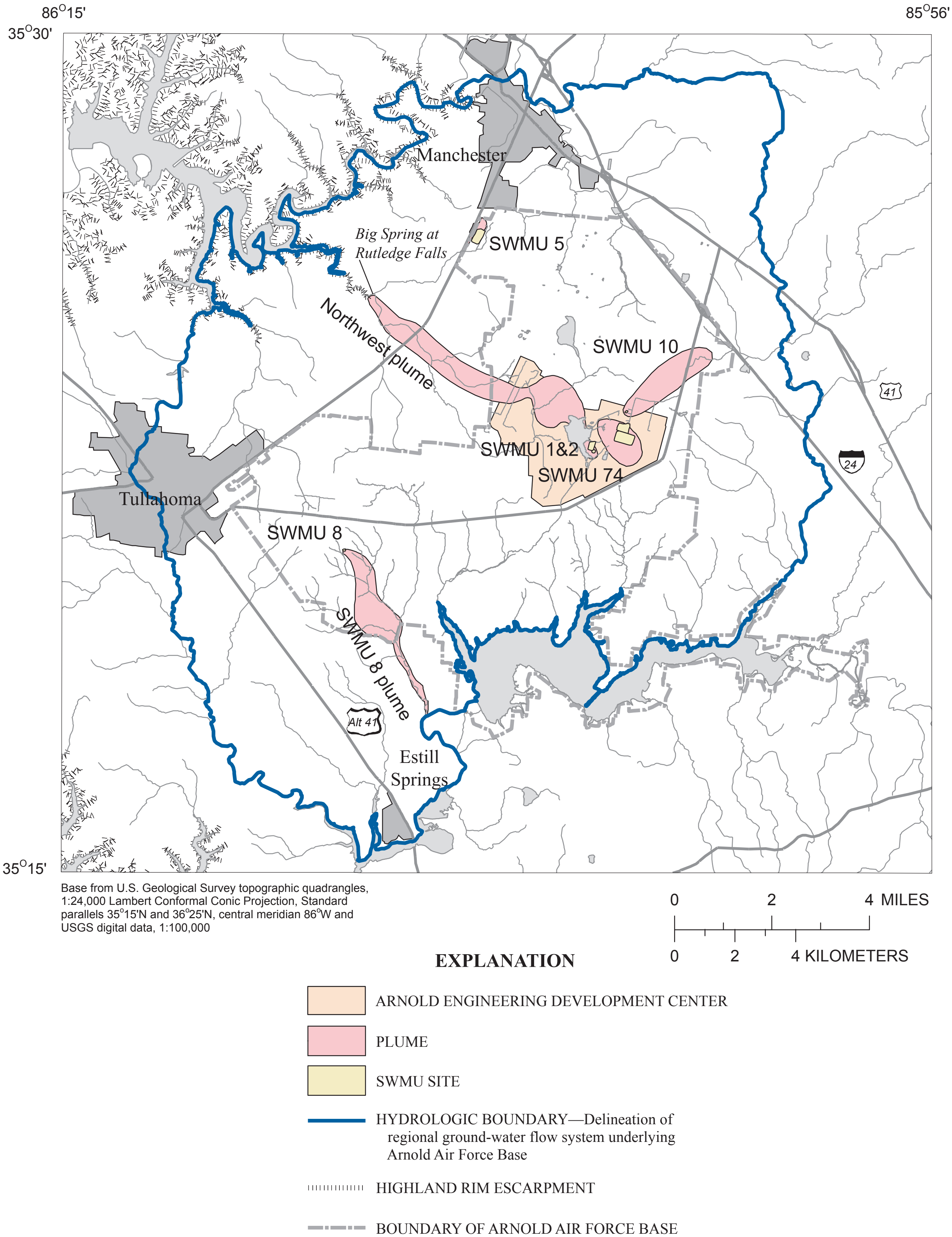


Figure 2. Location of Solid Waste Management Units (SWMUs) and ground-water contaminant plumes at Arnold Air Force Base.

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

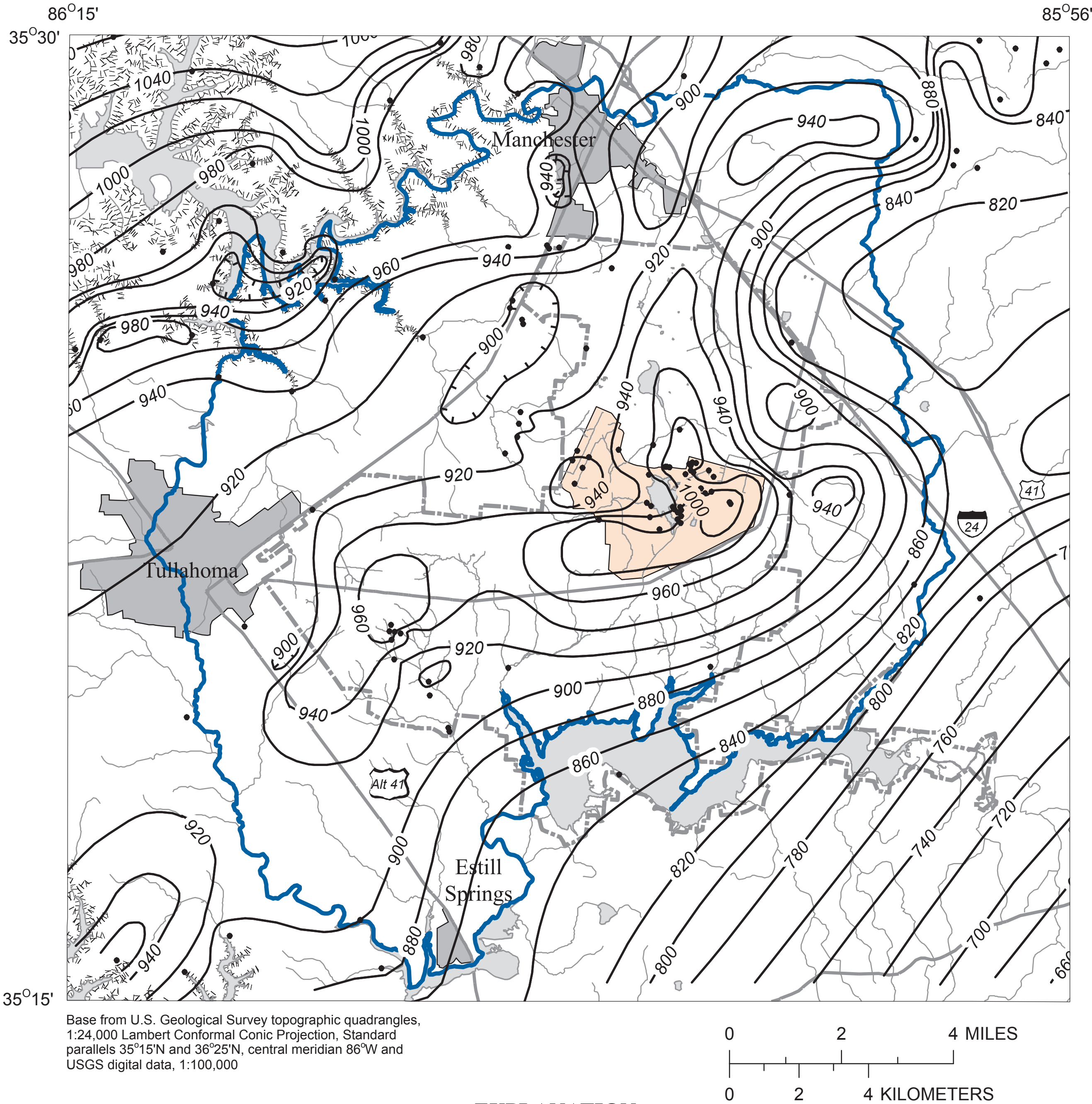
The Highland Rim aquifer system is the ground-water system of interest in the study area (Brahana and Bradley, 1986a, 1986b). The Highland Rim aquifer system can be divided into several different zones or aquifers (fig. 3). Hydrogeologic investigations by AEDC have typically designated the aquifers as 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



EXPLANATION

ARNOLD ENGINEERING DEVELOPMENT CENTER

— *880* — STRUCTURE CONTOUR—Shows altitude of the top of the Chattanooga Shale. 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 OR OUTCROP USED AS CONTROL

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

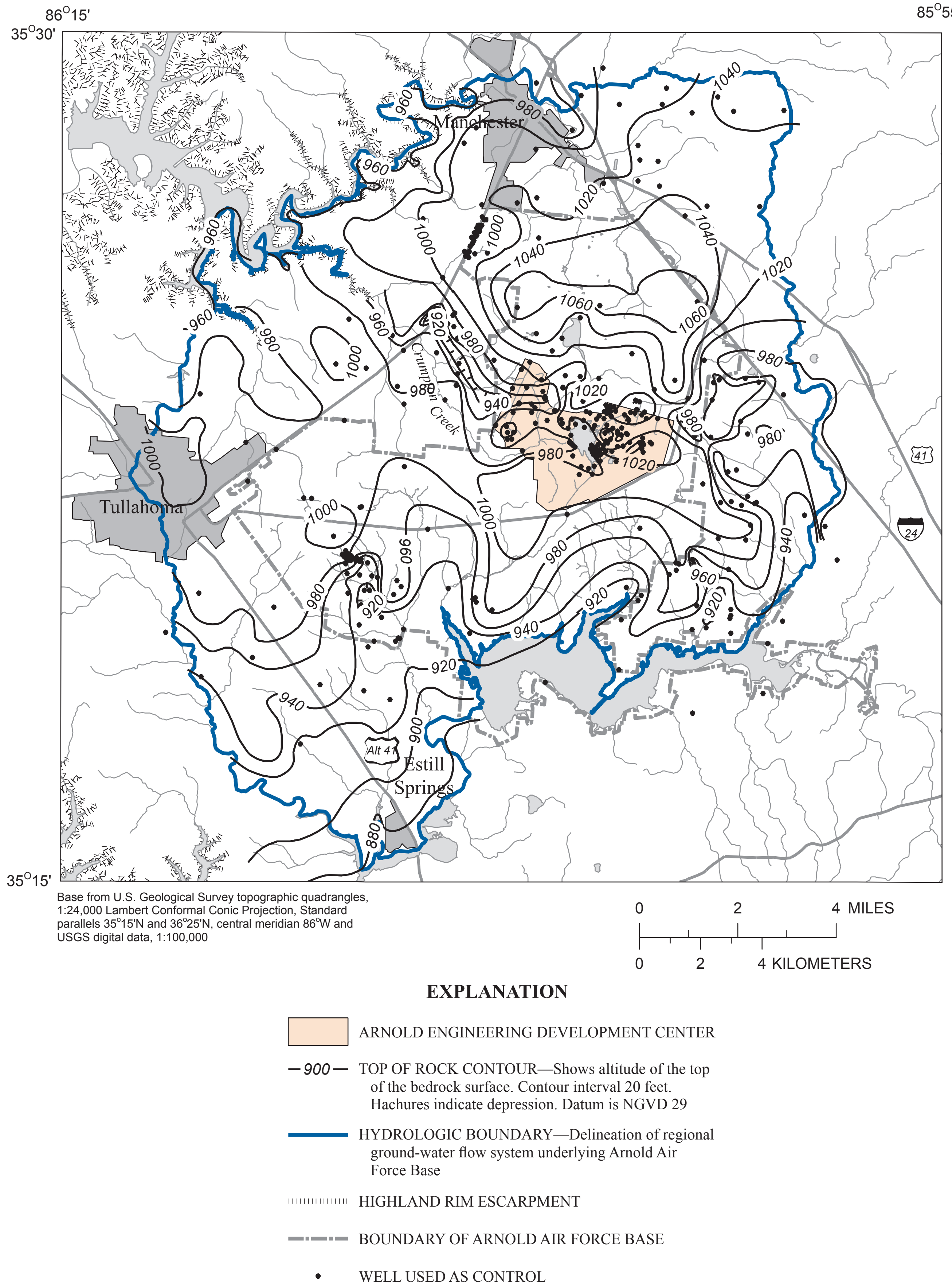


Figure 5. Altitude of the top of the bedrock surface in the Arnold Air Force Base area.

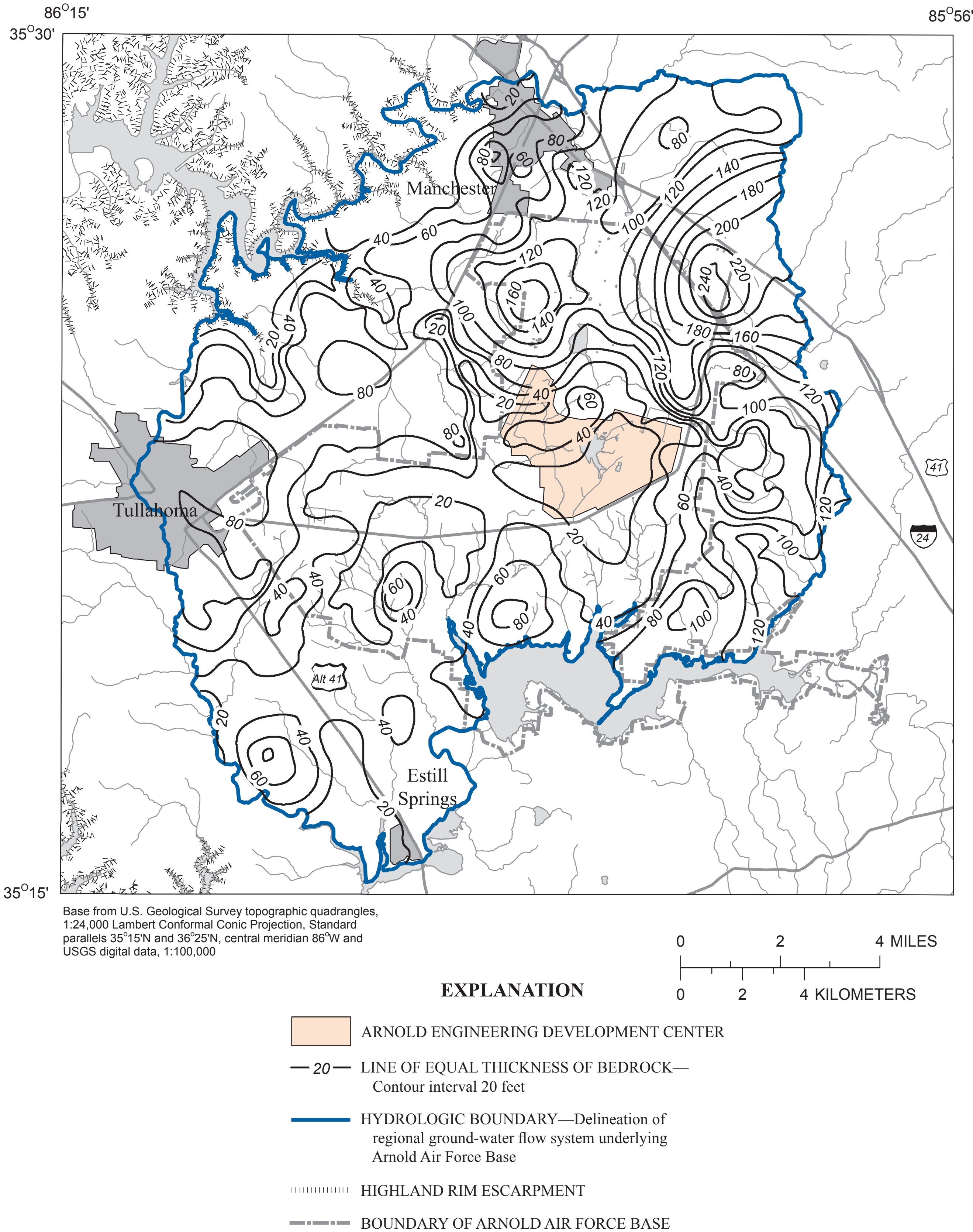


Figure 6. Thickness of bedrock above the Chattanooga Shale in the Arnold Air Force Base area.

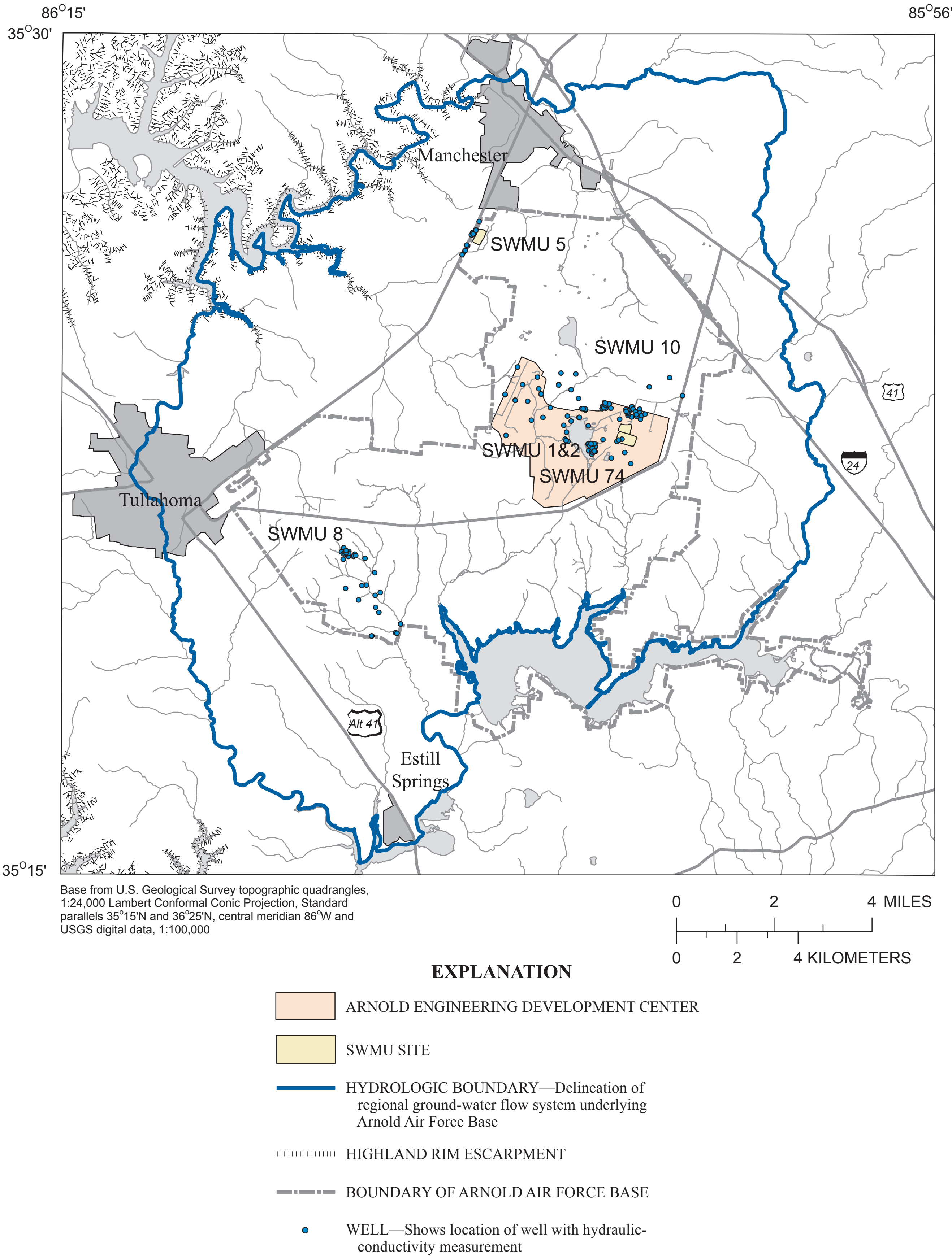


Figure 7. Location of wells with hydraulic-conductivity measurements at Arnold Air Force Base.

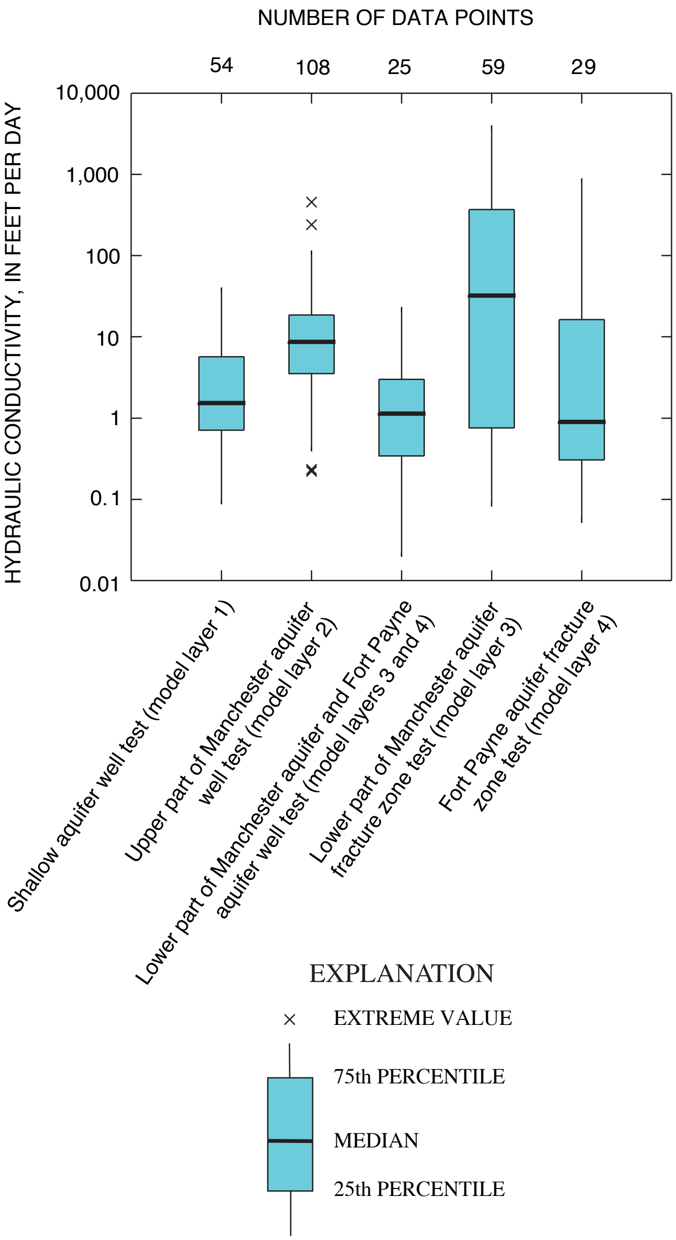


Figure 8. Ranges of hydraulic conductivity from wells and fracture zones at Arnold Air Force Base.

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

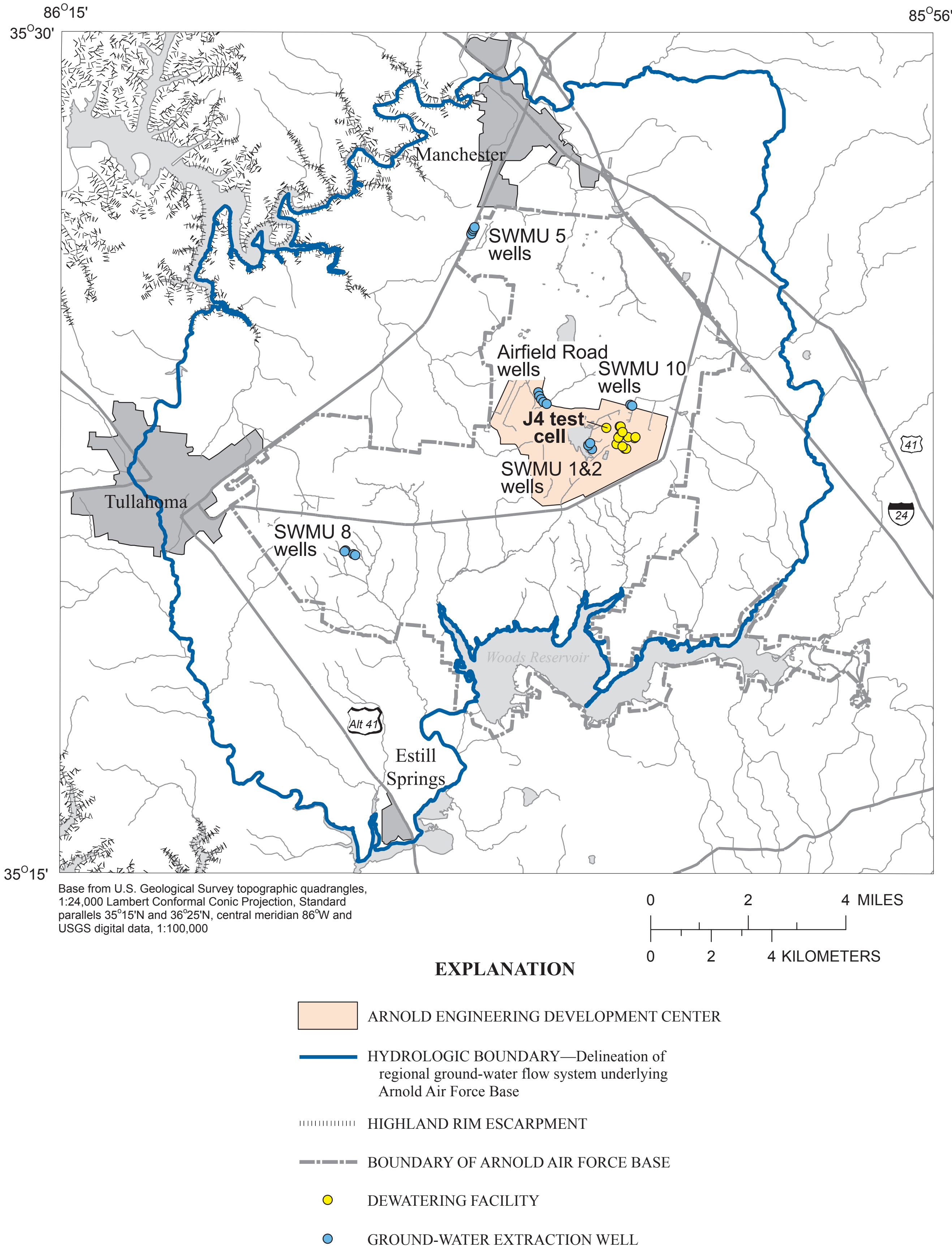


Figure 9. Location of ground-water withdrawal wells and dewatering facilities in the Arnold Air Force Base area.

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.

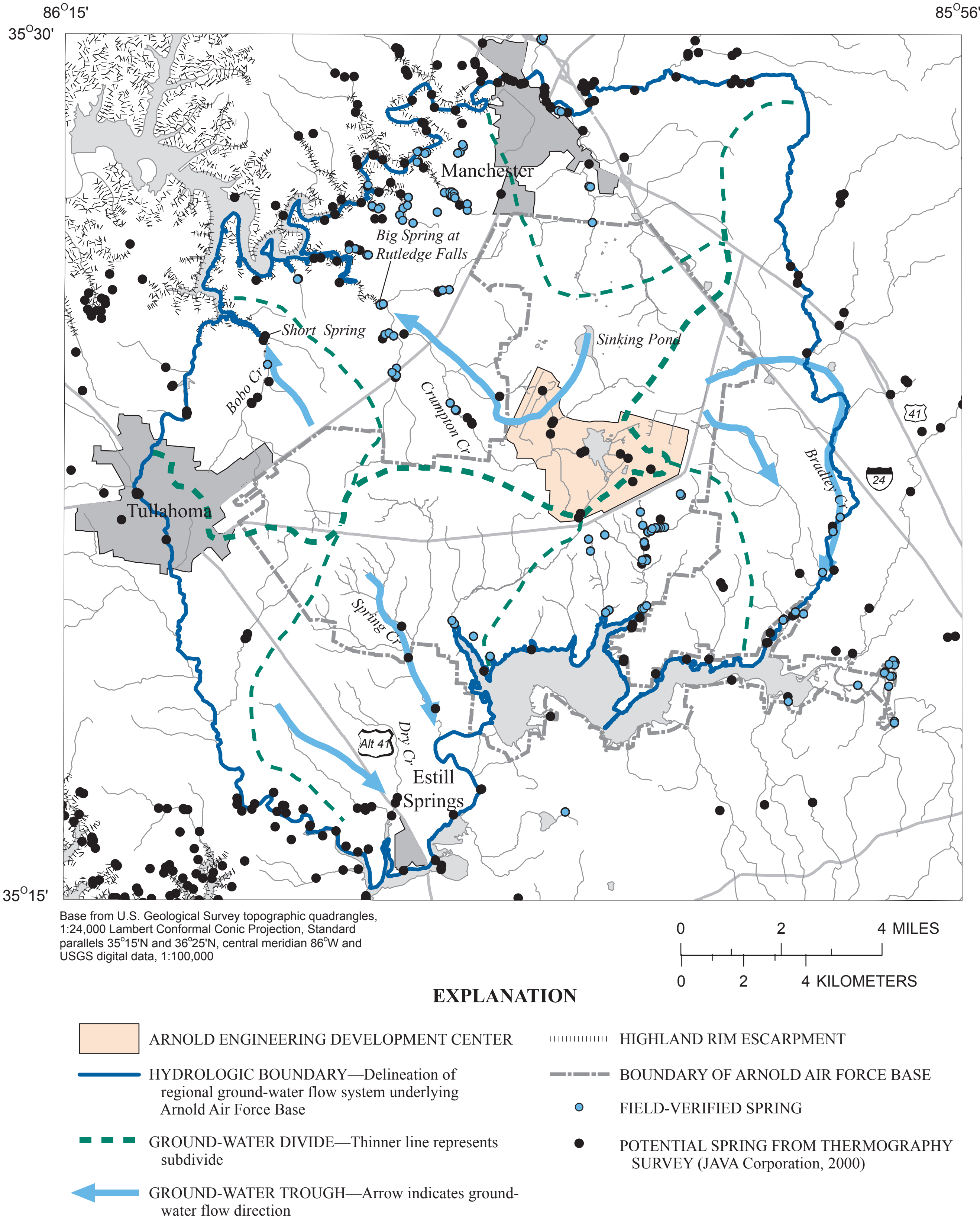


Figure 10. Location of springs in the Arnold Air Force Base area.

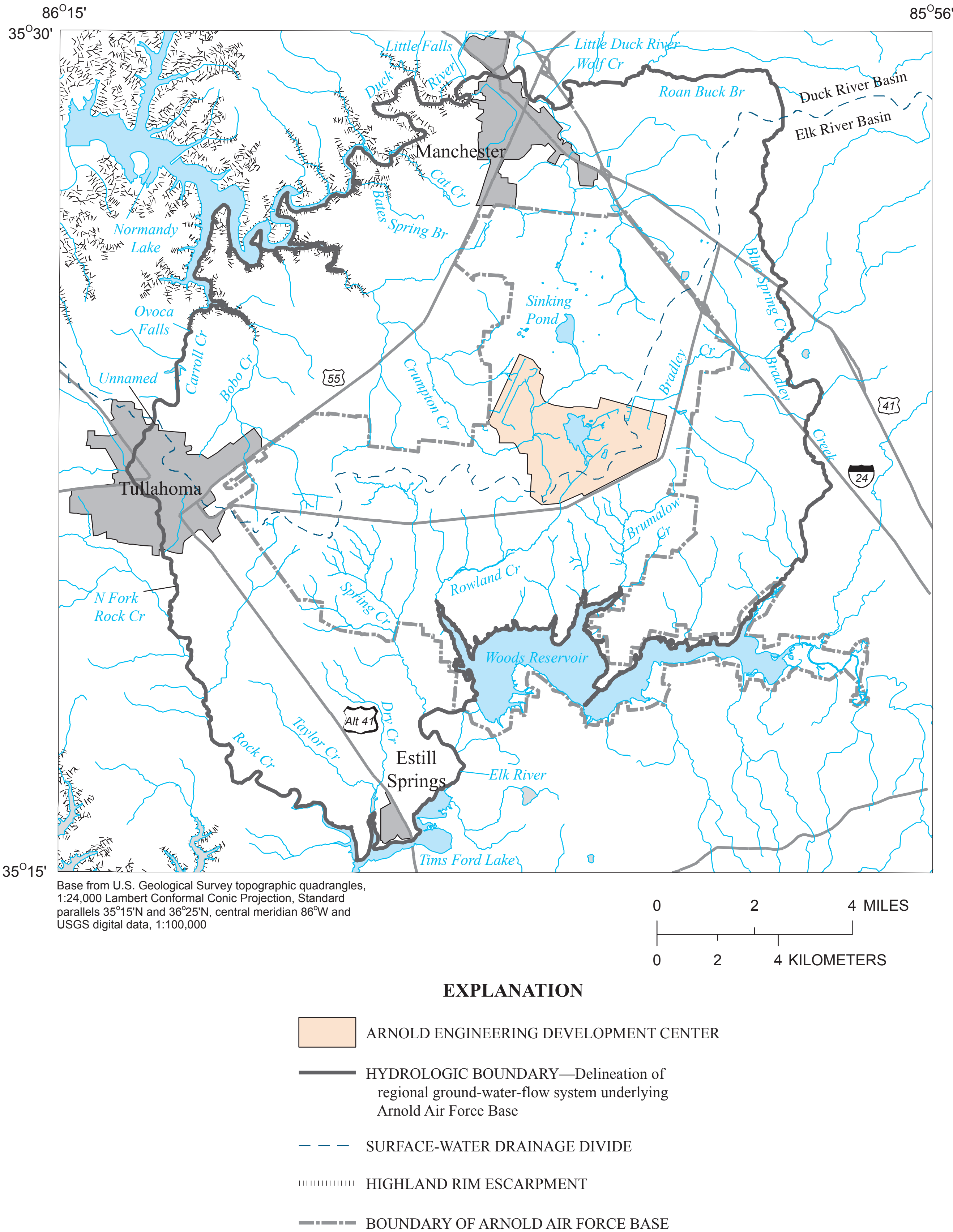


Figure 11. Regional flow boundaries for the Arnold Air Force Base area.

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

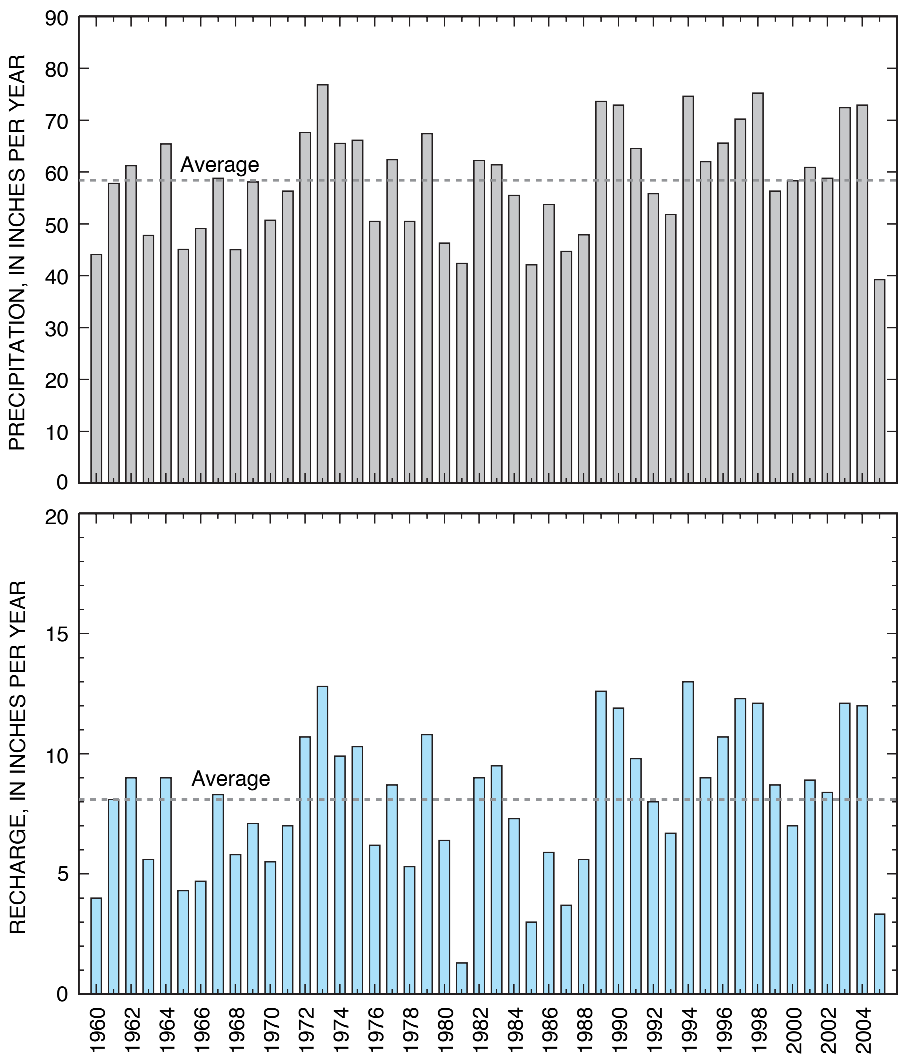


Figure 12. Precipitation and estimated recharge for the Arnold Air Force Base area, from 1960 to 2005.