In cooperation with

THE UNITED STATES AIR FORCE
DOVER AIR FORCE BASE

Hydrogeology and Simulation of Ground-Water Flow at Dover Air Force Base, Delaware

Water-Resources Investigations Report 99-4224

U.S. Department of the Interior

U.S. Geological Survey

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By Kurt C. Hinaman and Frederick J. Tenbus

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THE UNITED STATES AIR FORCE
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Baltimore Maryland
2000

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Abbreviations

CFC	Chlorofluorocarbon
CPS	counts per second
DAFB	Dover Air Force Base
DNREC	Department of Natural Resources and Environmental Control, State of Delaware
d	day
ft	foot
GIS	Geographic Information System
GRFL	Ground-Water Remediation Field Laboratory at Dover Air Force Base
HAZWRAP	Hazardous Waste Remedial Actions Program
in/yr	inch per year
IRP	Installation Restoration Program
K	hydraulic conductivity
LF	landfill
mi	mile
MODFLOW	A modular computer code that uses finite-difference numerical techniques for the simulation of ground-water flow.
MODPATH	A particle-tracking computer program for use with MODFLOW.
RI	Remedial Investigation; also used to refer to the "Remedial Investigation" Report (U.S. Army Corps of Engineers and Dames & Moore, Inc., 1994, 1997a, 1997b, and 1997c)
RMSE	root-mean-squared error
RTDF	Remediation Technology Development Forum
436 SPTG/CEV	436th Support Group, Civil Engineer Squadron, Environmental Flight
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WP	waste pit
yr	year

Conversion Factors and Vertical Datum

Multiply	By	To obtain
inch (in.)	2.54	centimeter
inch per year (in/yr)	2.54	centimeter per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
square foot (ft^2)	0.09290	square meter
foot squared per day (ft^2/d)	0.09290	meter squared per day
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
mile (mi)	1.609	kilometer
acre	4,047.0	square meter

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

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) by using the following equation:

$$°C = 5/9 \times (°F - 32)$$

Hydrogeology and Simulation of Ground-Water Flow at Dover Air Force Base, Delaware

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Abstract

Dover Air Force Base in Kent County, Delaware, has many contaminated sites that are in active remediation. To assist in this remediation, a steady-state model of ground-water flow was developed to aid in understanding the hydrology of the system, and for use as a ground-water-management tool. This report describes the hydrology on which the model is based, a description of the model itself, and some applications of the model.

Dover Air Force Base is underlain by unconsolidated sediments of the Atlantic Coastal Plain. The primary units that were investigated include the upper Calvert Formation and the overlying Columbia Formation. The uppermost sand unit in the Calvert Formation at Dover Air Force Base is the Frederica aquifer, which is the deepest unit investigated in this report. A confining unit of clayey silt in the upper Calvert Formation separates the Frederica aquifer from the lower surficial aquifer, which is the basal Columbia Formation. North and northwest of Dover Air Force Base, the Frederica aquifer subcrops beneath the Columbia Formation and the upper Calvert Formation confining unit is absent. The Calvert Formation dips to the southeast. The Columbia Formation consists predominately of sands, silts, and gravels, although in places there are clay layers that separate the surficial aquifer into an upper and lower surficial aquifer. The areal extent of these clay layers has been mapped by use of gamma logs.

Long-term hydrographs reveal substantial changes in both seasonal and annual ground-water recharge. These variations in recharge are related to temporal changes in evaporation, transpiration, and precipitation. The hydrographs show areas where extensive silts and clays are present in the surficial aquifer. In these areas, the vertical gradient between water levels in wells screened above and below the clays can be as large as several feet, and local ground-water highs typically form during normal recharge conditions. When drought conditions persist, water drains off these highs and the vertical gradients decrease. At the south end of Dover Air Force Base, hydrographs of water levels in the Frederica aquifer show that off-Base pumping can cause the water levels to decline below sea level during part of the year.

A 4-layer, steady-state numerical model of ground-water flow was developed for Dover Air Force Base and the surrounding area. The upper two layers represent the upper and lower surficial aquifers, which are in the Columbia Formation. In some areas of the model, a semi-confining unit is used to represent an intermittent clay layer between the upper and lower surficial aquifer. This semi-confining unit causes the local ground-water highs in the surficial aquifer. The third model layer represents the upper part of the Calvert Formation, a confining unit. The fourth model layer represents the Frederica aquifer. The model was calibrated to hydraulic heads and to ground-water discharge in Pipe Elm Branch, both of which were measured in September 1997. For the calibrated model, the root-mean-squared errors for the hydraulic heads and the ground-water discharge in the Pipe Elm Branch were 9 percent of the range of head and 3 percent of discharge, respectively. Heads simulated by use of the model were consistent with a map showing average water levels in the region.

The U.S. Geological Survey's MODPATH program was used to simulate ground-water-flow directions for several areas on the Base. This analysis showed the effects of the local ground-water highs. In these areas, ground water can flow

from the highs and then dramatically change flow direction as it enters the lower surficial aquifer.

The steady-state model has several limitations. The entire ground-water system is under transient hydraulic conditions, due mainly to seasonal and yearly changes in recharge and to withdrawal from irrigation wells. Yet this steady-state model is still considered to be an effective tool for understanding the ground-water-flow system underlying the Base for average conditions. If the ground-water system undergoes changes, such as an increase in pumping from existing or new wells in the surficial aquifer or in the Frederica aquifer at or near the Base, then the model may need to be verified for these conditions and, if necessary, recalibrated. Nevertheless, the model can be used to determine ground-water-flow pathlines in areas of the Base where flow directions are constant. In addition, the steady-state model is a necessary step in the development of transient models and solute-transport models, which are planned for future ground-water monitoring on the Base.

Introduction

Dover Air Force Base (DAFB), located in Kent County, Delaware (fig. 1a), has been in operation almost continuously since 1941. Various activities in support of the military mission have resulted in contamination of shallow ground water underlying the Base by synthetic organic compounds (Bachman and others, 1998). As a result, DAFB is now actively engaged in an Installation Restoration Program (IRP) to assess and remediate contaminated ground water underlying the Base.

Background

DAFB is an active military installation that covers an area of approximately 4,000 acres (fig. 1b). Ground-water contamination has been found in several areas on the Base. Some of these areas are adjacent to one another, some are adjacent to the Base boundary, some are affected by a unique geologic or hydrologic setting, and some are difficult to characterize because of physical-access problems. In 1995, the U.S. Geological Survey (USGS) in cooperation with the DAFB, and as part of a long-term-monitoring project, began work on a Base-wide ground-water-flow model to help assess the ground-water-contamination issue.

A significant amount of information about the environmental setting and contamination at and near DAFB has been collected and synthesized. Most of the work has been compiled in a summary by Dames & Moore, Inc., and HAZWRAP (Hazardous Waste Remedial Actions Program) (1993). Other environmental investigations with ground-

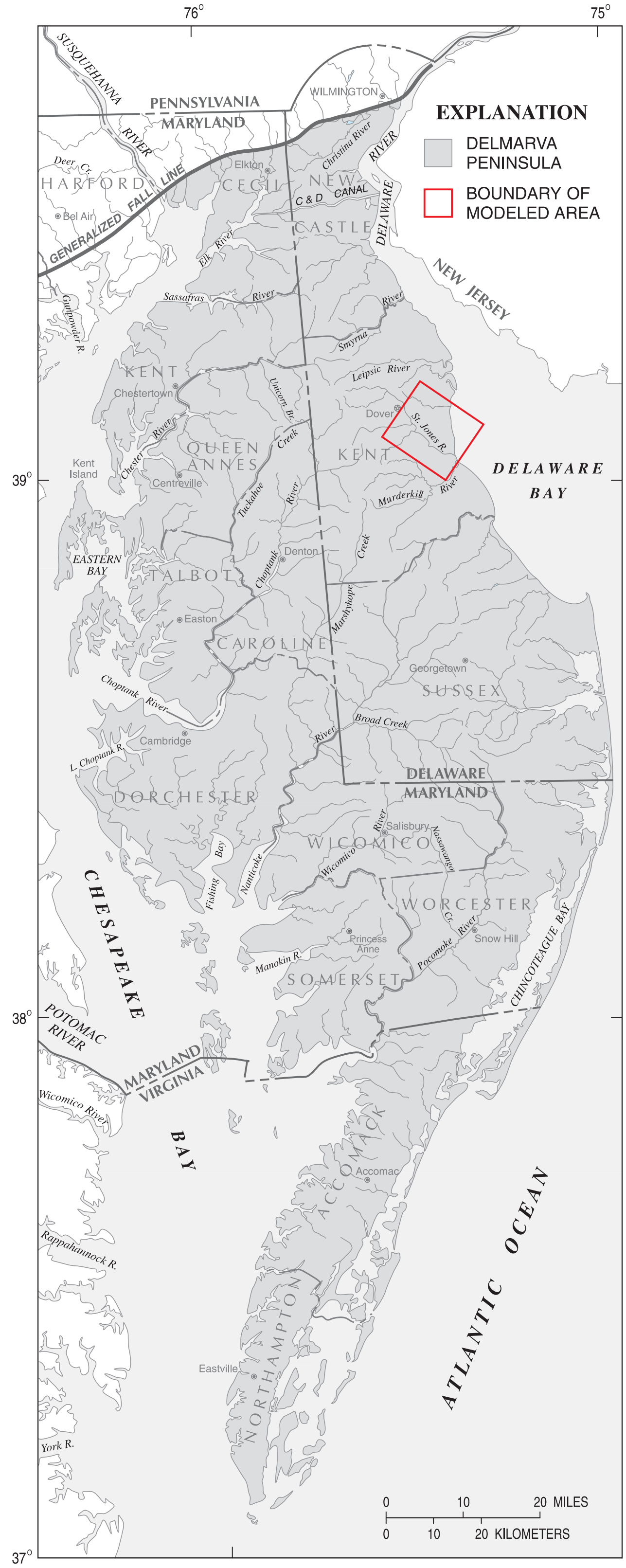
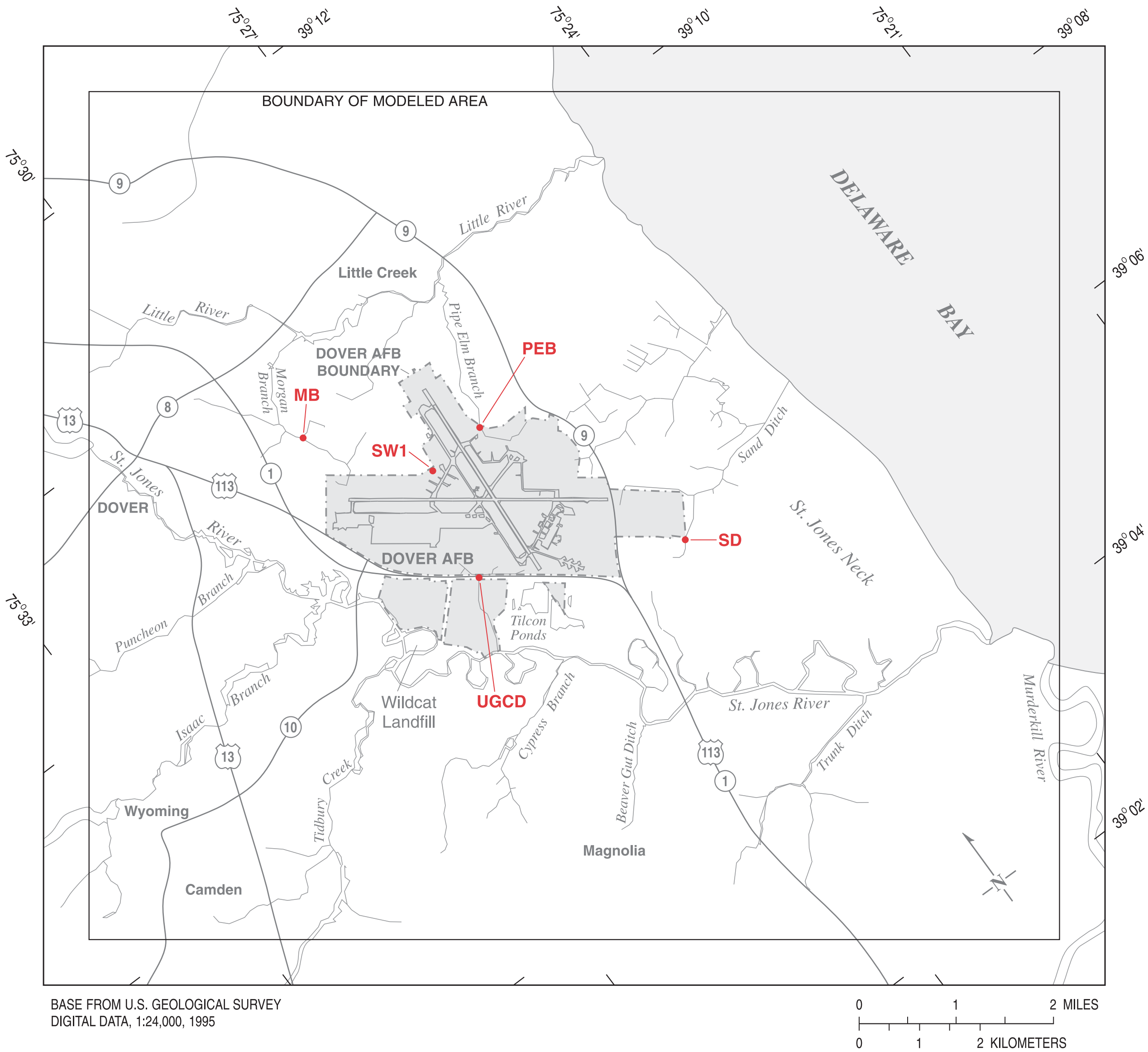


Figure 1a. Location of the Delmarva Peninsula and boundary of modeled area at Dover Air Force Base, Dover, Delaware.



EXPLANATION

BOUNDARY OF DOVER AIR FORCE BASE

SITES TO MEASURE SURFACE-WATER BASE FLOW:

MB	Morgan Branch
PEB	Pipe Elm Branch
SD	Sand Ditch
SW1	SW1 near exercise area
UGCD	Upper Golf Course Ditch

Figure 1b. Location of surface-water base-flow measurement sites and selected features near Dover Air Force Base, Delaware.

water components have been conducted near DAFB (CH2M Hill Southeast, Inc., 1988a, 1988b). A Base-wide remedial investigation (RI) has been completed recently (Dames & Moore, Inc., and HAZWRAP, 1993; U.S. Army Corps of Engineers and Dames & Moore, Inc., 1994; 1997a, 1997b, 1997c). In addition, DAFB has been selected as a ground-water remediation field laboratory (GRFL), where new technologies in ground-water remediation are tested (Applied Research Associates, Inc., 1996). An industrial and government consortium, Remediation Technology Development Forum (RTDF), has studied contamination at DAFB in order to develop other remediation technologies (U.S. Environmental Protection Agency, 1996a, 1996b, 1996c). Other groups also have studied ground-water contamination at DAFB (Ball and others, 1997; Eng, 1995; Johnston, 1996). The USGS recently investigated natural attenuation at several sites on the eastern side of the Base (Bachman and others, 1998) (fig. 1c).

In addition to the environmental investigations already conducted, DAFB and the surrounding area have been the subject of numerous geologic and hydrologic investigations, only a few of which are cited in this report. In the 1950's, Marine and Rasmussen (1955) studied the ground-water resources of Delaware. In the mid–1950's, DAFB drilled a high-capacity water-supply test well, which was documented in two reports (Rasmussen and others, 1958; Benson and others, 1985). Jordan (1962, 1964) and Johnston (1973) studied the geologic formations in the area. Several studies (Boggess and Adams, 1965; Adams and others, 1964; Davis and others, 1965; Boggess and others, 1965) compiled maps of the water table and soil-engineering characteristics. In the mid- to -late 1960's, the water resources of the Delmarva Peninsula were investigated (Cushing and others, 1973). In the 1970's, Leahy (1976 and 1979) determined the hydraulic characteristics of the Piney Point aquifer, which underlies the Calvert Formation, and the overlying confining units. During the 1970's, regional numerical simulations of ground-water flow in the Dover area were done for the unconfined aquifer (Johnston, 1976), the Piney Point aquifer (Leahy, 1979), and the Piney Point and Cheswold aquifers, which are in the lower part of the Calvert Formation (Leahy, 1982). In the early 1980's, geologic maps of the area were published (Pickett and Benson, 1983; Benson and Pickett, 1986). Spoljaric (1988, 1989a, 1989b, and 1991) compiled geologic and hydrologic information of the area. Spoljaric (1986) also studied the concentration of sodium in the Piney Point Formation. Vroblesky and Fleck (1991) reported the results of the USGS Regional Aquifer-System Analysis of the Northern Atlantic Coastal Plain, which included the Coastal Plain of Delaware. Phelan (1990) described the water use in the St. Jones River Basin, which includes DAFB.

As remedial activities proceed at DAFB, many factors need to be considered. It is important to know if remedial activities at one site will affect other sites, and which sites need to be remediated first. If long-term monitoring is used with the remediation process, it is essential that ground-water-monitoring wells be correctly placed to intercept flow from contaminated areas, and to select an appropriate monitoring frequency. It is useful to know the likelihood of contaminant transport in areas where physical access for installing monitoring wells is difficult. It is also important to know the likelihood of contaminant transport off Base or to deeper aquifers. An examination of the hydrogeology at DAFB, coupled with a numerical model of ground-water flow, is helpful in addressing these concerns.

This report is part of the Long-Term-Monitoring Project. This project is managed by the USGS for the 436th Support Group, Civil Engineer Squadron Environmental Flight (436 SPTG/CEV) of DAFB.

Purpose and Scope

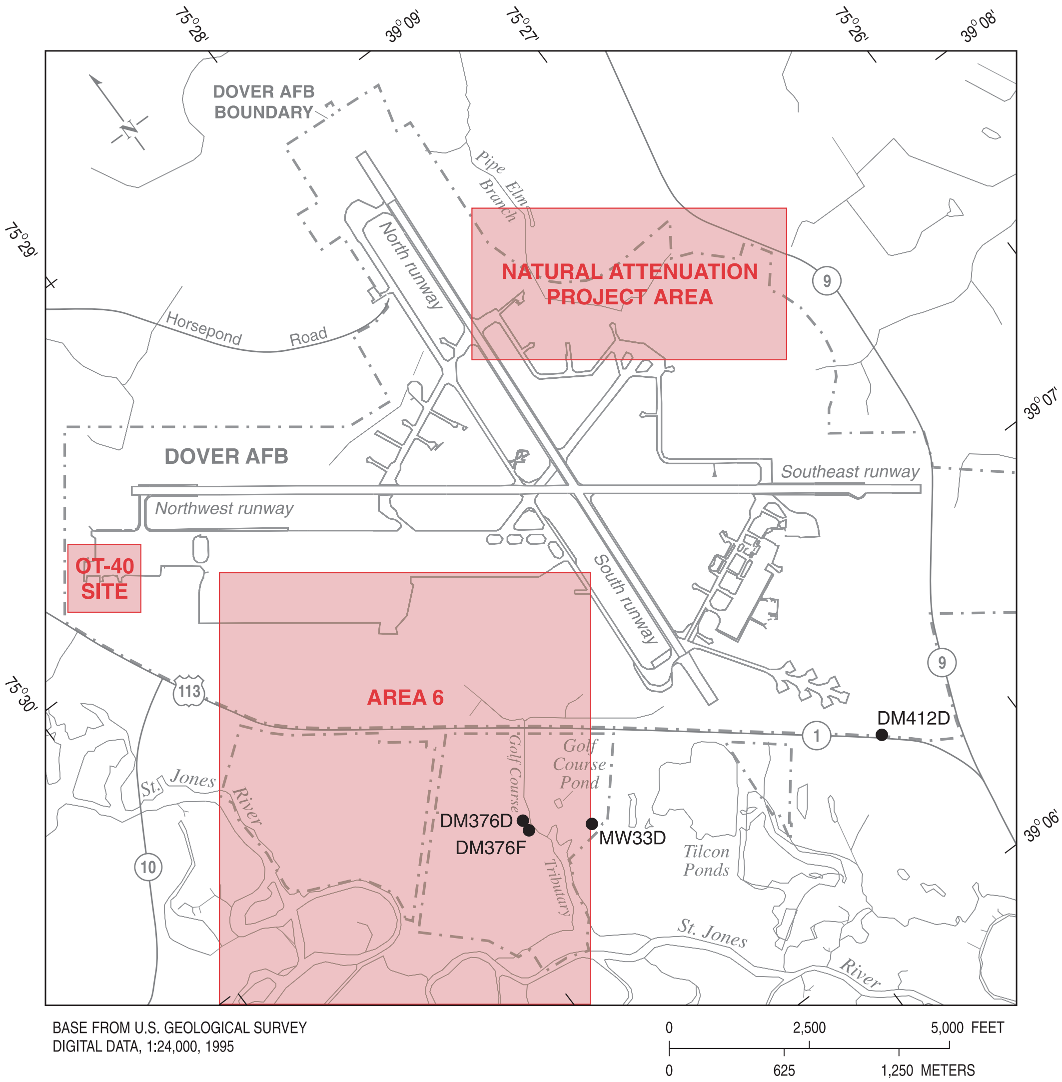
This report describes the hydrogeology of DAFB and the development and use of a numerical model that simulates steady-state ground-water flow at DAFB. The report includes a compilation of recharge, as well as a compilation of hydraulic conductivities for hydrogeologic units above the base of the Frederica aquifer. Also included are data, such as gamma logs and stream discharge, that were collected as part of this investigation, and an analysis of these data to describe the ground-water-flow system. A conceptual model developed on the basis of the compiled hydrogeologic data is presented. The report details the assembly of a numerical model and provides examples of the use of the model as a management tool for environmental work at DAFB, including simulations of ground-water pathways for several contamination sites.

Description of Investigation Area

DAFB is located in Kent County, Delaware, about 3.5 miles southeast of the center of Dover, Delaware (fig. 1b). It encompasses approximately 4,000 acres, including annexes, easements, and leased property (U.S. Army Corps of Engineers and Dames & Moore, Inc., 1994). Land use in the surrounding area is primarily cropland and wetlands, with some rural residential development.

Land use at DAFB can be divided into two main categories: areas with no manmade structures and areas with manmade structures (fig. 2). Most of the land areas with no manmade structures are located in the eastern, southern, and northern parts of the Base. These areas are mainly forests or fields. The areas with structures include runways and tarmacs, hangars and industrial buildings, offices, and on-Base housing east of US Route 113 and Delaware Route 1. Figure 2 shows the major areas in the vicinity of DAFB that are covered by pavement, such as runways and large parking lots (fig. 2). West of US Route 113 and Delaware Route 1, manmade structures include off-Base housing, the Base elementary school, and a golf course.

DAFB is located on the Delmarva Peninsula, within the Atlantic Coastal Plain. It is underlain by unconsolidated deposits of clay, silt, sand, and gravel that lie unconformably on crystalline basement. The sediments range in age from Early Cretaceous to Holocene (Benson and Spoljaric, 1996). The Coastal Plain sediments thicken to the southeast, with



EXPLANATION

LOCATION OF AREA WITH A PATHLINE ANALYSIS (Refer to Figures 39, 40, 41, and 42a-e.)

DM376D ● MONITOR WELL AND IDENTIFICATION NUMBER (The last letter refers to where the well is screened. D represents a well screened in the lower 10 feet of the surficial aquifer; F represents a well screened in the Frederica aquifer.)

Figure 1c. Location of selected areas and monitor wells at Dover Air Force Base, Delaware.

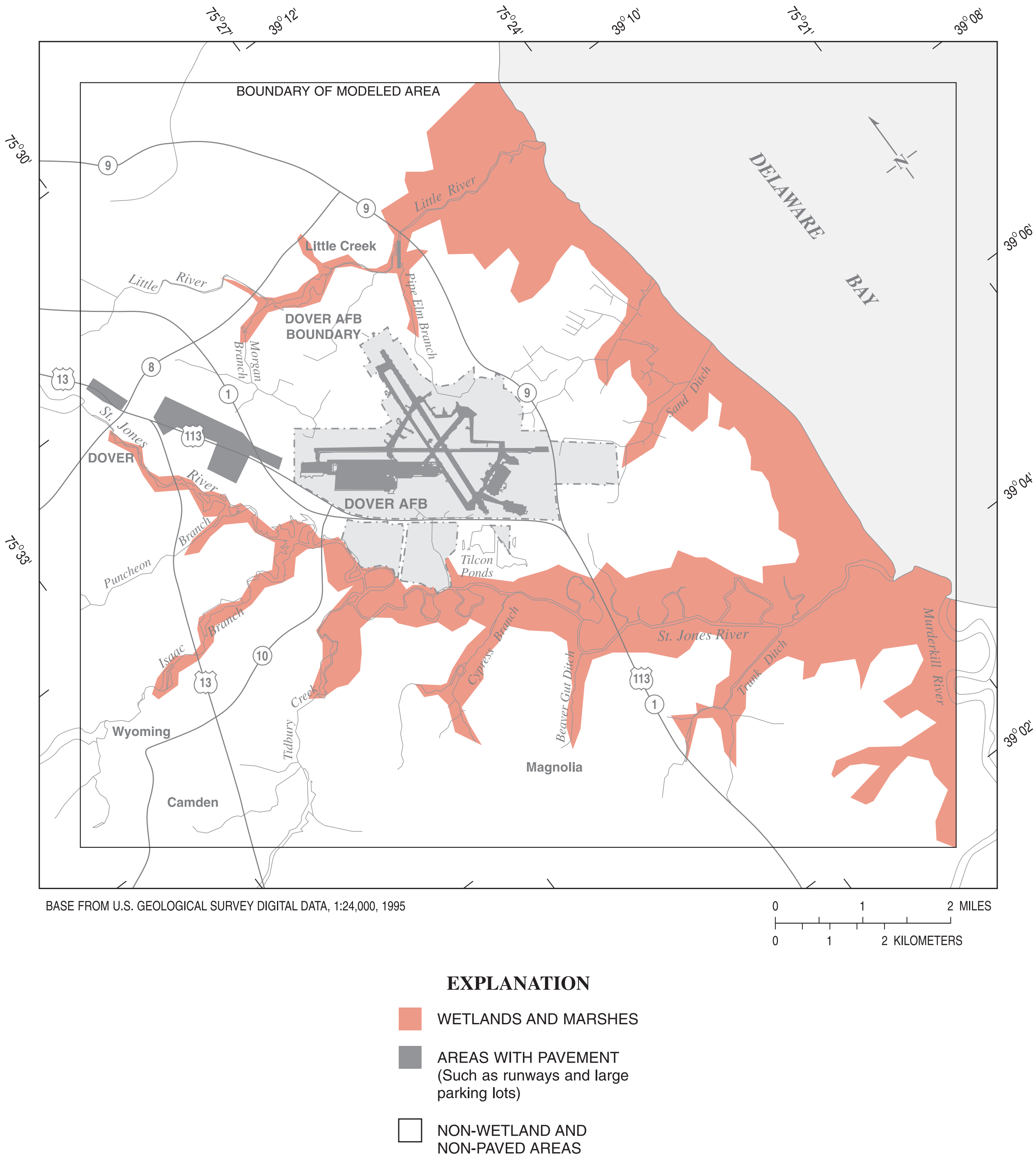


Figure 2. Location of large areas with pavement and wetlands at and near Dover Air Force Base, Delaware.

progressively younger units subcropping beneath a surficial blanket of Pleistocene deposits (Benson and Spoljaric, 1996).

The topography of DAFB is relatively flat with little spatial variation. The surface elevations range from about 5 ft above sea level near the St. Jones River, to about 30 ft above sea level at the northwestern boundary of the Base. The northwest-southeast trending runway has an elevation of 28 ft above sea level, which is higher than most of the surrounding area (U.S. Army Corps of Engineers and Dames & Moore, Inc., 1997a).

Delaware has a humid, continental climate with well-defined seasons. Delaware Bay, Chesapeake Bay, and the Atlantic Ocean have a considerable effect on the climate because winds from the bays and ocean tend to moderate temperatures. Summers are warm and humid. The winters are mild and there are few prolonged periods of freezing weather. Freezing of soils is rare and ground-water recharge occurs throughout most of the year. The proximity of large bodies of water and the inflow of southerly winds cause high relative humidity throughout the year (Rasmussen and others, 1958; U.S. Department of Agriculture, 1941; Wood, 1996).

Precipitation near DAFB averages about 46 in. per year and is distributed fairly uniformly, with the greatest amount during the summer. Monthly precipitation ranges from an average minimum of less than 3 in. in February, to an average maximum of more than 5 in. in August (National Oceanic and Atmospheric Administration, 1996; Wood, 1996). Mather (1969) estimated annual evapotranspiration losses in central Delaware to be about 25 in.

Acknowledgments

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Hydrogeology

Ground-water flow and solute transport are strongly influenced by the hydrogeologic framework of the DAFB area. The accuracy of results from model simulation of ground-water flow and the usefulness of these results to subsequently determine future ground-water conditions is dependent upon how well the ground-water-flow system is understood. For this reason, it was essential to develop an accurate conceptual model of the hydrogeology at DAFB.

One of the first tasks in the project was to review the historical literature for a description of the hydrogeologic system. This literature and records from regulatory agencies, primarily DNREC, provided historical hydro-geological data, such as well records. Concurrently, a geographical information system (GIS) data base of hydro-geological data was assembled. Use of a GIS allowed different types of data, such as well records and geologic maps, to be compiled and combined into one source. A conceptual model of the hydrogeologic system was developed on the basis of data and information located in the literature survey, and gaps in hydrogeologic data were identified. To fill these gaps, several types of data were collected. Synoptic ground-water levels were collected concurrently with measurements of ground-water discharge measured at streams and drains at and near DAFB. These data were necessary to calibrate the model. Continuous recorders were installed in many ground-water wells and on some surface-water bodies to determine the water-level fluctuations. Analyses of the concentrations of chloro-fluorocarbon and tritium in ground water was used to estimate ages of the water. These ages were then used to define the conceptual model of the ground-water-flow system, and to help calibrate the ground-water-flow model. Gamma logs were collected to determine the thickness of fine-grained sediments in the surficial aquifer. These logs also were used to determine the thicknesses and infer the lithology of the sediments in the upper Calvert Formation confining unit.

Geologic Framework

The stratigraphic units that have been identified in the DAFB area (Benson and Spoljaric, 1996) are shown in figure 3 and in table 1. In this area, the geologic formations dip gently and thicken to the southeast (Pickett and Benson, 1983; Benson and Pickett, 1986). North of DAFB, the

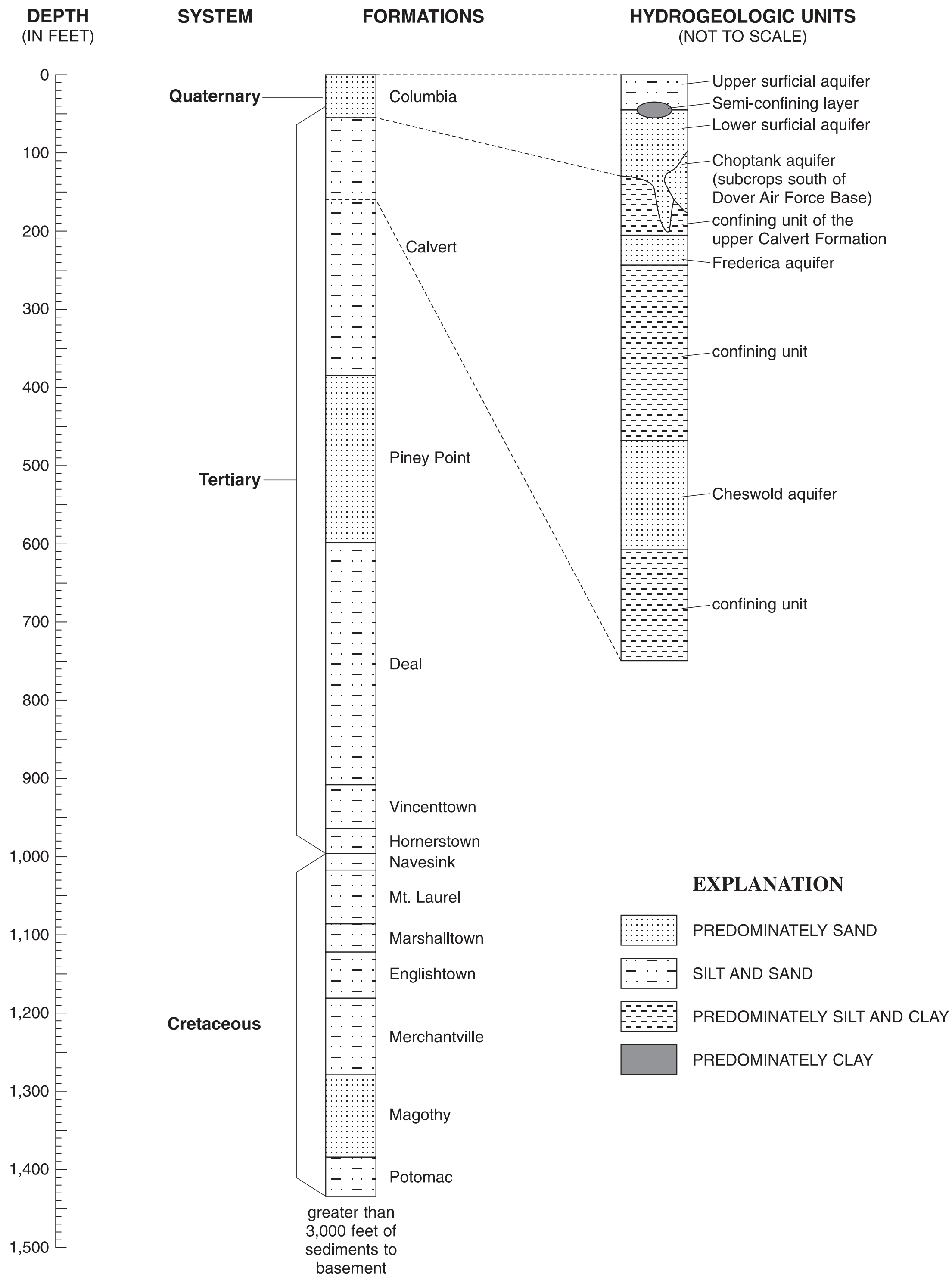


Figure 3. Stratigraphic column and hydrogeologic units in the Dover Air Force Base area, Delaware (stratigraphic column modified from Benson and Spoljaric, 1996).

Table 1. *Generalized stratigraphic, lithologic, and hydrologic characteristics of geologic formations underlying the Dover Air Force Base area, Delaware*

[Modified from Benson and Spoljaric, 1996; Benson, Jordan, and Spoljaric, 1985; DAFB, Dover Air Force Base; >, greater than]

System	Series	Formation	Approximate thickness at DAFB (feet)	General lithology	Hydrogeologic unit
Quaternary	Pleistocene	Columbia [A]	35-85	Sand, silt, gravel, clay	Surficial aquifer
Tertiary	Middle to Lower Miocene	Calvert	0 at DAFB subcrops south of DAFB	Sand	Choptank aquifer grouped with Surficial aquifer
			15-40	Silt	Confining unit
			25	Sand	Frederica aquifer
			90	Silt	Confining unit
			60	Sand	Cheswold aquifer
			100	Silt	Confining unit
			35	Glauconitic sand	Historically included with Piney Point aquifer
	Middle Eocene	Piney Point	215	Sand and sandy silt	Piney Point aquifer
	Middle to Lower Eocene	Deal	310	Silts and clays	Confining unit
	Upper Paleocene				
	Upper Paleocene	Vincenttown	55	Glauconitic sandy to clayey silt	Confining unit
	Lower Paleocene	Hornerstown	30	Glauconitic silt	Confining unit
Cretaceous	Upper Cretaceous	Navesink	20	Glauconitic silt	Confining unit
		Mt. Laurel	70	Silt-clay matrix with glauconite and shell calcite	Confining unit
		Marshalltown	35	Very fine sand and silt	Confining unit
		Englishtown	60	Fine to very fine sand	Confining unit
		Merchantville	100	Coarse silt and very fine sand	Confining unit
		Magothy	100	Sands and silts	Magothy aquifer
		Potomac	>50	Clays and sands	Confining units and aquifers in other parts of Delaware

[A] Quaternary deposits in Delaware Geological Survey stratigraphy.

Frederica aquifer, which consists of the upper sand of the Calvert Formation, subcrops under the overlying Columbia Formation (fig. 4) (Pickett and Benson, 1983). South of DAFB, the Choptank aquifer subcrops under the Columbia Formation and overlies the upper confining unit of the Calvert Formation (Benson and Pickett, 1986). Numerous publications include cross sections showing the geology of this area (see Pickett and Benson, 1983; Benson and Pickett, 1986; Benson and Spoljaric, 1996).

The Calvert Formation consists of a gray-to-blue to greenish-gray silt, with subordinate sand and shell beds (Leahy, 1982; Benson and others, 1985; Spoljaric, 1988; U.S. Army Corps of Engineers and Dames & Moore, Inc., 1997a). It ranges in thickness from about 290 ft beneath DAFB to over 600 ft in southern Delaware (U.S. Army Corps of Engineers and Dames & Moore, Inc., 1997a). In the DAFB area, it is divided into five units; two sandy layers that separate three silty layers (Marine and Rasmussen, 1955; Benson and others, 1985; U.S. Army Corps of Engineers and Dames & Moore, Inc., 1997a). This investigation focused on the upper parts of the Calvert Formation; the sand layer known as the Choptank aquifer, a clay and silt layer that forms the confining bed between the surficial aquifer and the underlying sand, and the Frederica aquifer (table 1).

At DAFB, the Columbia Formation [1] consists of fluvial deposits of fine-to-coarse sand with silt and clay lenses and less common lenses of gravel. The sediments generally fine upward (U.S. Army Corps of Engineers and Dames & Moore, Inc., 1997a), but the amount of fining varies. The top of the Columbia Formation throughout the investigation area is defined as the land surface, which was derived from USGS 7.5-minute quadrangle topographic maps with a contour interval of 5 ft. The base of the Columbia Formation (fig. 5) was defined using two different data sets. Within DAFB boundaries, the base of the surficial aquifer was determined from well logs. Outside of DAFB, the thicknesses of the Columbia Formation and recent marsh sediments (Benson and Pickett, 1986; Pickett and Benson, 1983) were subtracted from land-surface altitude to obtain the base of the surficial aquifer. The thickness of the formation ranges from about 35 ft in the northwestern corner of the Base to about 85 ft in the eastern part of the Base.

In some areas of DAFB, the upper Columbia Formation contains fine-grained sediments such as silts and clays, and the lower surficial aquifer consists of cleaner sands, silts and gravels. In some of these areas, a clay and silt sequence separates the upper and lower Columbia Formation. This sequence was seen at DAFB in split-spoon samples and direct-push cores. In areas outside the Base boundary, the sequence was not mapped.

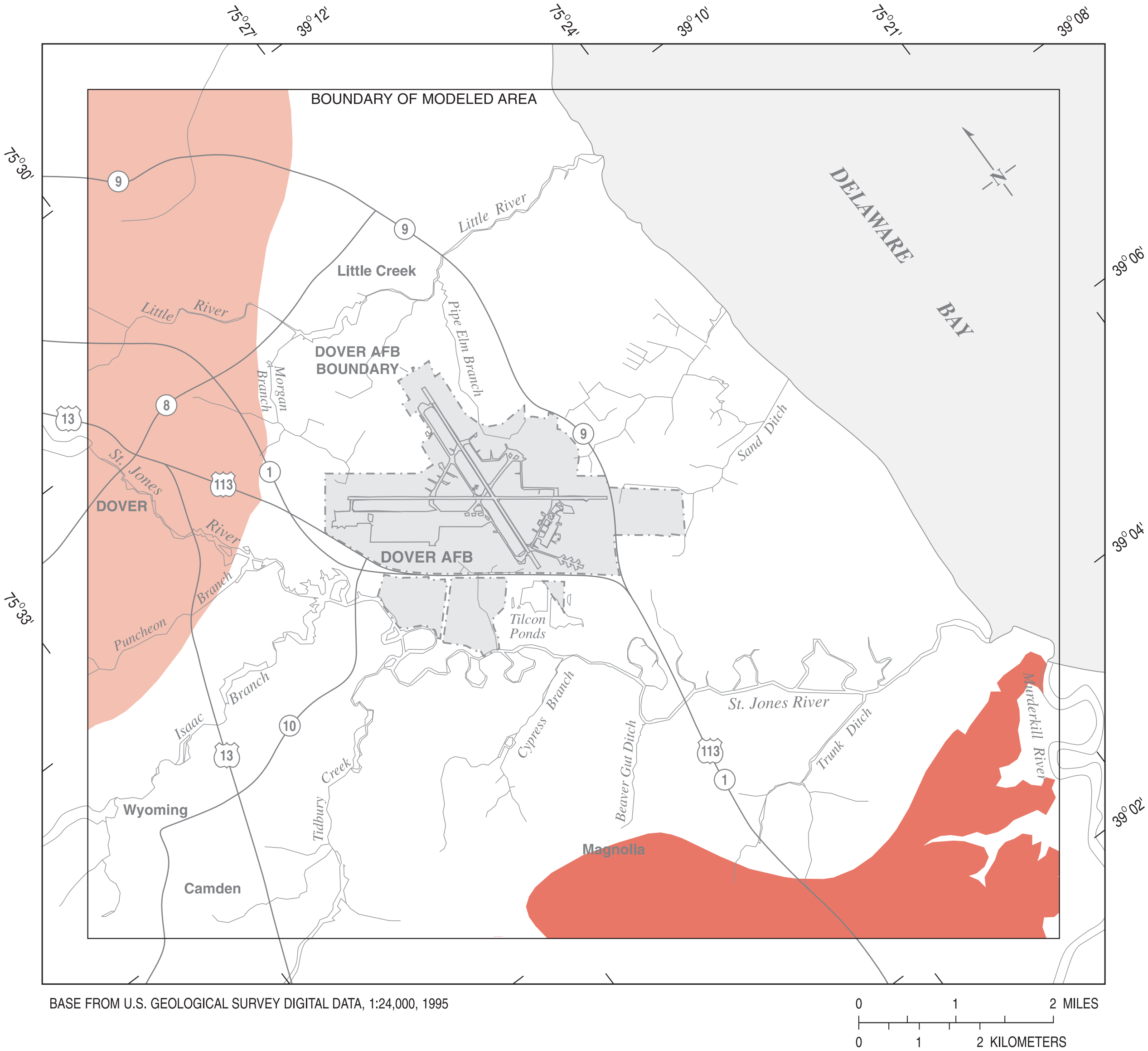
Gamma logs were used to extend the clay and silt sequence to areas with no split-spoon samples or direct-push cores. Figure 6 shows the locations of the gamma logs, which show the gamma radiation of the sediments. In general, higher gamma counts are correlated with finer-grained materials, which was confirmed by sediments in samples collected from wells. The gamma logs collected for this investigation were not calibrated; consequently, the gamma counts are relative counts. A count of 40 cps (counts per second) was used as a dividing line between sediments classified as fine-grained and coarser sediments. At each well, the total thickness of these finer-grained sediments was noted, as was the top and base of the finer-grained sediments. The top of the fine-grained sediments was subsequently compared to the average water level in the well. The average water levels are from regional data that includes the DAFB area. The thickness of the finer-grained sediments below the average water table was plotted and contoured (fig. 6). The rationale for mapping only that part of the section below the water table will be addressed later.

Hydrologic Framework

This investigation focused on ground-water flow in and through the shallow hydrogeologic system in the DAFB area. The units of interest included the upper and lower surficial aquifer, the confining unit in the upper part of the Calvert Formation, and the Frederica aquifer (fig. 3 and table 1). These units are of primary importance to the environmental work being conducted at DAFB for the following two reasons: The sources of contamination are all at or just below the ground surface, and most of the contamination discovered to date is in the surficial aquifer, with only minor amounts in the Frederica aquifer.

Ground-water recharge to the shallow hydrogeologic system in the DAFB area comes from precipitation that (a) does not run off directly into surface drainage ways, (b) is not evaporated, or (c) is not transpired by plants. Estimates of recharge rates range from a low of 4 in/yr (inches per year) (Applied Research Associates, Inc., 1996) to a high of 22 in/yr (Cushing, Kantrowitz, and Taylor, 1973), with most estimates of yearly recharge ranging from 8.5 in/yr to 16 in/yr (Marine and Rasmussen, 1955; Woodruff, 1967; Johnston, 1973, 1977; Talley, 1988). Discharge from the shallow ground-water system flows to local surface-water bodies, to pumped wells, or into the deeper, regional aquifers in the area. Four major surface-water bodies surround the Base: Little River, Delaware Bay, St. Jones River, and several water-filled sand-mining pits adjacent to the southwestern part of the Base at a quarry operated by Tilcon Delaware, Inc. (referred to in this report as the Tilcon ponds) (figs. 1b and 1c).

[1.] The Delaware Geological Survey (DGS) is redefining the extent of the Columbia Formation in Delaware. When DGS remaps the Dover Area, the Columbia Formation may not extend to DAFB. It is beyond the scope of this investigation to formally rename the geologic units at DAFB. For consistency with other hydrogeologic investigations at the Base, the term “Columbia Formation” is used in this report as the equivalent of the unconfined, surficial aquifer.

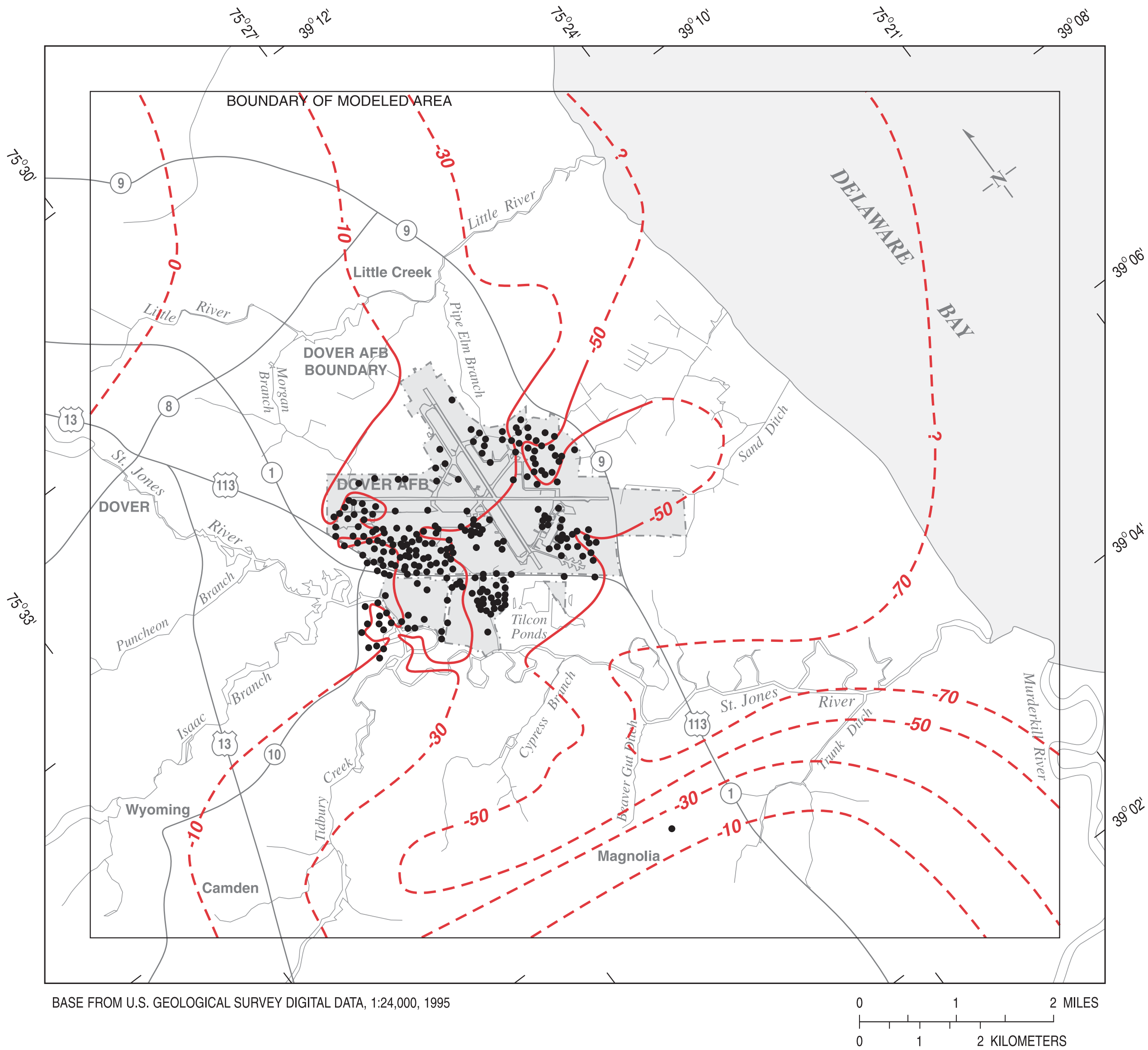


EXPLANATION

FORMATIONS AND HYDROGEOLOGIC UNITS THAT SUBCROP THE COLUMBIA FORMATION:

- FREDERICA AQUIFER
- THE CONFINING UNIT ABOVE THE FREDERICA AQUIFER IN THE UPPER CALVERT FORMATION
- CHOPTANK AQUIFER

Figure 4. Geology of the Dover Air Force Base area, Delaware (modified from Pickett and Benson, 1983; Benson and Pickett, 1986).



EXPLANATION

—-10—?— ALTITUDE OF BASE OF COLUMBIA FORMATION, IN FEET (Datum is sea level.) (Dashed where uncertain; queried where highly uncertain)

● DATA POINT

Figure 5. Altitude of the base of the Columbia Formation in the Dover Air Force Base area, Delaware.

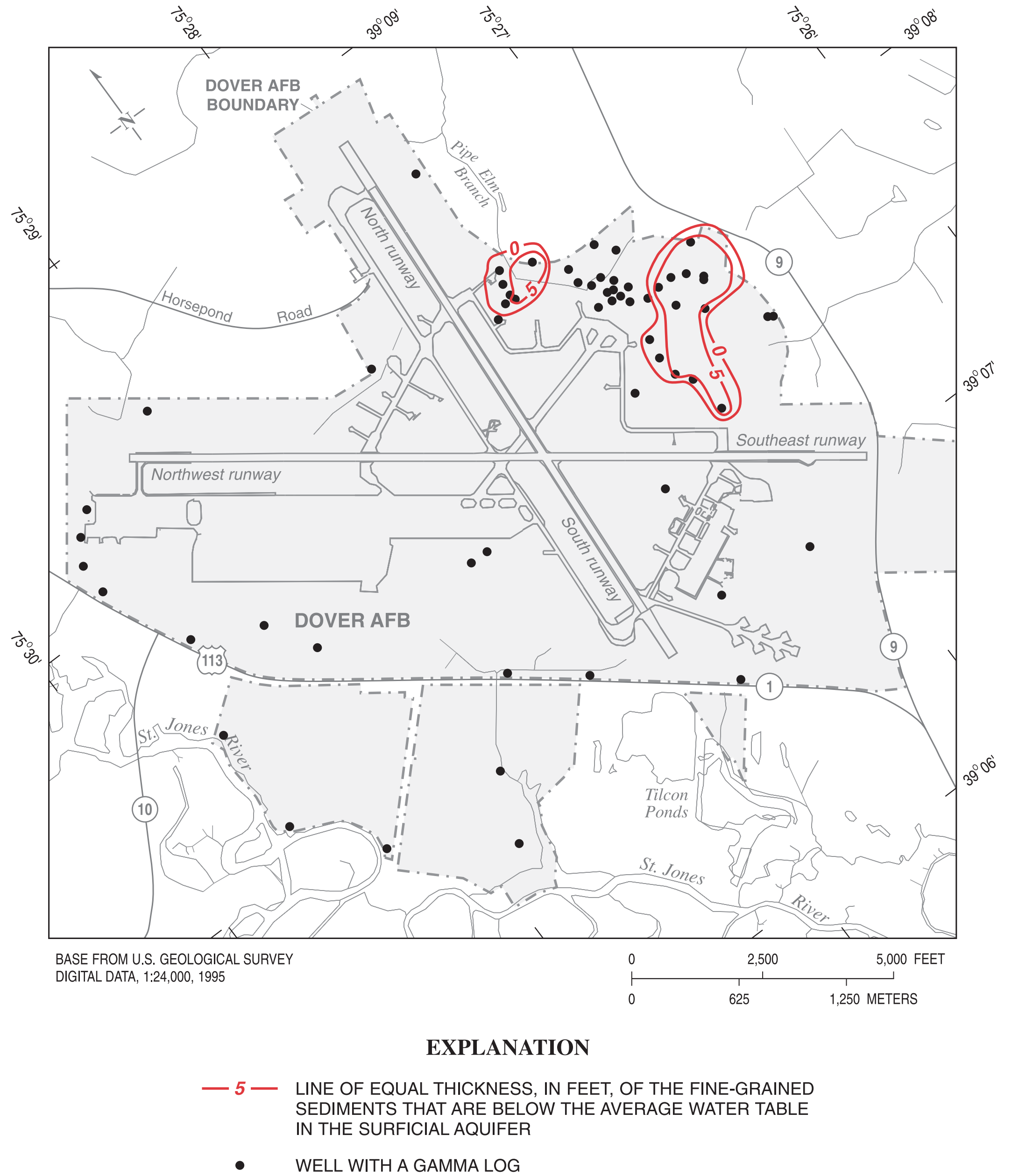


Figure 6. Locations of gamma logs and thickness of the fine-grained sediments in the Columbia Formation that are at, or below, the water table at Dover Air Force Base, Delaware.

Table 2. *Base flow at surface-water sites at Dover Air Force Base, Delaware*

Date	Discharge at selected surface-water sites (in cubic feet per day)				
	SW1-near exercise area	Pipe Elm Branch [A]	Upper Golf Course Ditch	Sand Ditch	Morgan Branch
July 16, 1997	15,552	51,840	6,048	864	864
Sept. 16-17, 1997	2,592	39,744	5,184	0	0
Nov. 20, 1997	20,736	81,216	2,592	1,728	8,640
July 27, 1998	21,600	25,920	2,592	0	0

[A] Pipe Elm Branch is affected by tides and by a manmade structure. Twice a day the tides cause a rise in stage of about one foot. A surface-water pollution-control structure, located downstream, forms a small pond that controls the low water stage of Pipe Elm Branch.

The surface-water drainage at DAFB is controlled primarily by overland flow to a storm-water drainage system consisting of underground pipes and open ditches. Surface runoff from the southwestern part of the Base flows through the drainage system and eventually discharges to the St. Jones River. Surface runoff from the eastern part of the Base flows toward the Morgan and Pipe Elm Branches of the Little River. Most of the Base drainage is collected in open or covered ditches and directed towards Pipe Elm Branch, which then enters the Little River. The lower reaches of Pipe Elm Branch are tide affected and this tidal zone extends to DAFB. There are gaining reaches upstream from the tidally influenced reaches. The golf course is drained by a tributary to the St. Jones River that gains water in the area of the golf course, and empties into a series of ponds that are connected to the St. Jones River. The St. Jones River and the Little River empty into the Delaware Bay, which is about 2.5 mi east of DAFB.

Surface-water base-flow measurements were made at several surface-water bodies 5 days after the most recent rainfall event, when it was assumed that no surface runoff was still occurring and all the base flow was ground-water discharge. These measurements could be made only in the branches and streams entering the St. Jones River, the Little River, and the Delaware Bay (fig. 1). Measurements were not possible within the rivers or the Bay because of the tidal effects. These measurements show that Pipe Elm Branch receives most of the ground-water discharge at DAFB (table 2).

The surface drainage system is necessary to keep the runways dry, and the system has all but eliminated wetlands over most of the Base. Some wetlands remain, however, along sections of Morgan Branch and Pipe Elm Branch and along some drainage ditches. On the Base, these wetlands are only a few feet wide. The most extensive wetlands are along the banks of the St. Jones River on the southwestern boundary of the Base. Outside the Base, the lower reaches of the St. Jones River and the shore of the Delaware Bay are extensive wetlands (fig. 2). The wetlands shown on figure 2 are compiled from topographic maps, infrared aerial photographs, and field surveys.

The only pond on DAFB is on the Base golf course southwest of Delaware Route 113 (fig. 1c). This pond is not part of the stormwater drainage system, but is used to hold irrigation water for the golf course. Water enters this pond from ground-water discharge and surface runoff, and is occasionally replenished from the Base water system (D. Phelan, U.S. Geological Survey, oral commun., 1995). The water levels in the pond vary depending on recharge and withdrawal from the pond.

Surficial Aquifer The surficial aquifer extends across the entire DAFB area. It consists of the sediments of the Columbia Formation, which were described earlier in this report.

Hydraulic-Head Distribution and Fluctuations—In general, the configuration of the water table appears to be controlled by the locations of surface-water bodies such as the St. Jones River, Little River, and Delaware Bay, and by the amount of recharge. The shape of the water table varies according to the amount of precipitation. If there is no recharge and no pumping from the surficial aquifer, the water table would be a gently sloping surface (fig. 7a). The altitude of the water table would be determined by the stages of the Delaware Bay, the St. Jones River, the Little River, and Pipe Elm Branch. The slope of the water table depends on the tidal range and the damping effect of the aquifer material, but it would be nearly horizontal (flat), with an altitude of about one foot.

How recharge changes the shape of the water table would depend on the hydraulic conductivity of the aquifer and the distance from the recharge areas to the discharge areas. DAFB lies on a peninsula-like feature that is surrounded by the Delaware Bay, the St. Jones River, and the Little River (fig. 7a). If the Delaware Bay, the St. Jones River, and the Little River were the only surface-water features surrounding DAFB, then the water-table contours would reflect the outline of those features (fig. 7b), culminating in one elongated water-table high centered at about DAFB. Several streams intersect this area—Morgan Branch,

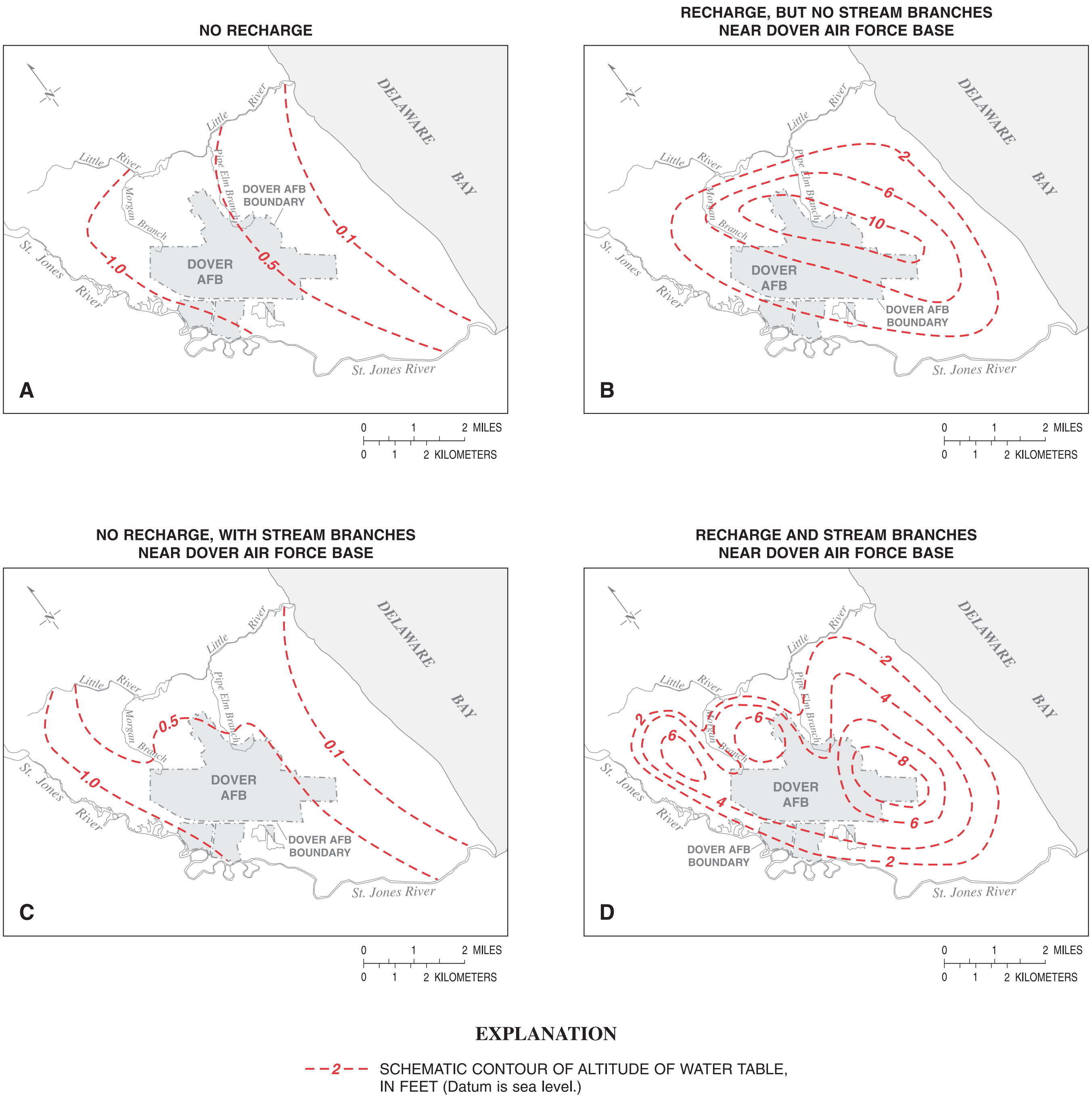


Figure 7. Expected water table for the following conditions: (**A**) no recharge, (**B**) recharge, but no stream branches near Dover Air Force Base, (**C**) no recharge, with stream branches near Dover Air Force Base, and (**D**) with recharge and stream branches near Dover Air Force Base, Delaware.

Pipe Elm Branch (fig. 7c). These streams would intersect any water-table high and the result is a series of water-table highs located roughly along the axis of this area (fig. 7d). The exact location of the highs is controlled by the distance from the recharge area to the discharge area, and by the hydraulic conductivity of the aquifer.

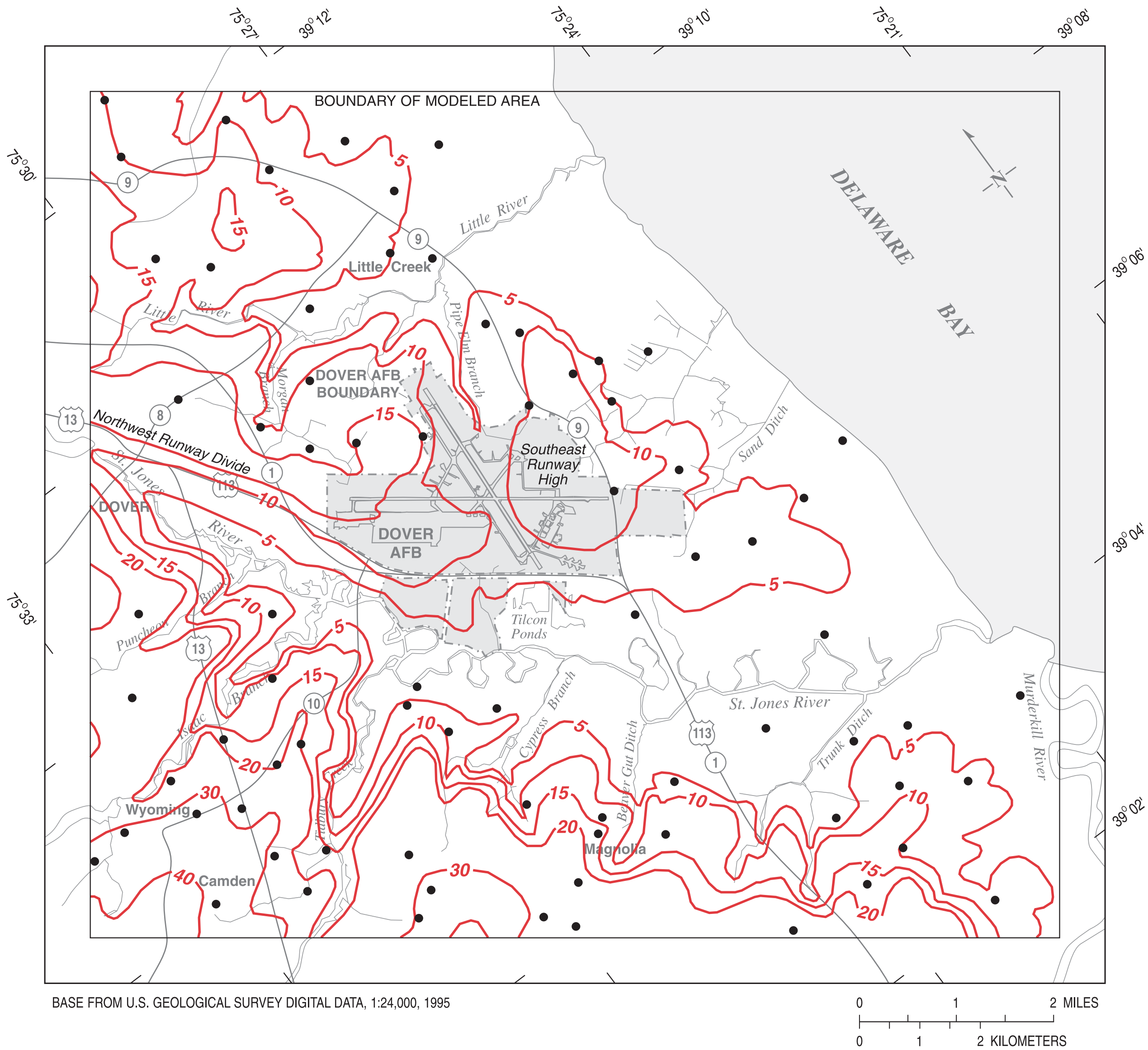
The relations discussed above can be seen in regional maps of the water table, the depth of which varies seasonally and spatially, and can range from ground surface to about 30 ft below ground surface. A general picture of the average configuration of the water table over the entire DAFB area was compiled from historical data (Adams and others, 1964; Boggess and Adams, 1965; Boggess and others, 1965; Davis and others, 1965) and is shown in figure 8. The Northwest Runway Divide trends from Route 8 east of Route 113 through the Northwestern part of the Base. The Southeast Runway High is a closed elliptical water-table high that is over the eastern part of the Base. Ground-water troughs form along river tributaries: Pipe Elm Branch and the Golf Course Tributary. Within DAFB boundaries these highs and lows roughly divide the Base into quarters (U.S. Army Corps of Engineers and Dames & Moore, Inc., 1997a) (fig. 9).

Variation in recharge causes these highs and divides to increase and decrease in amplitude. During periods of low recharge (fig. 10), the Southeast Runway High becomes very broad while the amplitude of the Northwest Runway Divide decreases. During periods of higher recharge (fig. 11), the Southeast Runway High becomes more pronounced and the amplitude of the Northwest Runway Divide increases.

Superimposed upon this recharge-controlled water table are local features seen in the upper surficial aquifer, which are referred to as "local ground-water highs" in this report. Continuous-recorder data of water levels, gamma logs, and lithologic samples were collected to study these local water-table highs. Water levels were recorded at well pairs consisting of shallow and deep wells screened in the surficial aquifer. The shallow wells have 10-ft screens placed near the water table. The deep wells have 10-ft screens placed at the base of the surficial aquifer. In well pairs, water-level hydrographs show a significant head difference of up to about 6 ft, with the higher head in the shallow well. This difference is sustained through normal wet and dry periods. During abnormally long dry periods, the difference in head decreases, and at one well pair, the difference decreased to about 0.05 ft (see DM348 S and D, fig. 12). The surficial aquifer is saturated to the level of the screens in the shallow wells, because the water levels in the deep wells are as high as the screens in the shallow wells; therefore, the water in the shallow wells is not perched (fig. 13). Gamma logs show layers with higher gamma counts towards the top of the log (fig. 13). Lithologic samples indicate that the layers with higher gamma counts are finer-grained sediments such as clays and silts, while the layers with the lower gamma counts are mainly sands. Figure 14 summarizes the relations between the local ground-water highs and the depth of well screens relative to clays in the surficial aquifer. If both wells are screened above the clay layer, then the water levels in both wells are about the same (fig. 14a). If the shallow well is screened above the clay layer and the deep well is screened below the clay layer, during times of recharge the water levels in the shallow well are higher than the water levels in the deeper well (fig. 14b). If the shallow well is screened in the clay layer and the screen does not penetrate the layer, there can be a local ground-water high (fig. 14c). If both wells are screened below the clay layer, there is not a large difference in heads from the two wells and a local ground-water high can can go unrecognized (fig. 14d). In summary, two conditions must be met to form a local ground-water high that can be recognized: (1) the fine-grained sediments must be continuous over an area that can support a local ground-water high, and (2) the screen in the shallow well must be in or above the fine-grained sediments. If these conditions are met, local ground-water highs can form and be recognized under average recharge conditions (fig. 15). These local ground-water highs show a similar response to recharge as do regional highs. For example, the amplitude of the high that is near the Southeast Runway increases as recharge goes from drier (fig. 16) to wetter (fig. 17) conditions.

Comparison of hydrographs from on-Base wells to a hydrograph from a long-record well, Jd42-03, approximately 2 mi. northwest of DAFB, shows that the dry and wet periods seen in the mid–1990's are common (fig. 12). The hydrographs from wells DM110S and DM110D at DAFB show the rise in the water table from a relatively dry time, October 1995, to a relatively wet time, July 1996, and back to an average summer of 1997 (fig. 12). The long-record hydrograph from the area of DAFB shows that the synoptic water-level measurements mentioned earlier were obtained during extremes in the water table. The December 1993 (fig. 16) synoptic was collected during a period when the water table was low. The May 1994 synoptic (fig. 17) was collected during a period when the water table was high. Transient water-level conditions should be considered in the design of any long-term remedial systems. If a remedial system was built during a dry period and it was necessary to collect samples at the water table, then the sampling points placed at the water table during the dry period could be under the water table during the wetter periods.

Two of the hydrographs (DM412D and MW33D) in figure 12 show water-level declines that may be related to operations in the Tilcon Ponds, which are used in surface mining of sands and gravels. The water levels in these ponds are affected by the gravel mining operations. Sand and gravel are removed with a dredge system, mixed with water from the pond that is being actively mined, and transported in a slurry through a pipe to the cleaning and separating plant. Water from the slurry is discharged into a pond near the plant, and returns to the active pond through a series of canals. The water levels in the pond that is being actively mined may be lowered due to the removal of water from this pond, especially if the return canals are blocked for some

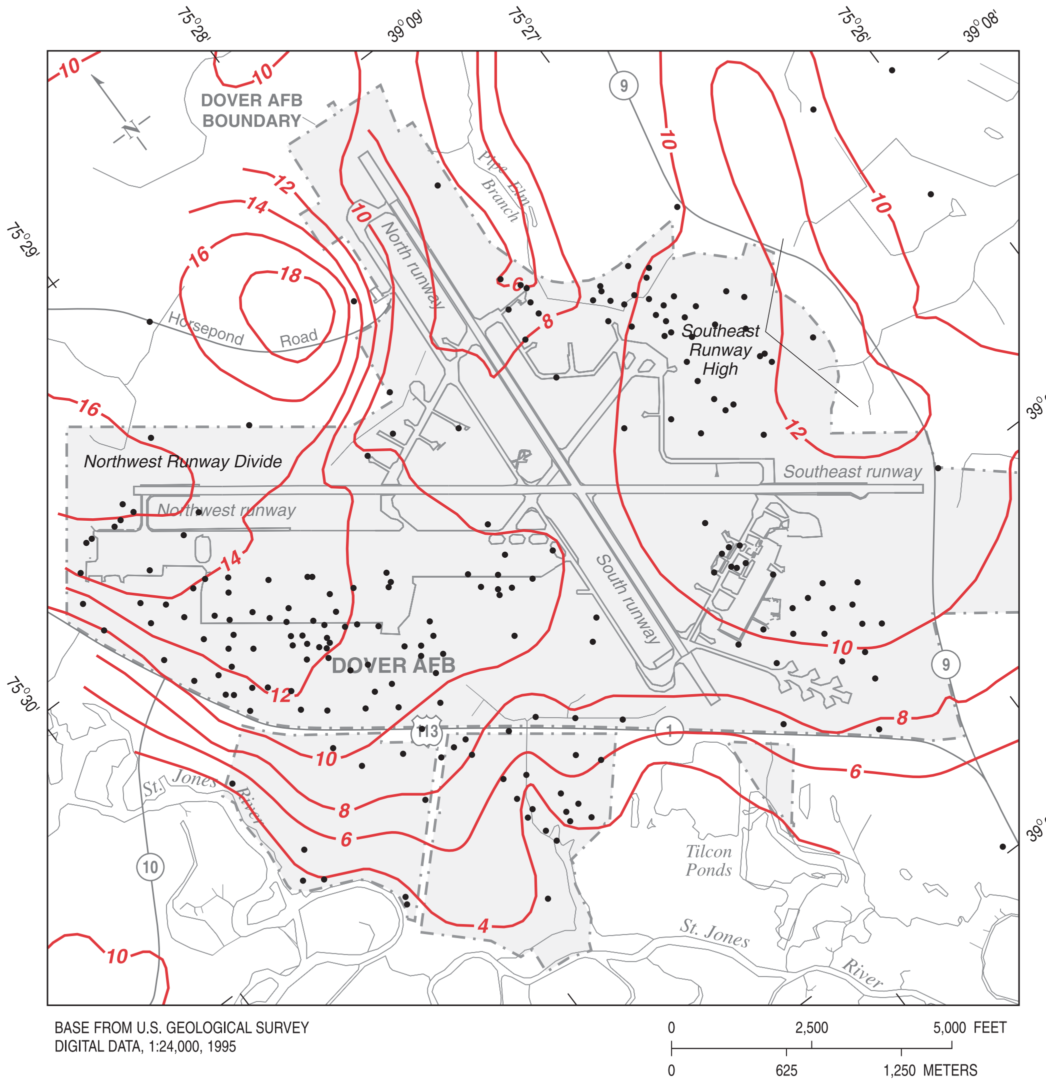


EXPLANATION

—10— ALTITUDE OF WATER TABLE UNDER AVERAGE RECHARGE CONDITIONS (October 1959), IN FEET (Datum is sea level.) (Regional data from Adams and others, 1964; Boggess and Adams, 1965; Boggess and others, 1965; Davis and others, 1965)

● DATA POINT

Figure 8. Hydraulic head in the lower surficial aquifer in the Dover Air Force Base area under average recharge conditions, October 1959.

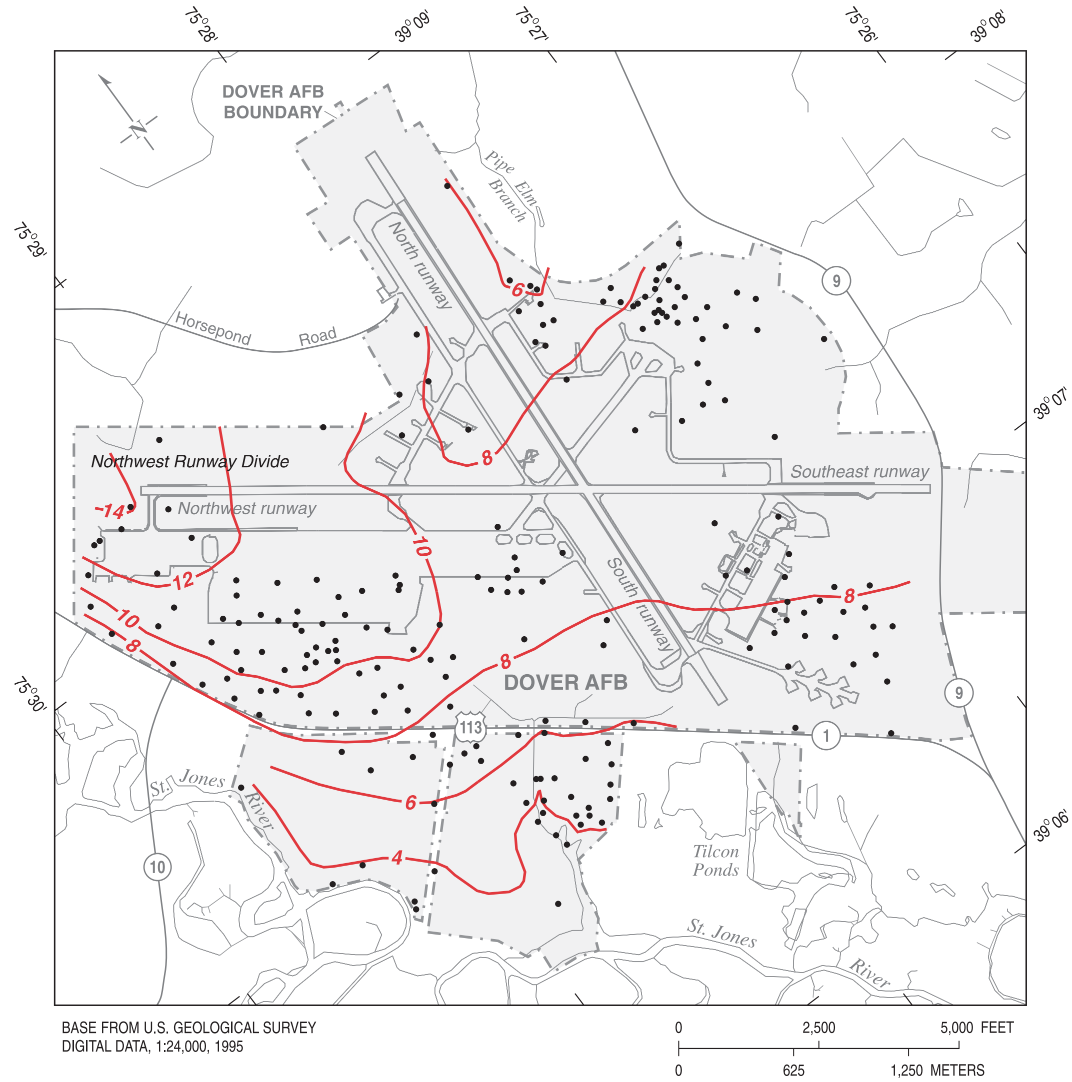


EXPLANATION

—10— ALTITUDE OF WATER TABLE UNDER AVERAGE RECHARGE CONDITIONS (October 1959), IN FEET (Datum is sea level.) (Regional data from Adams and others, 1964; Boggess and Adams, 1965; Boggess and others, 1965; Davis and others, 1965. Local detail by U.S. Geological Survey from interpretation of data from U.S. Army Corps of Engineers and Dames & Moore, 1997a.)

● DATA POINT

Figure 9. Average hydraulic head in the lower part of the surficial aquifer in the detailed investigation area at Dover Air Force Base, Delaware, October 1959.

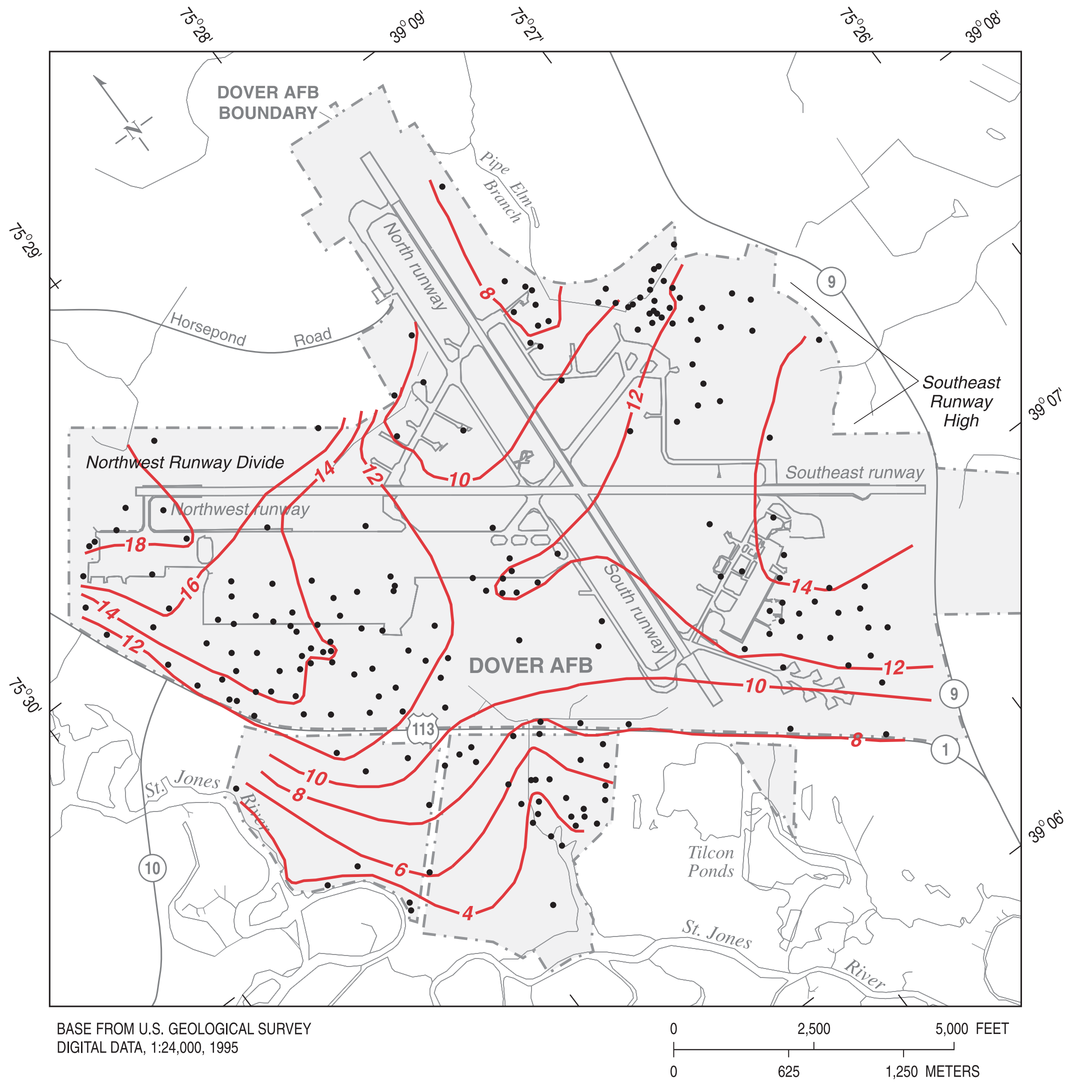


EXPLANATION

—10— ALTITUDE OF WATER LEVELS IN THE LOWER SURFICIAL AQUIFER (December 1993), IN FEET (Datum is sea level.) (Data from U.S. Army Corps of Engineers and Dames & Moore, 1997a; contours by U.S. Geological Survey)

• DATA POINT

Figure 10. Hydraulic head in the lower surficial aquifer in the detailed investigation area at Dover Air Force Base, Delaware, December 1993.

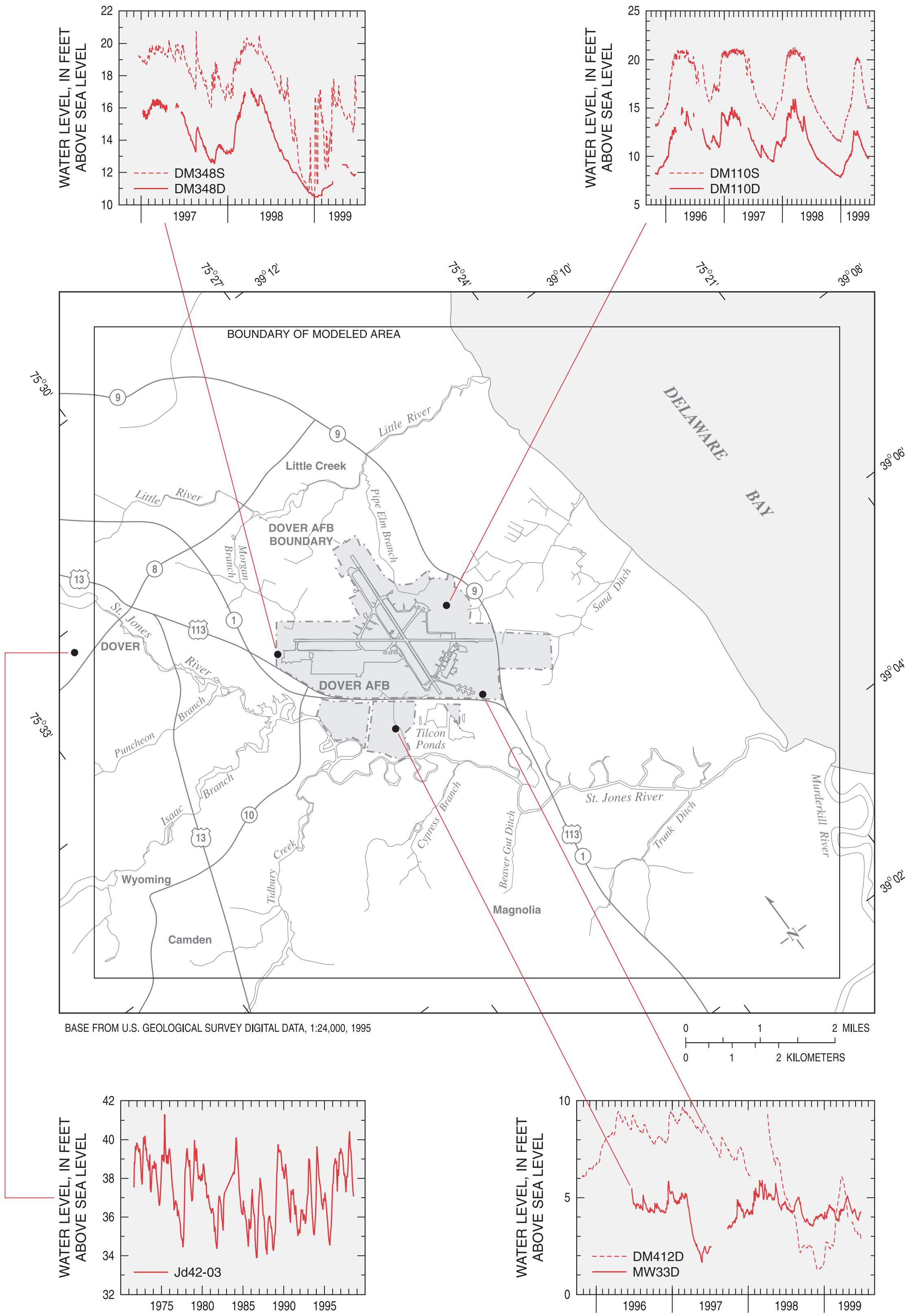


EXPLANATION

—10— ALTITUDE OF WATER LEVELS IN THE LOWER SURFICIAL AQUIFER (May 1994), IN FEET (Datum is sea level.) (Data from U.S. Army Corps of Engineers and Dames & Moore, 1997a; contours by U.S. Geological Survey)

● DATA POINT

Figure 11. Hydraulic head in the lower surficial aquifer in the detailed investigation area at Dover Air Force Base, Delaware, May 1994.



EXPLANATION

DM348S ● MONITOR WELL AND IDENTIFICATION NUMBER (The last letter refers to where the well is screened. S represents a shallow well, screened in the upper surficial aquifer; D represents a deep well, screened in the lower surficial aquifer.)

Figure 12. Water levels for six wells completed in the surficial aquifer at Dover Air Force Base and for one long-record well (Jd42-03) completed in the surficial aquifer, Dover Air Force Base area, Delaware.

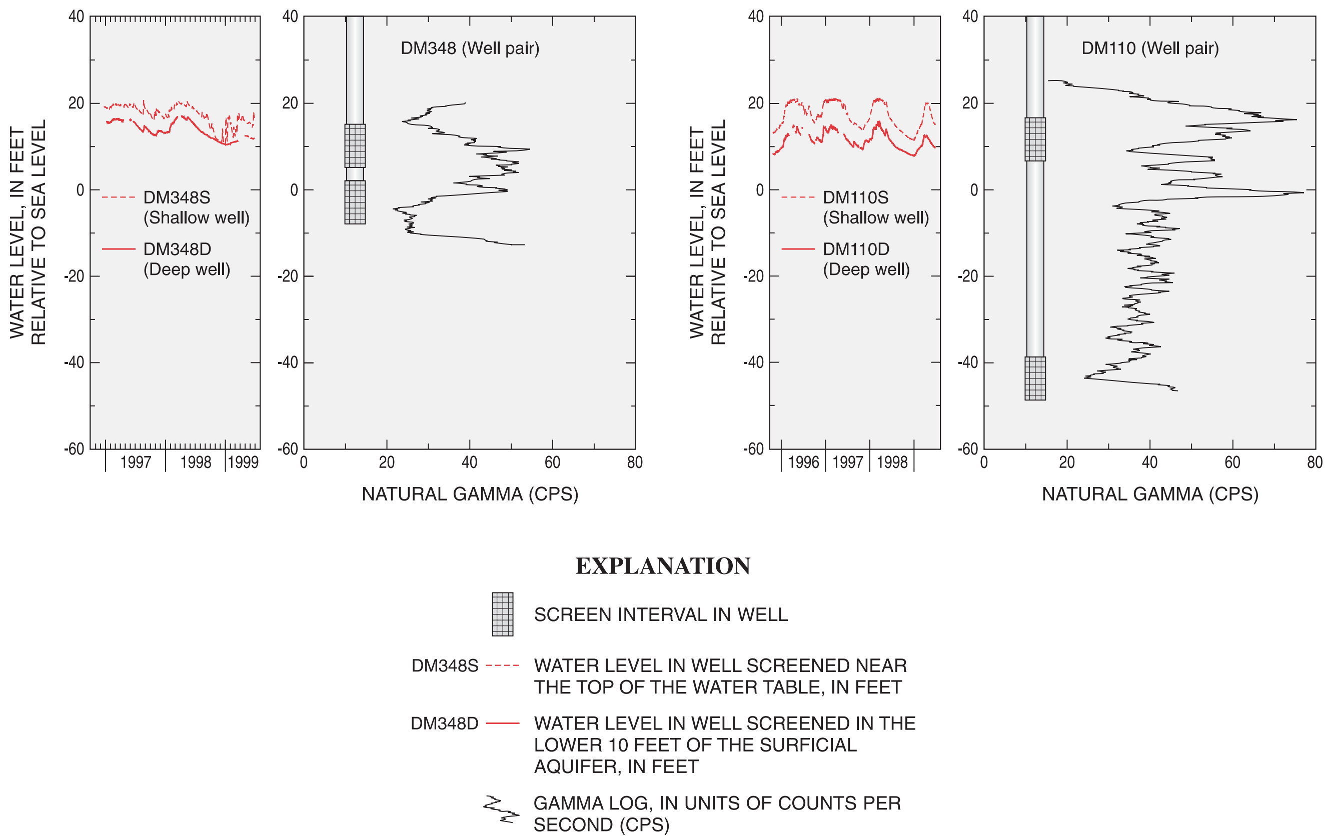


Figure 13. Water levels, screen intervals, and natural gamma logs for two well pairs (locations shown in figure 12) at Dover Air Force Base, Delaware.

reason. During the summer of 1998, Tilcon Delaware, Inc., began dredging operations in a new mining pond approximately 2,000 ft southwest of monitoring well DM412D, on the southwestern side of DAFB. The water level in DM412D shows a marked drop for this period (fig. 12). A possible explanation is that pumping in the actively mined pond lowered the water level in this pond, thus depressing the water table, which is reflected in the hydrograph. A similar decline in water level is seen in the spring of 1997 for well MW33D, which is also adjacent to the Tilcon Delaware, Inc., property (fig. 12). The mining operation was not monitored at this time, however, and it is unknown if this decline in water level at MW33D was due to mining in the pond adjacent to MW33D, or to some other cause.

Hydraulic Conductivity—Hydraulic conductivity values for the surficial aquifer were obtained from various investigations in the DAFB area (table 3), and range from about 0.1 ft/d (feet per day) (Eng, 1995) to about 250 ft/d (CH2M Hill Southeast, Inc., 1988b). Such hydraulic conductivity values are typical of the sediments that make up the surficial aquifer at DAFB, which range from clays and silts to clean sands.

For the upper part of the surficial aquifer, hydraulic conductivity was assumed to be relatively constant within each of two regions in the investigation area—the fine-grained sediments adjacent to major surface-water bodies, and the coarse-grained sediments in the upland areas farther away. Silts and mud deposited in wetlands adjacent to the Delaware Bay and smaller estuaries give these areas a finer sediment texture than the sands and gravels that predominate in the uplands. The extent of the wetlands and marshes is shown in figure 2. Fine-grained sediments in the upper surficial aquifer are seen at the Wildcat Landfill (CH2M Hill Southeast, Inc., 1988a, 1988b). Slug tests of 10 wells screened in the upper surficial aquifer yield a mean value of 1.86 ft/d (U.S. Army Corps of Engineers and Dames & Moore, Inc., 1997a).

No hydraulic conductivities have been determined for the clays that separate part of the upper surficial aquifer from the lower surficial aquifer. Values from previously published studies were used as a basis for estimated values. Fetter (1988) suggests 2.8×10^{-3} ft/d to 2.83×10^{-6} ft/d as the range of hydraulic conductivities of clay, although it is not noted if this is a horizontal or vertical hydraulic conductivity.

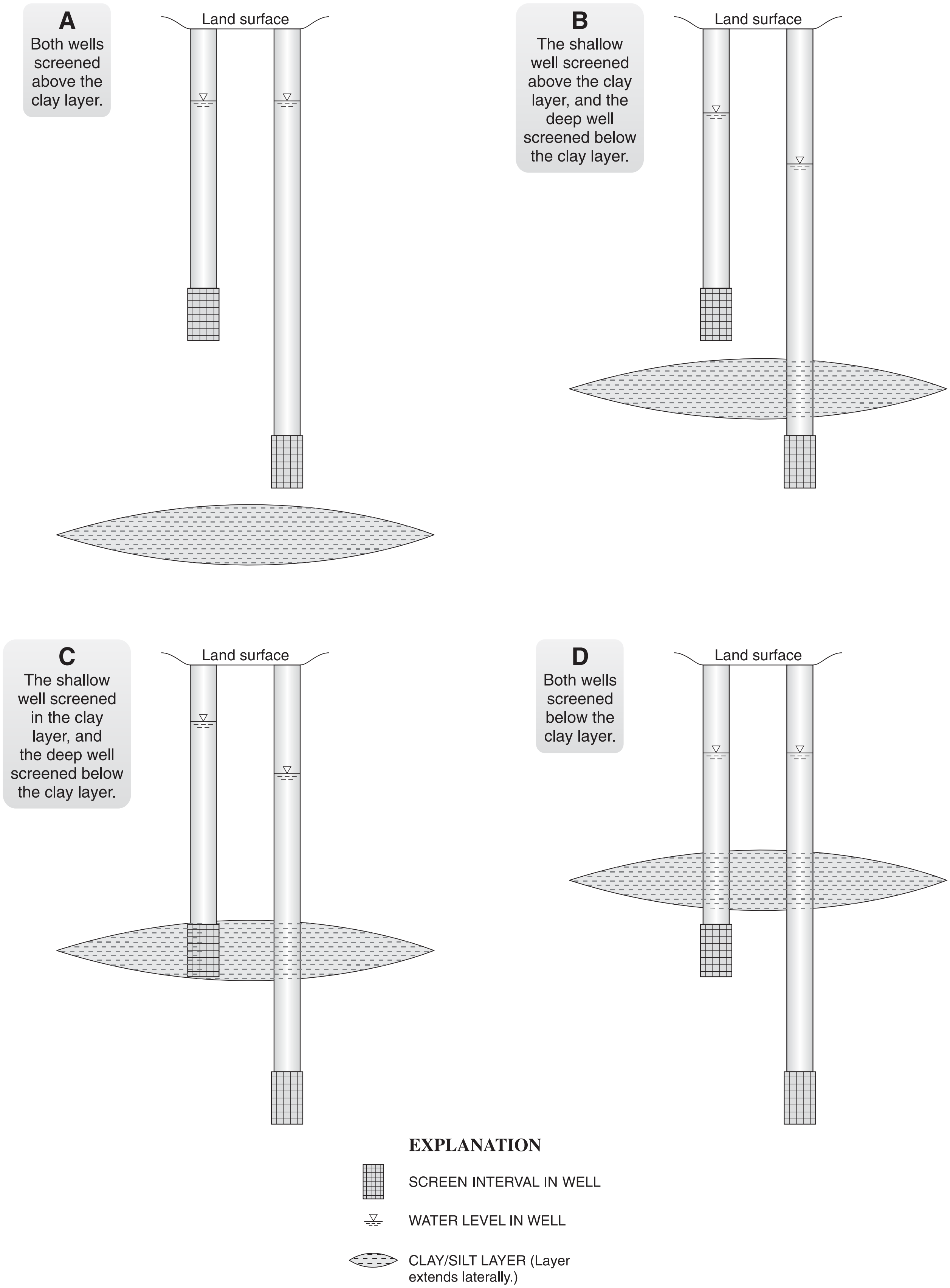
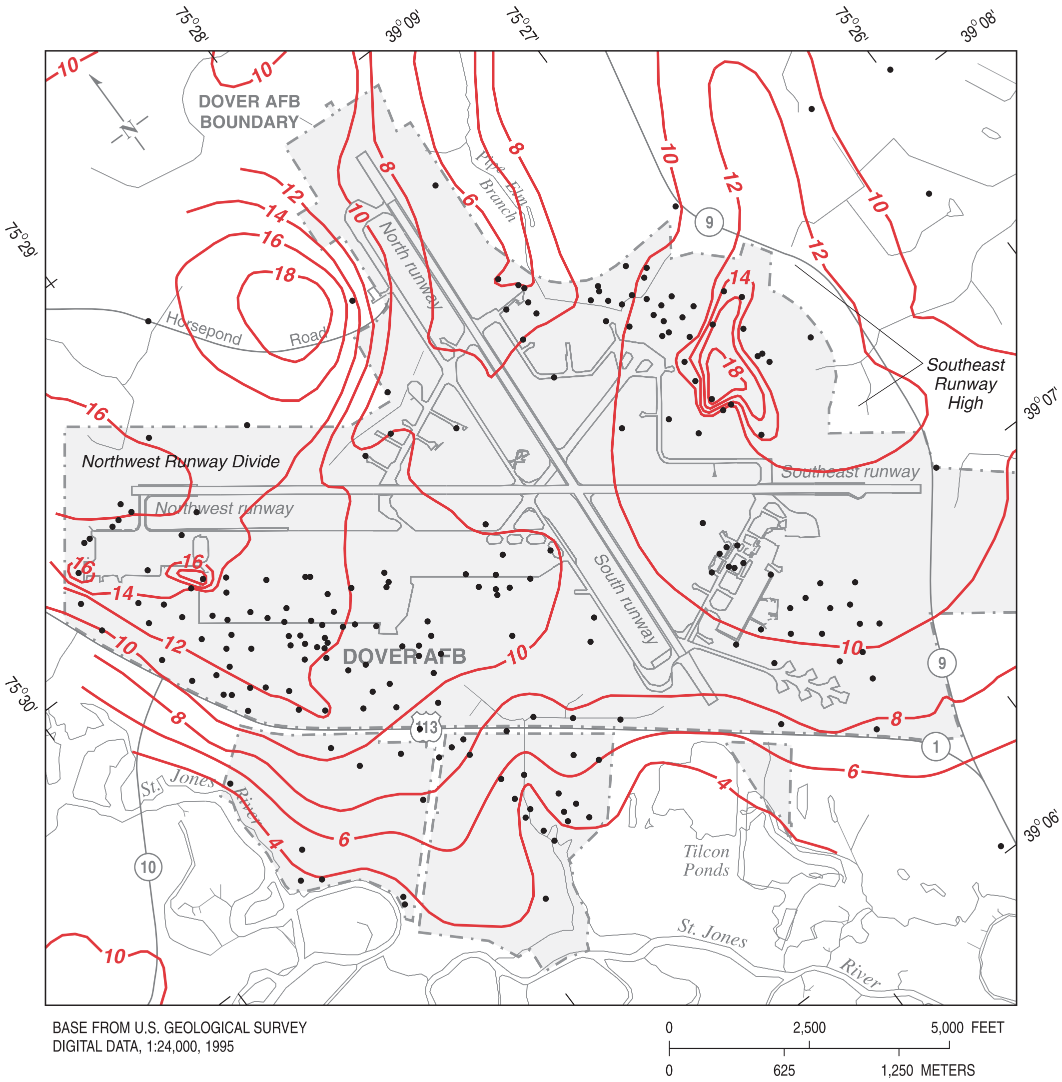


Figure 14. Screen interval in relation to a clay layer in the surficial aquifer, and the recognition of local ground-water highs at Dover Air Force Base, Delaware.

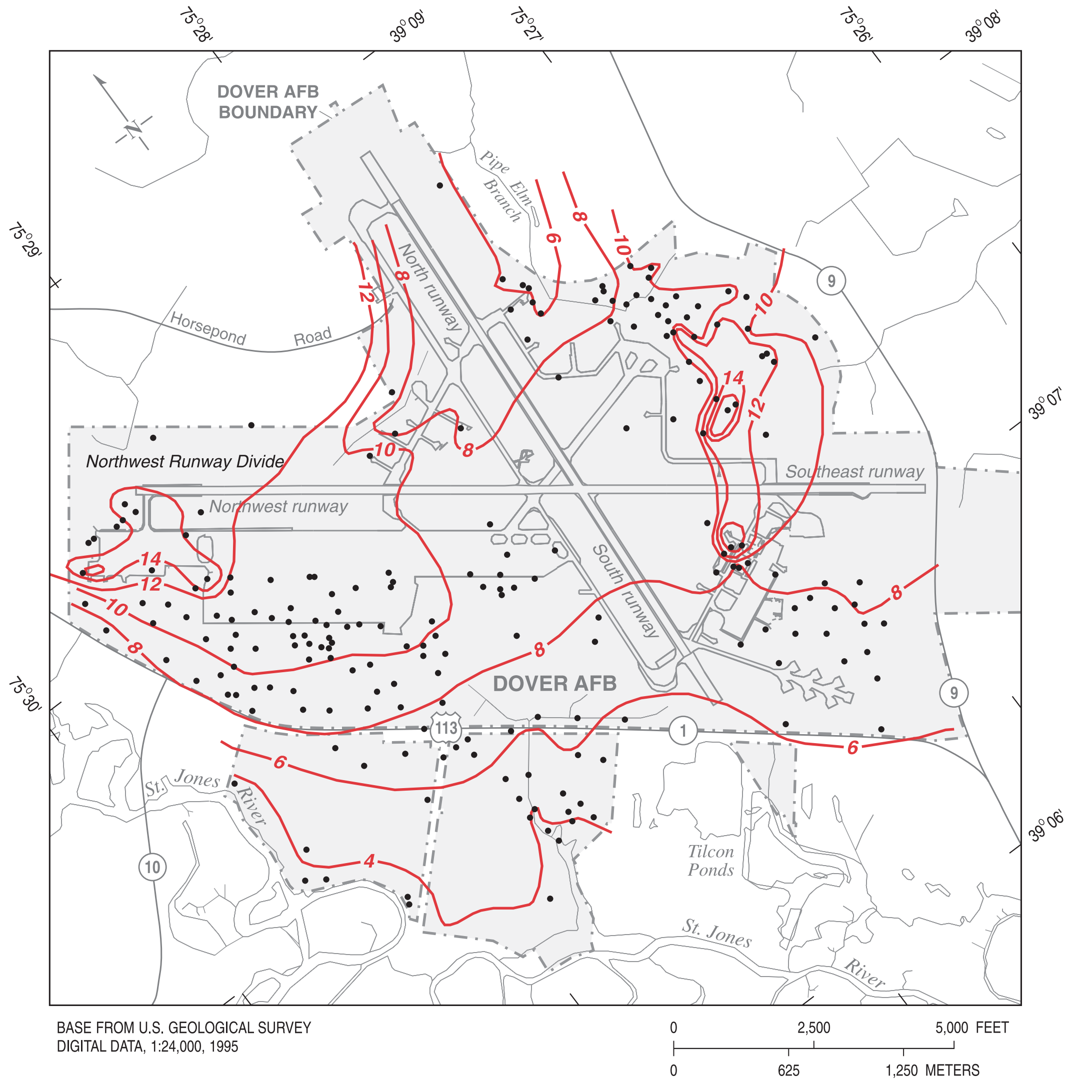


EXPLANATION

—10— ALTITUDE OF WATER TABLE UNDER AVERAGE RECHARGE CONDITIONS (October 1959), IN FEET (Datum is sea level.) (Regional data from Adams and others, 1964; Boggess and Adams, 1965; Boggess and others, 1965; Davis and others, 1965. Local detail by U.S. Geological Survey from interpretation of data from U.S. Army Corps of Engineers and Dames & Moore, 1997a. Estimate of local water-table high near eastern Base boundary from U.S. Geological Survey observations of water levels, 1995-1999.)

● DATA POINT

Figure 15. Average hydraulic head in the upper surficial aquifer in the detailed investigation area at Dover Air Force Base, Delaware (October 1959 data with the values of the eastern ground-water high based upon observations from 1995 to 1999).

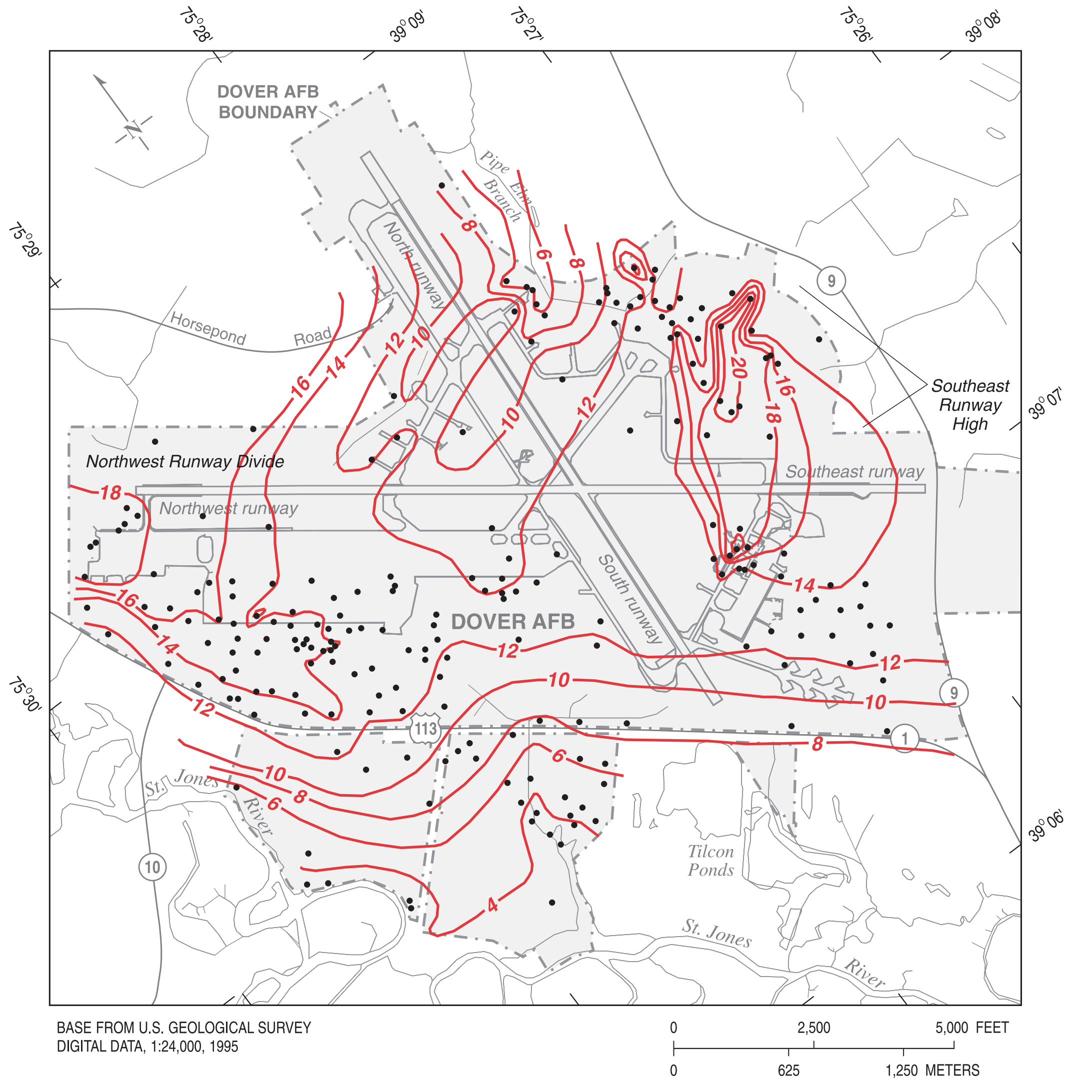


EXPLANATION

—10— ALTITUDE OF WATER TABLE IN THE UPPER SURFICIAL AQUIFER (December 1993), IN FEET (Datum is sea level.) (Data from U.S. Army Corps of Engineers and Dames & Moore, 1997a; contours by U.S. Geological Survey)

● DATA POINT

Figure 16. Hydraulic head in the upper surficial aquifer during a period of low recharge in the detailed investigation area at Dover Air Force Base, Delaware, December 1993.



EXPLANATION

—10— ALTITUDE OF WATER TABLE IN THE UPPER SURFICIAL AQUIFER (May 1994), IN FEET (Datum is sea level.) (Data from U.S. Army Corps of Engineers and Dames & Moore, 1997a; contours by U.S. Geological Survey)

● DATA POINT

Figure 17. Hydraulic head in the upper surficial aquifer during a period of high recharge in the detailed investigation area at Dover Air Force Base, Delaware, May 1994.

Table 3. *Hydraulic properties for selected aquifers and confining units in the Dover Air Force Base area, Delaware*

[The table is arranged in alphabetical order by author and year in the reference column; in/yr, inches per year; ft/d, feet per day; ft, feet; ft²/d, feet squared per day; –, no data available; *K*, hydraulic conductivity; GRFL, Ground-Water Remediation Field Laboratory]

Reference	Comments	Recharge to surficial aquifer (in/yr)	Horizontal hydraulic conductivity of the upper surficial aquifer (ft/d)	Horizontal hydraulic conductivity of the lower surficial aquifer (ft/d)	Confining unit hydraulic conductivity (ft/d)	Frederica aquifer horizontal hydraulic conductivity (ft/d)
This investigation		12	0.1 to 5	65	0.002	25
Applied Research Associates, Inc. (1996)	[A] This value used for a ground-water-flow model for the area of the GRFL. [B] This value is an estimated value, range of two pumping tests and slug test, 1.76 to 45.52. [C] This value is an average value, range of six cone-penetrometer tests, 2.2×10^{-3} to 4.2×10^{-2}.	4 [A]	–	8.5 [B]	0.0084 [C]	–
CH2M Hill Southeast, Inc. (1988a, 1988b)	[D] Aquifer test, Table G-4, Volume II, CH2M Hill Southeast, Inc. (1988b). [E] Slug test, p. 4-29. CH2M Hill Southeast, Inc. (1988a). [F] Slug test in wetland silts. [G] CH2M Hill Southeast, Inc. (1988a, p. 4-29), do not consider the Frederica aquifer values to be representative because of recharge from the St. Jones River.	–	–	77 to 200 [D] 7.1 to 94 [E]	0.05 to 5.1 [F]	11 to 36 [G]

Table 3. *Hydraulic properties for selected aquifers and confining units in the Dover Air Force Base area, Delaware–Continued*

Reference	Comments	Recharge to surficial aquifer (in/yr)	Horizontal hydraulic conductivity of the upper surficial aquifer (ft/d)	Horizontal hydraulic conductivity of the lower surficial aquifer (ft/d)	Confining unit hydraulic conductivity (ft/d)	Frederica aquifer horizontal hydraulic conductivity (ft/d)
Cushing, Kantrowitz, and Taylor (1973)	[H] From analysis of base flow of 33 streams on the Delmarva Peninsula. [I] Represents total range of values from extreme years.	8.5 [H], 2.2 to 22 [I]	–	–	–	–
EA Engineering, Science, and Technology, Inc. (1991)	[J] Average of two slug tests on wells completed only in the lower 10 ft of the surficial aquifer. This report also had two transmissivities determined by a pump test (approximately 18,500 ft^2/d and approximately 10,900 ft^2/d) with an average of 14,800 ft^2/d, which gives a *K* of 537 ft/d when the transmissivity is divided by a reported saturated thickness of 27.5 ft.	–	–	32 [J]	–	–
Eng (1995)	[K] Determined by analysis of grain size. Maximum range of values from fig. 8 of Eng (1995).	–	–	0.3 to 160 [K]	–	–
Johnston (1973)		14	–	–	–	–
Johnston (1976)	[L] Values given are discharge to streams, which is added to evapotranspiration to obtain the ground-water recharge cited in most studies; the four values are from four small basins that Johnston studied.	13, 12, 14, 15 [L]	–	–	–	–

Table 3. *Hydraulic properties for selected aquifers and confining units in the Dover Air Force Base area, Delaware–Continued*

Reference	Comments	Recharge to surficial aquifer (in/yr)	Horizontal hydraulic conductivity of the upper surficial aquifer (ft/d)	Horizontal hydraulic conductivity of the lower surficial aquifer (ft/d)	Confining unit hydraulic conductivity (ft/d)	Frederica aquifer horizontal hydraulic conductivity (ft/d)
Johnston (1977)		14	–	50 to 250	–	–
Marine and Rasmussen (1955)		10	–	–	–	–
Science Applications International Corporation (1989)	[M] Science Applications International Corporation (1989) determined transmissivity at two wells then applied this transmissivity to other parts of the Base and divided by an aquifer thickness at other parts of the Base to obtain hydraulic conductivity values.	–	–	110 [M]	–	–
Talley (1988)		13 to 16	–	–	–	–
U.S. Army Corps of Engineers and Dames & Moore, Inc. (1997a)	[N] Average of slug tests on 10 shallow wells in the surficial aquifer. [O] Average of slug tests on 10 deep wells in the surficial aquifer. [P] Average of slug tests on three wells completed in the Frederica aquifer.	–	1.9 [N]	12 [O]	.0015 to .0068	6.9 [P]
Woodruff (1967)		12	–	–	–	–

Freeze and Cherry (1979) indicate a similar range of hydraulic conductivities—2.83×10^{-4} ft/d to 2.83×10^{-7} ft/d—for clay, but again do not specify whether this is a horizontal or a vertical hydraulic conductivity.

The lower part of the surficial aquifer has a higher hydraulic conductivity than the upper part of the aquifer (table 3) (M. Noll, Applied Research Associates, Inc., oral commun.; 1995; R. Lyon, Dames & Moore, Inc., oral commun., 1995). Slug tests of ten wells screened in the lower surficial aquifer yield a mean value of 11.70 ft/d (U.S. Army Corps of Engineers and Dames & Moore, Inc., 1997a). Other investigators also used slug tests to determine hydraulic conductivities from 7.09 ft/d to 93.54 ft/d, and aquifer tests to determine hydraulic conductivities from 76.82 ft/d to 198.43 ft/d (CH2M Hill Southeast, Inc., 1988a, 1988b). Eng (1995) used a grain-size analysis to determine that hydraulic conductivities ranged from 0.3 ft/d to 155.9 ft/d. Applied Research Associates, Inc. (1996) used slug tests and aquifer tests to determine that hydraulic conductivities ranged from 1.76 ft/d to 45.52 ft/d.

Upper Confining Unit of Calvert Formation The upper confining unit of the Calvert Formation underlies the surficial aquifer. Its top and bottom surfaces are equivalent to the base of the surficial aquifer and the top of the Frederica aquifer, respectively. As discussed in earlier sections of this report, the altitudes of these surfaces were obtained from various data sources. Within DAFB, the top and bottom of the confining unit were determined from lithologic logs. Gamma logs also were collected in most of the wells that penetrated this unit. Outside DAFB, the altitude of the bottom of the surficial aquifer is somewhat less reliable, and the altitude of the top of the Frederica aquifer was determined from well-completion reports in the DNREC water-supply files. A GIS was used to combine the altitude information for the top of the Frederica aquifer. These values were then contoured manually. By use of a GIS, the thickness of the confining unit (fig. 18) was calculated by subtracting the altitude of the top of the Frederica aquifer from the altitude of the base of the surficial aquifer. Only a few of the wells that penetrate the Frederica aquifer outside DAFB have reliable lithologic logs; thus the map outside of DAFB is generalized.

The clays and silts of the upper Calvert Formation act as a confining unit for the underlying Frederica aquifer. The U.S. Army Corps of Engineers and Dames & Moore, Inc., (1997a) estimated that ground-water flow from the surficial aquifer to the Frederica aquifer through the confining unit would take approximately 100 years. To obtain this number, they assumed an average thickness of 19.6 ft, a vertical hydraulic conductivity (given as permeability in the RI) of 1.98×10^{-3} ft/d, a head gradient of 0.11 ft (for December 1993 conditions) and a porosity of 40 percent (U.S. Army Corps of Engineers and Dames & Moore, Inc., 1997a, p. 3–67). In the center of DAFB, U.S. Army Corps of Engineers and Dames & Moore, Inc., (1997a) discovered a small area, just to the west of where the runways cross, where the confining unit is missing and the surficial aquifer is in direct contact with the Frederica aquifer. A gamma log for well MW85P (on file at the USGS office, Dover, Delaware), however, shows about 5 ft of fine-grained material at this location. Thus, it is likely that a thin confining unit is present between the surficial aquifer and the Frederica aquifer in the area.

No wells are completed in this section of the Calvert Formation so there are no maps of hydraulic-head distribution nor any data on hydraulic-head fluctuations. Falling-head permeameter measurements were used to determine that the vertical hydraulic conductivity of the confining unit ranges from 0.00153 ft/d to 0.00683 ft/d (U.S. Army Corps of Engineers and Dames & Moore, Inc., 1997a).

Frederica Aquifer Beneath the upper confining unit of the Calvert Formation is the Frederica aquifer, a sand about 20 ft thick in the DAFB area (U.S. Army Corps of Engineers and Dames & Moore, Inc., 1997a). On the Base, 14 monitoring wells are screened in this aquifer. The approximate altitude of the top of the Frederica aquifer is shown in figure 19. Information about the altitude of the bottom of the Frederica aquifer is limited, so for this investigation, the thickness is assumed to be constant.

Hydraulic-Head Distribution, Fluctuation, and Gradient—The Frederica aquifer is recharged from the subcrop area (fig. 4) and from leakage through the confining unit. Figure 20 shows an interpretation of its potentiometric surface. In general, the fluctuation of head in the Frederica aquifer is similar to that of the head in the surficial aquifer. An exception to this pattern occurs during periods of irrigation in the growing season. Figure 21 shows the water level in wells DM102F and DM421F declining to below sea level during the growing seasons of 1996 to 1999. These declines were not seen in another well (DM378F) screened in the Frederica aquifer, which is located in the northwestern part of the Base. The cause of these declines may be irrigation pumping from the Frederica aquifer south and east of the Base. Although the wells can be seen from the road, the State of Delaware does not have records on the wells; thus, it is not known which specific wells pump from the Frederica aquifer, nor is the amount of pumpage known.

For most of DAFB, the vertical head gradient is from the lower surficial aquifer towards the Frederica aquifer. For a well group located on the golf course and near the St. Jones River (fig. 1c) however, this gradient can reverse. Table 4 shows this reversal. For most of the synoptic water-level measurements, the vertical head gradient is from the Frederica aquifer towards the lower surficial aquifer. The month of July 1998 fell within an extended dry period when the gradient reversed, perhaps due to pumping in the Frederica aquifer (see fig. 21). During this time, the vertical head gradient was from the lower surficial aquifer towards the Frederica aquifer. December 1993 also fell during a dry period, and the gradient was from the surficial aquifer towards the Frederica aquifer. During this time, it is highly unlikely that there was any irrigation that would lower the head in the

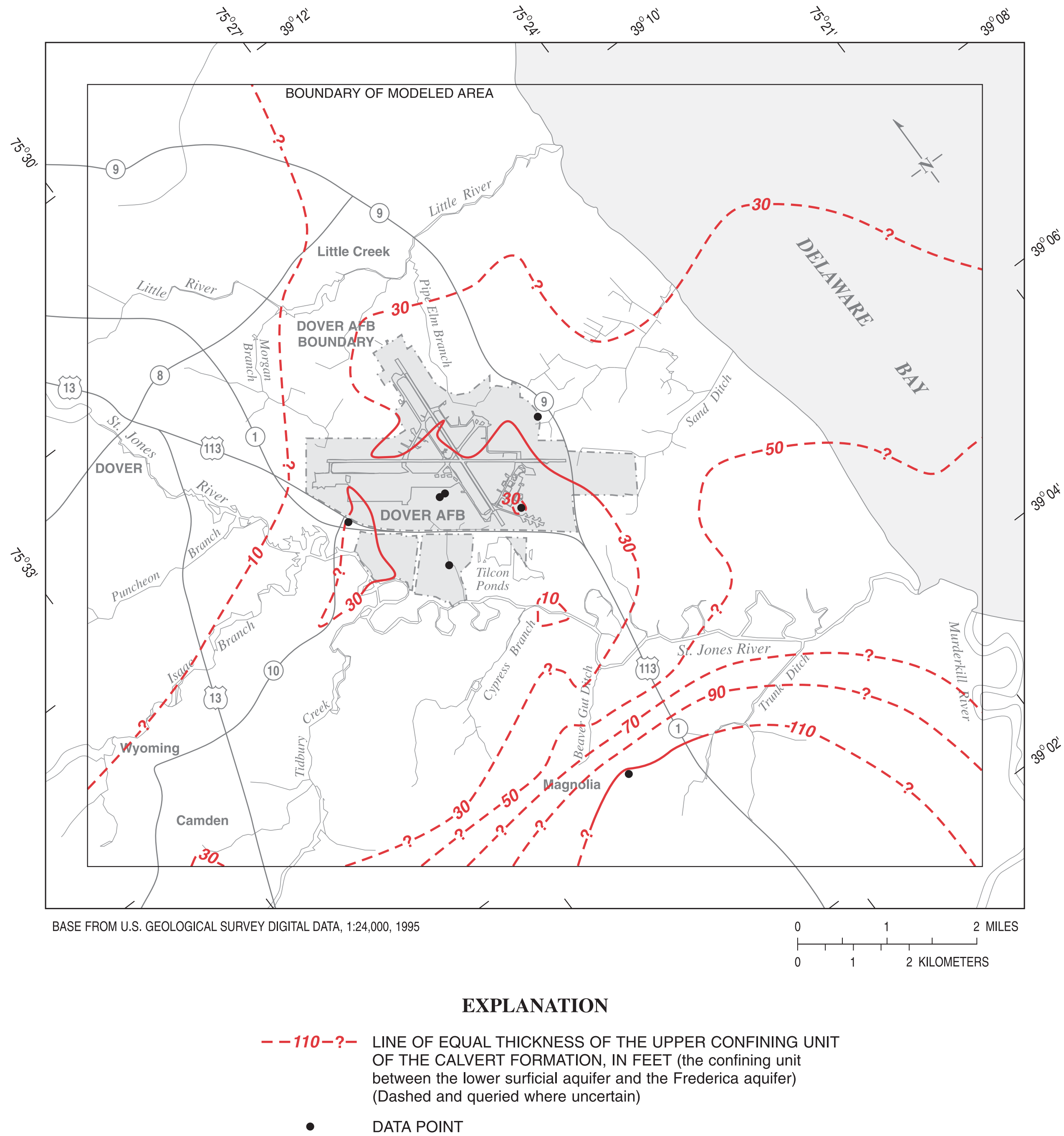


Figure 18. Approximate thickness of the upper confining unit of the Calvert Formation, Dover Air Force Base area, Delaware.

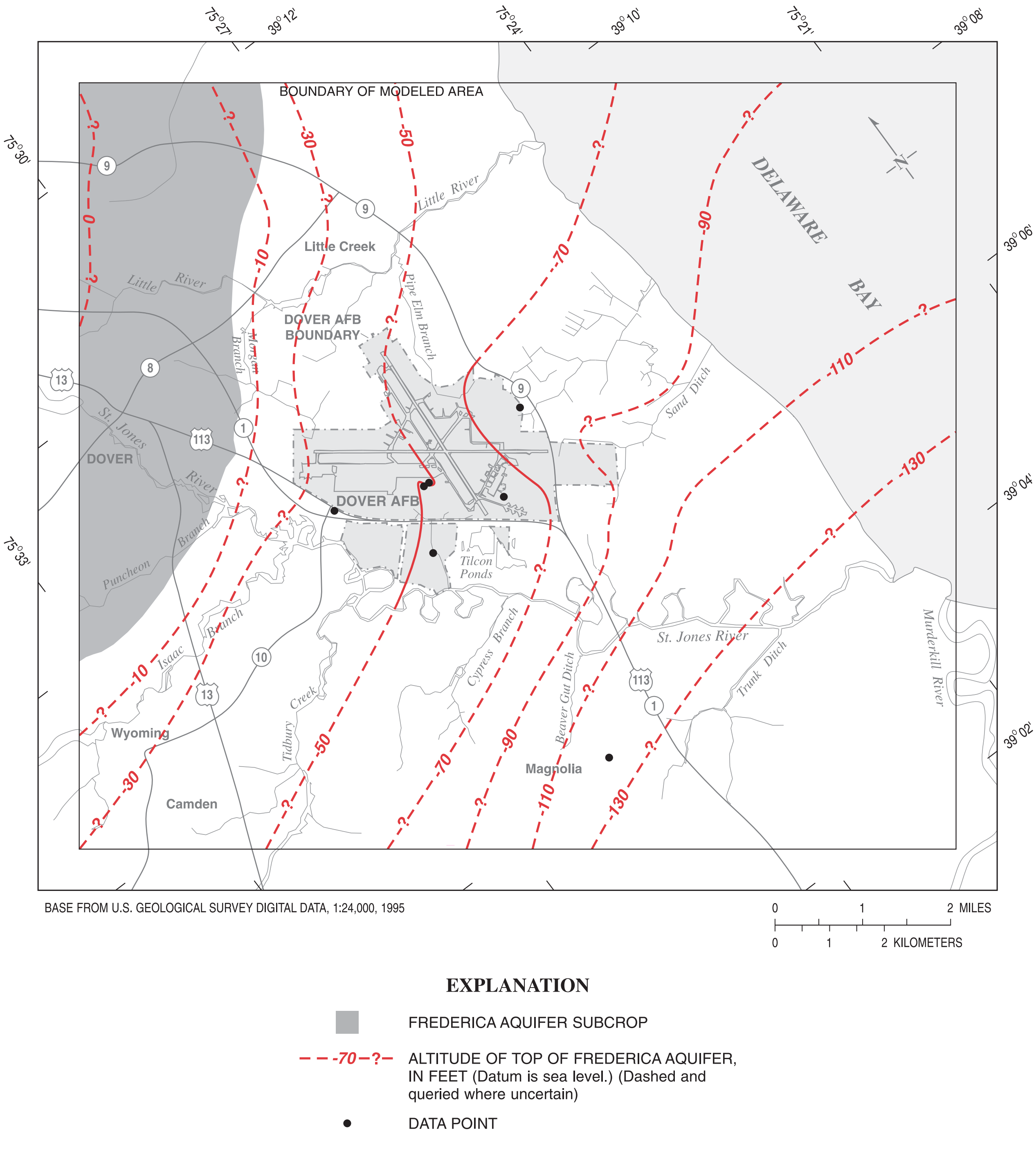
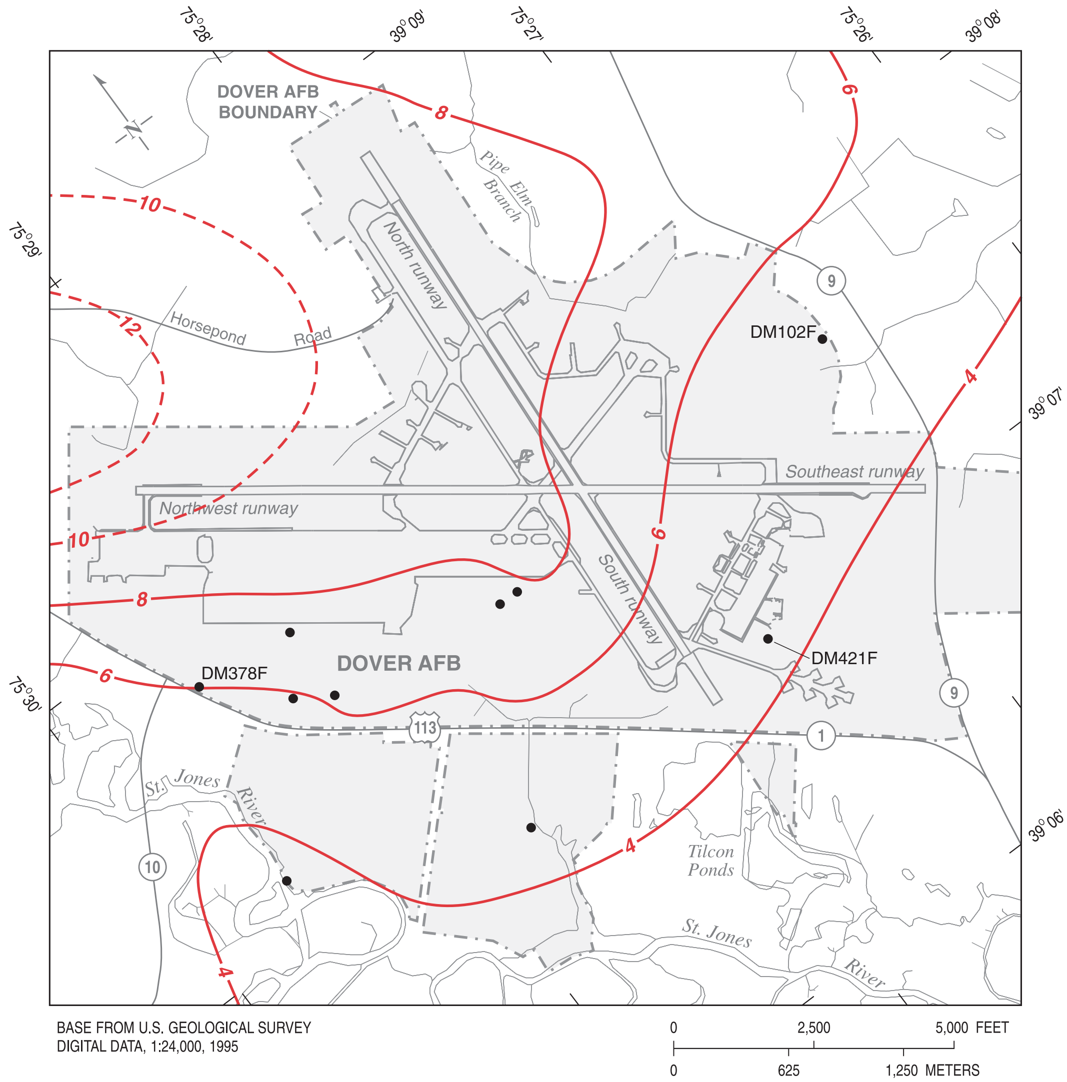


Figure 19. Approximate altitude of the top of the Frederica aquifer, Dover Air Force Base area, Delaware.



EXPLANATION

—10— — ESTIMATE OF AVERAGE HYDRAULIC HEAD IN THE FREDERICA AQUIFER, IN FEET (Datum is sea level.) (Dashed where uncertain)

DM378F ● DATA POINT AND IDENTIFICATION NUMBER

Figure 20. Potentiometric surface in the Frederica aquifer, Dover Air Force Base, Delaware.

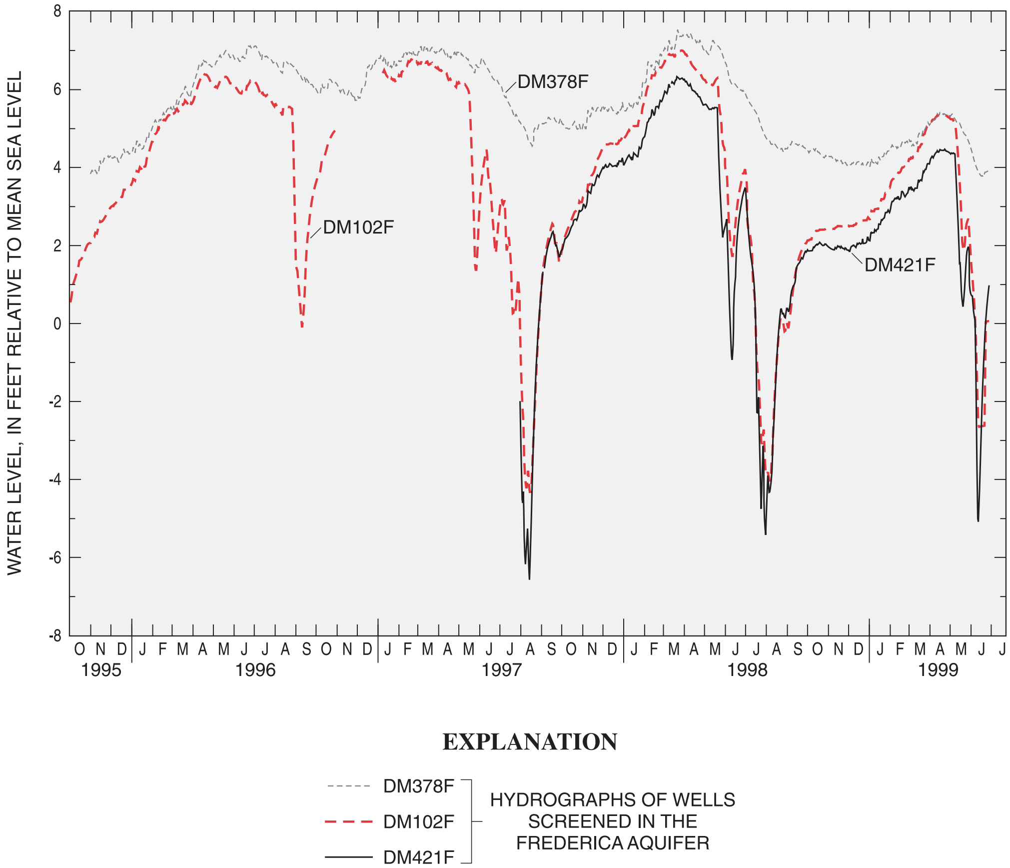


Figure 21. Water levels in selected wells completed in the Frederica aquifer (locations shown in figure 20), Dover Air Force Base, Delaware.

Table 4. *Hydraulic gradient between the Frederica aquifer and the surficial aquifer at well pair DM376D and DM376F (location shown on figure 1c) at Dover Air Force Base, Delaware*

Date	Water levels, in feet above mean sea level		Hydraulic gradient, in feet per foot [A]
	Well DM376D	Well DM376F	
July 1998	3.06	2.20	-0.041
November 1997	3.30	4.10	0.038
September 1997	3.02	3.38	0.017
May 1994	3.27	5.50	0.105
December 1993	2.99	2.97	-0.001

[A] Negative value indicates flow is from the surficial aquifer towards the Frederica aquifer.

Frederica aquifer, although its low value may have been the result of summer irrigation from which the aquifer had not recovered. With no records of water levels for the summer however, this idea is just speculation.

Hydraulic Conductivity—The hydraulic conductivity of the Frederica aquifer ranges from about 7 ft/d to 36 ft/d (table 3). Results of slug tests in the Frederica aquifer at DAFB indicate an average hydraulic conductivity of 6.92 ft/d, with a range of 2.84 ft/d to 14.5 ft/d (U.S. Army Corps of Engineers and Dames & Moore, Inc., 1997a). At well MW16, the hydraulic conductivities ranged from 11 ft/d to 36 ft/d. These values were determined from a pumping test; however, the investigators thought that the latter values may be too high, due to leakage of water from the St. Jones River (CH2M Hill Southeast, Inc., 1988b, Table G–4).

Ground-Water Age

Information about the age of ground water can be used in several ways. First, the age can be used to test a conceptual model of the ground-water-flow system. Second, the age of ground water can give an idea of when the water will reach a particular point or boundary. Third, the age can be used to help calibrate a numerical model of ground-water flow. The age of ground water at DAFB was determined by use of two dating methods—one of which is based on concentration of chlorofluorocarbons in the water, and the other on the concentration of tritium (Plummer and others, 1993; Reilly and others, 1994; Szabo and others, 1996). These two methods were used because the results from a single method are not always unique or easily interpreted. If one method produces ambiguous results, the second method can be used to corroborate, or discount the accuracy of those results.

Chlorofluorocarbon Dates Chlorofluorocarbons (CFCs) are stable volatile organic compounds that were first produced in the 1930's, and have been found useful in dating young ground water (Plummer and others, 1993). There are three main types of CFCs: dichlorodifluoromethane, $CC_{l2}F_2$, or CFC–12, which was first produced in the 1930's; trichlorofluoromethane, $CC_{l3}F$ or CFC–11, first produced in the 1940's; and trichlorotrifluoromethane, $C_2C_{l3}F_3$ or CFC–113.

Ground water can be dated to within a few years by use of CFCs under the following optimal conditions: the temporal variations of atmospheric CFC concentrations are known, there are no local sources of CFCs, there are no local chlorinated solvents in ground water, and there are no anoxic zones, which can support bacteria that use CFCs in their metabolism (Plummer and others, 1993). Chlorinated solvents and/or anoxic conditions are present in some parts of DAFB. The wells sampled in these areas had to be carefully selected to avoid these problems. Another factor that can affect the accuracy of the results is the recharge temperature. Noble gases were collected to obtain data on the recharge temperature. Because of these difficulties associated with the interpretation of CFC data, the ages presented in this report are not considered exact, and the ages are referred to as "apparent ages."

Between August 21 and 28, 1996, water samples were collected from 15 wells for CFC and tritium dating (fig. 22). At DAFB, for most of the wells in the surficial aquifer, the CFC ages of ground water are consistent with the hydrogeologic settings of the wells. For well pairs, the ages of water samples from the upper surficial aquifer are younger than the ages of samples from the lower surficial aquifer. This relationship is expected Basewide except in ground-water-discharge areas, but no samples were collected from wells in discharge areas, such as near streams or drains. The ages of samples collected farther along the flow paths are older than the ages of samples collected along shorter flow paths. An example is the apparent age of water in DM206D compared to the younger apparent age of water in DM342D (fig. 22).

The ages given in column A of table 5 were estimated with recharge temperatures that were determined by analysis of noble gases (for a discussion of this method see the following papers: Dunkle and others, 1993; Heaton, 1981; Heaton and Vogel, 1981). Because of concerns about the recharge temperature varying over the Base, this temperature was changed to an average temperature of 8.8 ^{o}C and the ages recalculated (column B). This change resulted in recharge ages that are slightly different than the recharge ages calculated by use of the recharge temperatures. The following are the mean differences between these two recharge ages: 4.2 yr (years) for CFC–11, 4.0 yr for CFC–12, and 2.8 yr for CFC–113.

Tritium Dates Tritium, the radioactive isotope of hydrogen, can be used to age-date ground water relative to the atmospheric testing of hydrogen bombs in the 1950's and 1960's (Plummer and others, 1993). Several approaches can be used for dating ground water using tritium; the simplest approach is to determine whether tritium is present in ground-water samples. If it is present, at least some of the water in the sample entered the system as recharge since 1953 (Plummer and others, 1993). If it is not detectable, then significant amounts of post–1953 water are not present (Plummer and others, 1993).

The simplest tritium-dating approach (pre– or post–1953 dates, described above) was used. The concentrations of tritium in samples in which it was detected was low (8 to 25 tritium units). At this concentration range, it is difficult to determine accurate post–1953 dates because a large range of years is possible. For this reason, tritium dates were used only to augment the dates determined by CFC analysis.

The concentration of tritium in water samples from the surficial aquifer (about 8 to 25 tritium units) indicates that the ages of all the samples are post–1953. These ages are consistent with the CFC ages for the surficial aquifer. Tritium was not detected in samples from the Frederica aquifer, which indicates that the ground water was recharged before atmospheric testing of hydrogren bombs began in 1953. This age is consistent with the hydrogeologic setting and with the ages determined by CFC analysis.

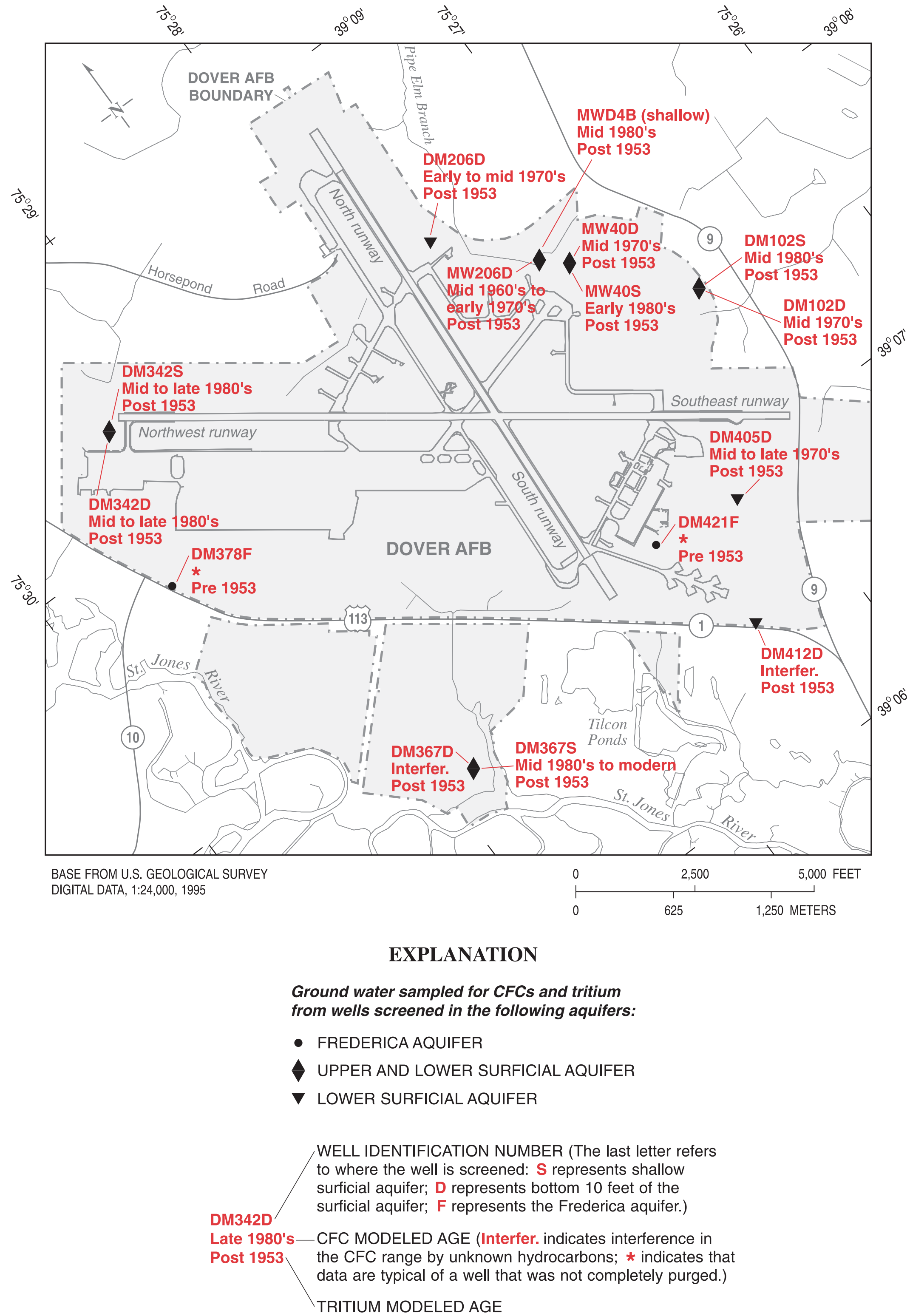


Figure 22. Chlorofluorocarbon (CFC) recharge dates and tritium recharge dates for water in selected wells, Dover Air Force Base area, Delaware.

Table 5. *Age of ground water from analysis of chlorofluorocarbons (CFCs) in selected wells at Dover Air Force Base, Delaware*

[Recharge elevation is 30 ft; well no., well number; T, recharge temperature in degrees Celsius; Modern age, 1994 and younger; A, CFC age indicated by use of the recharge temperature in the "T" column; B, CFC age calculated by use of an average recharge temperature of 8.8 °C; 1980.5, 1980 + 6 months; Interference, interference by unknown halocarbon at the CFC range on the chromatograph; the concentration of these unknown halocarbons are at the nanogram/liter level or higher]

Well no.	Sampling date	T (°C)	Estimated CFC recharge dates for each CFC: CFC–11 A	CFC–11 B	CFC–12 A	CFC–12 B	CFC–113 A	CFC–113 B	Interpreted CFC age for each well or comments
					UPPER SURFICIAL AQUIFER				
MW40S	08/21/1996	8.2	1980.0	1980.5	Interference	Interference	1983.0	1983.5	
MW40S	08/21/1996	8.2	1980.0	1981.0	Interference	Interference	1983.5	1984.0	Early 1980's
MW40S	08/21/1996	8.2	1980.0	1980.5	Interference	Interference	1983.5	1984.0	
DM102S	08/23/1996	11.1	1986.0	1983.5	1985.5	1983.0	1986.0	1984.5	
DM102S	08/23/1996	11.1	1985.5	1983.0	1984.5	1982.0	1986.5	1985.5	Mid–1980's
DM102S	08/23/1996	11.1	1986.5	1983.5	1985.5	1982.5	1986.5	1985.5	
DM342S	08/23/1996	13.3	1987.0	1982.0	1989.5	1984.5	1988.0	1986.0	
DM342S	08/23/1996	13.3	1986.5	1981.5	1990.0	1985.0	1988.5	1986.0	Mid– to Late–1980's
DM342S	08/23/1996	13.3	1987.0	1982.5	1988.0	1983.5	1986.5	1984.5	
DM367S	08/21/1996	12.4	1988.0	1984.5	1991.5	1986.5	1985.5	1984.0	Mid–1980's to Modern
DM367S	08/21/1996	12.4	1991.5 A 1997.0	1986.0	Interference	Interference	1987.0	1985.5	
MWD4B	08/27/1996	8.9	1986.5	1986.5	Interference	Interference	1986.5	1986.5	
MWD4B	08/27/1996	8.9	1986.5	1986.5	Interference	Interference	1987.0	1987.0	Mid–1980's
MWD4B	08/27/1996	8.9	1986.5	1986.5	Interference	Interference	1987.0	1987.0	

Table 5. *Age of ground water from analysis of chlorofluorocarbons (CFCs) in selected wells at Dover Air Force Base, Delaware--Continued*

Well no.	Sampling date	T (°C)	Estimated CFC recharge dates for each CFC						Interpreted CFC age for each well or comments
			CFC–11		CFC–12		CFC–113		
			A	B	A	B	A	B	
LOWER SURFICIAL AQUIFER									
MW40D	08/21/1996	8.2	1975.5	1975.5	1972.5	1972.5	1954.5	1954.5	
MW40D	08/21/1996	8.2	1975.0	1975.5	1972.5	1972.5	1954.5	1954.5	Mid–1970's
MW40D	08/21/1996	8.2	1975.0	1975.5	1973.0	1973.0	1963.0	1963.0	
DM102D	08/23/1996	11.6	1974.0	1973.0	1974.5	1973.0	1974.5	1973.0	
DM102D	08/23/1996	11.6	1974.0	1972.5	1975.0	1973.5	1974.0	1972.5	Mid–1970's
DM102D	08/23/1996	11.6	1974.0	1972.5	1975.5	1974.0	1973.0	1972.0	
DM206D	08/28/1996	14.1	1972.0	1970.0	1977.0	1974.0	1975.5	1973.5	
DM206D	08/28/1996	14.1	1972.0	1970.0	1977.5	1974.5	1971.5	1969.5	Early– to Mid–1970's
DM206D	08/28/1996	14.1	1972.0	1970.0	1978.5	1975.0	1978.0	1975.5	
DM342D	08/23/1996	8.4	1985.0	1985.0	1990.0	1991.0	1986.5	1986.5	
DM342D	08/23/1996	8.4	1984.5	1985.0	1990.0	1991.0	1986.5	1987.0	Mid– to Late–1980's
DM342D	08/23/1996	8.4	1983.5	1984.0	1988.0	1988.5	1986.0	1986.0	
DM367D	08/21/1996	13.4	Interference	Interference	Interference	Interference	1977.0	1975.0	No reliable date

Table 5. *Age of ground water from analysis of chlorofluorocarbons (CFCs) in selected wells at Dover Air Force Base, Delaware--Continued*

Well no.	Sampling date	T (°C)	Estimated CFC recharge dates for each CFC						Interpreted CFC age for each well or comments
			CFC–11		CFC–12		CFC–113		
			A	B	A	B	A	B	
LOWER SURFICIAL AQUIFER--Continued									
DM405D	08/28/1996	12.1	1982.5	1978.5	1978.0	1975.5	1971.5	1970.0	
DM405D	08/28/1996	12.1	1981.0	1977.5	1976.5	1974.5	1977.0	1975.5	Mid– to Late–1970's
DM405D	08/28/1996	12.1	1981.5	1978.0	1976.5	1974.5	1978.0	1976.5	
DM412D	08/28/1996	13.9	Interference	Interference	Interference	Interference	Interference	Interference	
DM412D	08/28/1996	13.9	Interference	Interference	Interference	Interference	1954.5	1954.5	No reliable date
DM412D	08/28/1996	13.9	Interference	Interference	Interference	Interference	1954.5	1954.5	
MW206D	08/27/1996	8.4	1964.5	1964.5	1970.0	1970.5	1954.5	1954.5	
MW206D	08/27/1996	8.4	1964.5	1964.5	1969.0	1969.5	1954.5	1954.5	Mid–1960's to early 1970's
MW206D	08/27/1996	8.4	1964.0	1964.5	1970.5	1971.0	1957.0	1957.0	
FREDERICA AQUIFER									
DM378F	08/23/1996	12.6	1975.0	1973.5	1983.0	1979.5	1992.0 1997.0	1988.5	
DM378F	08/23/1996	12.6	1971.0	1969.5	1974.5	1973.0	1987.0	1985.5	Data are typical of a well that was not completely purged.
DM378F	08/23/1996	12.6	1964.5	1963.5	1966.5	1965.5	1987.0	1985.0	
DM421F	08/27/1996	8.4	1964.5	1964.5	1967.0	1967.0	1982.0	1982.0	
DM421F	08/21/1996	8.4	1956.0	1956.0	1959.5	1960.0	1954.5	1954.5	--do--
DM421F	08/21/1996	8.4	1956.5	1956.5	1957.0	1957.0	1955.0	1955.0	

[A] Two dates are given because the CFC curve has peaked and the concentrations of CFC–11 correspond to two dates, which bound the peak in the curve.

Table 6. *Water budget for the Dover Air Force Base area, Delaware*

[ft^2, square feet; in/yr, inches per year; ft/d, feet per day; ft^3/d, cubic feet per day]

Recharge area (ft^2)	Average precipitation (in/yr)	Average recharge (in/yr)	Average overland flow and evapotranspiration (in/yr)	Recharge (ft/d)	Recharge into the investigation area (ft^3/d)	Discharge from the ground-water system to surface-water bodies (ft^3/d)
1.5×10^{9}	46	12	34	2.74×10^{-3}	4.1×10^{6}	4.1×10^{6}

Water Budget

In an estimate of the water budget for the ground-water system in the DAFB area, recharge constituted flow into the ground-water system and ground-water discharge to surface-water bodies constituted flow out of the system. In this water budget, the source of water is precipitation. Not all of this precipitation enters the ground-water system—some of the precipitation is lost to surface-water bodies by overland runoff, and another part of the precipitation is used by plants as transpiration. What is left of precipitation is available for recharge. Cushing, Kantrowitz, and Taylor (1973) studied these relations extensively for the Delmarva Peninsula and the analysis in this report follows their interpretation. About 4.1 million cubic feet of water flow through the system in a day (table 6). The recharge area was estimated from a map of the area. No recharge was allowed into the major surface-water bodies, such as the Delaware Bay, the St. Jones River, or the Little River, or for runways, shopping centers, and other paved areas. Seasonal effects of irrigation pumpage from the Frederica aquifer or from the surficial aquifer were ignored. Finally, the amount of recharge is assumed to equal the amount of discharge into the surface-water bodies.

Simulation of Ground-Water Flow

A ground-water-flow model was constructed to simulate the hydrogeology of the DAFB area. The design of the model was developed on established principles, which have been summarized in numerous publications (van der Heijde, 1992; American Society for Testing and Materials Committee E 978–92, 1992; American Society for Testing and Materials Committee D 5447–93, 1993; American Society for Testing and Materials Committee D 5490–93, 1994a; American Society for Testing and Materials Committee D 5609–94, 1994b; American Society for Testing and Materials Committee D 5611–94, 1994c; American Society for Testing and Materials Committee D 5610–94, 1995; Anderson and Woessner, 1992). The simulation used the USGS modular three-dimensional ground-water-flow model known as MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996).

Conceptual Model

The numerical model is based on a conceptual model of ground-water flow that was developed on the basis of the hydrogeologic information presented earlier in this report. The major features of this conceptual model are shown in figure 23, which is a schematic diagram rather than a cross-section. The main source of water into the model is recharge. This water flows through the ground-water system to surface-water bodies.

The conceptual model has four layers (fig. 23). The top two layers represent the surficial aquifer, with the uppermost layer representing the upper surficial aquifer. The hydraulic conductivity of the upper surficial aquifer is constant at 5 ft/d except near large surface-water bodies, where there can be extensive areas of marsh sediments that have a lower hydraulic conductivity (0.1 ft/d). The surface-water bodies in this top layer are represented by the St. Jones River, the Delaware Bay, and an ephemeral drain. The river and the drain have a thin layer (1 ft thick) of streambed sediments with a horizontal hydraulic conductivity of 1 ft/d. This layer does not impede ground-water discharge to these surface-water bodies. The marsh sediments can impede the ground-water discharge to a greater degree, while the flow of water to the drains is not impeded by sediment type. The Delaware Bay is represented in the model by a constant-head boundary, and there is no sediment layer in this representation. Below layer 1 is layer 2, the lower surficial aquifer, except in two areas where a semi-confining clay unit is present. These clay units are shown between the St. Jones River and the Delaware Bay.

The second layer represents the lower surficial aquifer. The hydraulic conductivity of this aquifer is uniform at 65 ft/d. The thickness of the lower surficial aquifer can vary. One area of exceptional thickness is under the upper reaches of the St. Jones River in the model area, where the river channel has eroded part of the upper Calvert confining unit. The question marks in figure 23 indicate that the exact nature of these sediments is unclear, but show that there is a thinning of the confining unit. Another area of thinning of the confining unit is shown to the right of the St. Jones River. This thinning represents the thinning seen locally under DAFB.

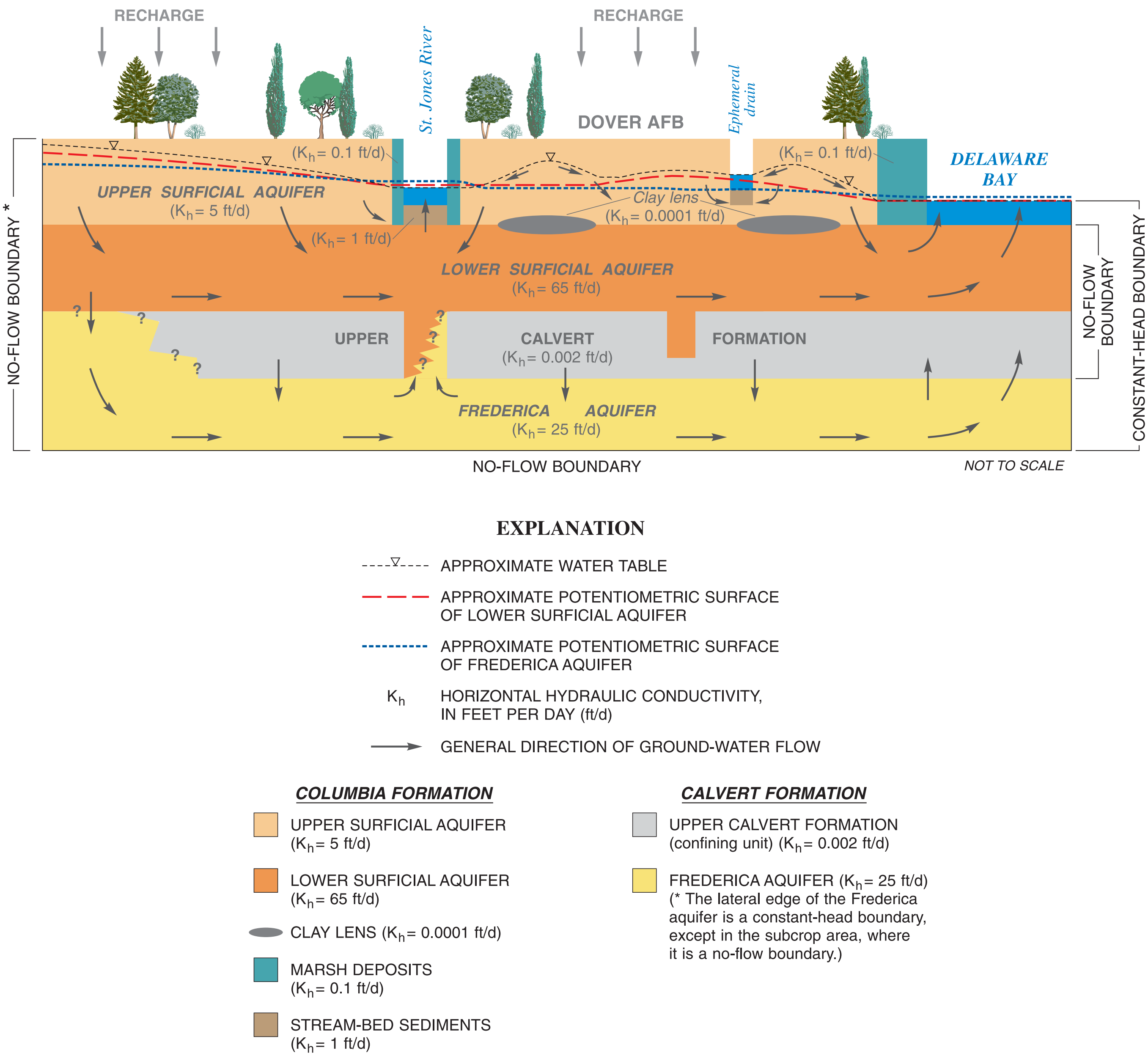


Figure 23. Conceptual model of the upper ground-water-flow system at Dover Air Force Base, Delaware.

The third model layer represents the upper Calvert confining unit, which is between the lower surficial aquifer and the Frederica aquifer. There are two places where this layer does not represent this unit. These areas include the subcrop of the Frederica aquifer, and in the model area, the upper reaches of the St. Jones River. In the subcrop area of the Frederica aquifer, the upper Calvert confining unit is missing and in the model, it is given the properties of a thin layer (approximately 1 ft) of sand (*K*, or hydraulic conductivity = 50 ft/d). This subcrop area is shown on the left side of the diagram. The subcrop area extends down the upper reaches of St. Jones River Valley in the model area to the Wildcat Landfill area, where the upper Calvert confining unit is missing in the subsurface (CH2M Hill Southeast, Inc., 1988b). The fourth layer of the conceptual model represents the Frederica aquifer, with a horizontal hydraulic conductivity of 25 ft/d.

In recharge areas, the gradient is downward from the water table to the potentiometric surface for the lower surficial aquifer. In discharge areas, such as the St. Jones River or the Delaware Bay, this slight gradient is reversed. In areas where semi-confining clay units are present at the base of the upper surficial aquifer, there is an increase in the vertical gradient between the water table and the potentiometric surface for the lower surfical aqufier.

Figure 23 also shows the potentiometric surface of the Frederica aquifer. In the left part of the figure, the head gradient is downward from the water table towards the potentiometric surface of the Frederica aquifer. This surface slopes down towards the Delaware Bay, where it is slightly above the average water level in the Bay. For most of this distance, the potentiometric surface of the Frederica is lower than the water table with one exception. This area is on the golf course, near the St. Jones River, where the water table drops to meet the average stage of the St. Jones River. As was discussed earlier in this report, near the St. Jones River the head in the lower surficial aquifer is lower than the head in the Frederica aquifer, except during dry periods, when water is pumped from the Frederica aquifer. A non-pumping condition is shown in figure 23.

The assumed boundary conditions of the ground-water system are also shown in figure 23. For layer 1, the lateral boundaries are no-flow boundaries except for the Delaware Bay. For layers 2 and 3, all of the lateral boundaries are no-flow boundaries. For layer 4, the Frederica aquifer, all of the lateral boundaries are constant-head, except for the subcrop area where it is a no-flow boundary. The Frederica aquifer is underlain by about 20 ft of silt that represents a no-flow boundary and constitutes the bottom of the model.

Model Design and Boundary Conditions

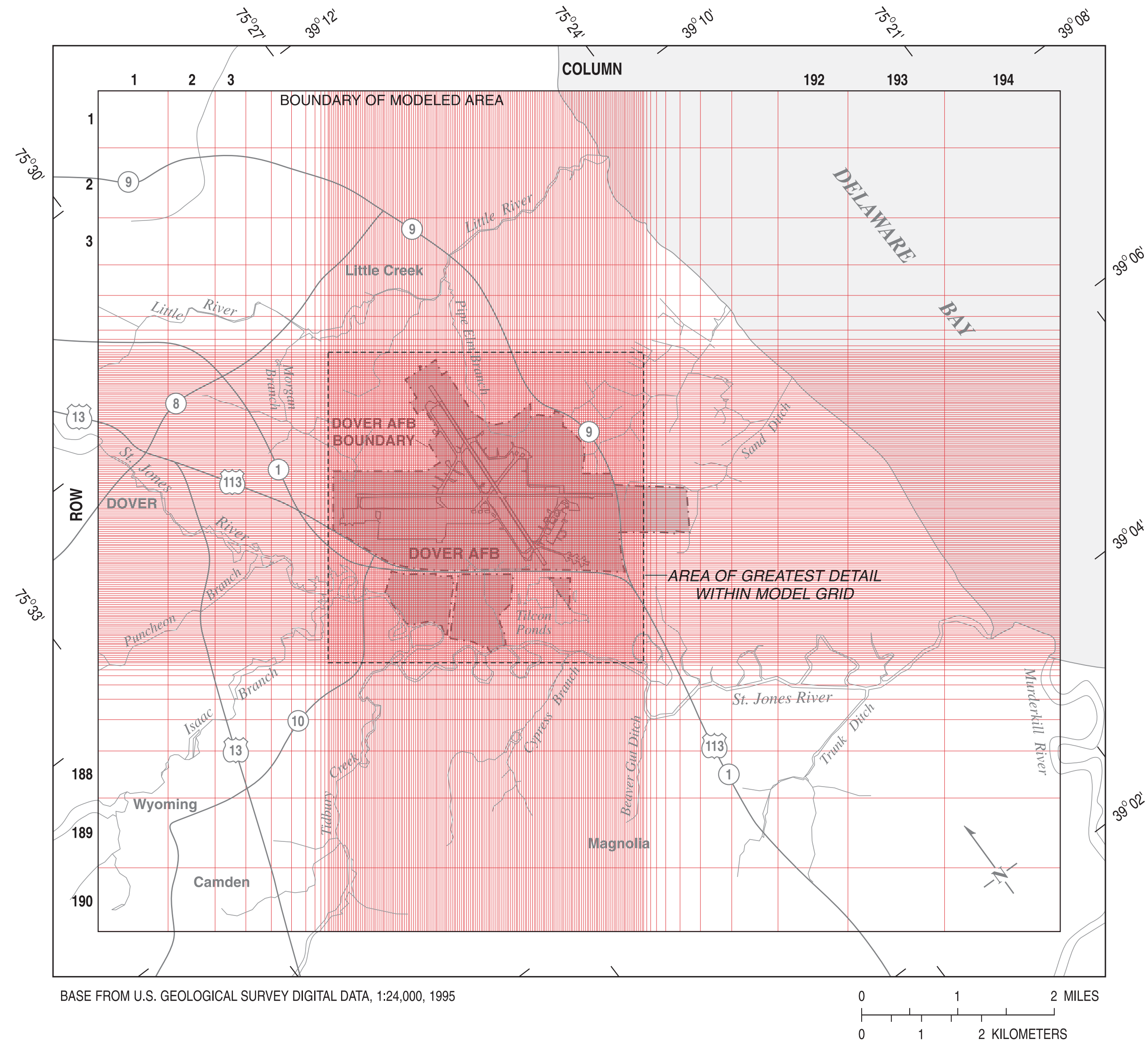
MODFLOW was designed to simulate ground-water flow in a multi-layer system using one of two approaches—the three-dimensional approach or the quasi-three-dimensional approach. In the three-dimensional approach, aquifers and confining units are simulated as active layers, with hydraulic-head solutions for each layer. In the quasi-three-dimensional approach, the aquifers are simulated as active layers, and the confining units are simulated as a conductance term between the layers. These two approaches were used in this model for the following reason. When the top of the clay was used as the base of the unconfined layer, many dry cells formed. Use of the "wet-dry" package of MODFLOW made the model unstable. Therefore, the upper and lower surficial aquifer were represented by two separate model layers, with the semi-confining unit between them represented by a vertical conductance term. The upper confining unit of the Calvert Formation was represented by a model layer, and the Frederica aquifer was represented by a layer. The top of the confining unit below the Frederica was simulated as the base of the model, and was represented in MODFLOW as a no-flow boundary.

A finite-difference simulation of ground-water flow requires that the model area be discretized into a grid. The grid constructed for the DAFB area has 4 layers, 190 rows, and 194 columns (fig. 24). The model grid rows are oriented parallel to the northwest-southeast runway, which is the approximate location of one of the ground-water divides at DAFB, and roughly parallel to the reach of the St. Jones River that is closest to DAFB.

Within the DAFB boundary, the model cells are 100 ft by 100 ft (fig. 24). Outside of DAFB, the model cells increase in size because there is less need for detailed information and there are less data available. This increase in model-cell size is no greater than 1.5 times the adjacent model-cell size. Expansion of the grid spacing was necessary to reduce the computation time for the simulations, and an expansion ratio of 1.5:1 or less was required for a stable solution of the finite-difference equations. The largest model cells (those far outside the area of interest) are 5,280 ft by 6,320 ft.

Initial values for the model grid were obtained by use of GIS techniques, many of which were described in Hinaman (1993). Values were assigned to grid nodes by assuming the value of the parameter at the center of the grid cell was uniform throughout the cell.

As the MODFLOW model was assembled, the guiding premise was to avoid making the model any more complicated than necessary. Hydraulic conductivities of the layers and recharge were assumed uniform. After some initial simulations, further development of the model was guided by the simulation results. For example, the model was modified by adding recharge zones. It was assumed that no recharge takes place under paved areas (such as runways, tarmacs, parking lots, and large shopping areas in southern Dover, shown in fig. 2). In all other areas of the model a uniform recharge of 12 in/yr was simulated. Approximately 8 in/yr is an estimate of the average recharge to land surfaces in the area of the simulation. An additional modification was made for the upper surficial aquifer, where the wetlands (fig. 2) along the St. Jones River and the Delaware Bay were assigned a horizontal hydraulic conductivity of 0.1 ft/d. This low conductivity zone was based on observations at Wildcat Landfill (CH2M Hill Southeast, Inc., 1988a, 1988b). In model layer 3, which represents the upper Calvert confining unit, a horizontal hydraulic conductivity of 50 ft/d was



EXPLANATION

AREA OF GREATEST DETAIL WITHIN MODEL GRID (100 foot x 100 foot cells)

Figure 24. Model grid used in the simulation of ground-water flow in the Dover Air Force Base area, Delaware.

assigned to the Frederica subcrop area and to the upper reaches of the St. Jones River in the model. In this area, the upper Calvert confining unit has eroded away and the lower surficial aquifer is lying directly on the Frederica aquifer. In the model, there is still a layer for the upper Calvert confining unit, and to simulate the lower surficial aquifer lying on the Frederica aquifer in the subcrop area the following was done: The model layer representing the upper Calvert confining unit was assigned a small thickness (1 ft), and was also assigned a hydraulic conductivity of 50 ft/d, which is between the hydraulic conductivity of the overlying lower surficial aquifer (65 ft/d) and the hydraulic conductivity of the Frederica aquifer (25 ft/d).

Vertical hydraulic conductances were calculated by use of formulas from McDonald and Harbaugh (1988, p. 5–11 to p. 5–18). Vertical hydraulic conductances were calculated by use of arrays of the tops and bottoms of the hydrogeologic layers (aquifer or confining layer) and by use of arrays of the horizontal hydraulic conductivities between the following units: (1) the lower surficial aquifer and the upper Calvert confining layer, and (2) the upper Calvert confining layer and the Frederica aquifer. These calculations were made by use of a computer program, in which it was assumed that the vertical hydraulic conductivities were 10 percent of the horizontal hydraulic conductivities. The vertical hydraulic conductance between the upper and lower surficial aquifer was calculated in a different way, which accounted for the semi-confining unit between the two layers. This semi-confining unit represents a clay and silt sequence that is present in only one part of the surficial aquifer (fig. 5). The method used to map this sequence was discussed earlier in this report. Where the water table was below the clay and silt sequence, the sequence was ignored and an arbitrary conductance was assigned based on a thickness of 1 ft and a horizontal hydraulic conductivity of 50 ft/d. Where the water table intersected this clay and silt sequence, the thickness used in the calculations was the amount of clay and silt below the water table. In this area, the clay and silt sequence was assigned a horizontal hydraulic conductivity of 0.0001 ft/d. An array of vertical hydraulic conductance between the upper and lower surficial aquifer was calculated using arrays of the thicknesses of the upper surficial aquifer, the intervening clay and silt sequence, and the lower surficial aquifer, along with arrays of hydraulic conductivities of the upper surficial aquifer, the intervening clay and silt sequence, and the lower surficial aquifer.

Boundary conditions for each of the model layers (figures 25, 26, 27, and 28) were set to provide a simulation that was sufficiently accurate. Where possible, boundary conditions were selected to mimic the natural hydrologic boundaries within the modeled area. In some cases, however, natural hydrologic boundaries do not exist or are difficult to define. In these cases, the boundary conditions were set far enough away from the principal areas of interest so that they would have minimal influence on simulation results for those areas.

All or part of the top three model layers are represented by no-flow boundaries. The model area was designed to be large enough so that these distant boundaries would have a negligible effect on the flow field at DAFB. For the upper surficial aquifer, the no-flow boundaries are either at or very close to surface-water divides, which are assumed to coincide with ground-water divides for the surficial aquifer. In the upper surficial aquifer layer, the model cells that represent the Delaware Bay and the ponds at Tilcon also were assigned constant heads. For the Frederica aquifer layer, cells in the outer edge of the model were assigned constant heads, except those in the subcrop area, which were assigned variable heads, which represent active model cells (fig. 28).

River nodes were used to simulate the St. Jones River and the tidal reaches of the Little River and the St. Jones River (figs. 29 and 30). River stages were calculated from actual measurements and from topographic maps. The streambed hydraulic conductivity was assumed to be 1 ft/d. Parts of the streambed are sandy and other parts are silty, but the detailed distribution of these sediments is not known. The 1 ft/d value for hydraulic conductivity of the streambed sediments was used as a compromise value for hydraulic conductivity. The sediments were assumed to be 1 ft thick, and the channel was assumed to be 10 ft wide. As discussed earlier in this report, the hydraulic conductivity of the upper surficial aquifer, layer 1 of the model, was set to 0.1 ft/d in marshy areas, which were identified on aerial photographs and topographic maps. In areas with marshes, the 0.1 ft/d horizontal hydraulic conductivity controls ground-water discharge to rivers.

The “drain package” of MODFLOW was used to simulate open drains and ephemeral streams. Actual drains at DAFB are classified as open drains or covered drains. Covered drains were not simulated in the model. Sediments in the streambeds of the open drains and ephemeral streams were given a hydraulic conductivity of 1 ft/d. As was the case with the rivers, the beds of some of the drains are sand while others are silt. The distribution of these sediments was not mapped. Sediment thickness was assumed to be 1 ft, and the width of the channel was assumed to be 5 ft. In the area with marshes, the 0.1 ft/d horizontal hydraulic conductivity controls ground-water discharge to drains.

Calibration of the Model

The ground-water-flow model of the DAFB area was calibrated by systematically adjusting hydrologic parameters within the known range of measured values until simulated heads and flow were consistent with measured hydraulic heads and flow to within an acceptable error range. Calibration of the model ensures that it closely represents the actual head distribution in order to properly simulate heads and flow directions within the natural ground-water-flow system. Some details of the flow system will always be unknown, however, and the model, when calibrated, will represent some average of these unknowns.

Figure 25. Boundary conditions of layer 1 (upper surficial aquifer), used to simulate ground-water flow in the Dover Air Force Base area, Delaware.

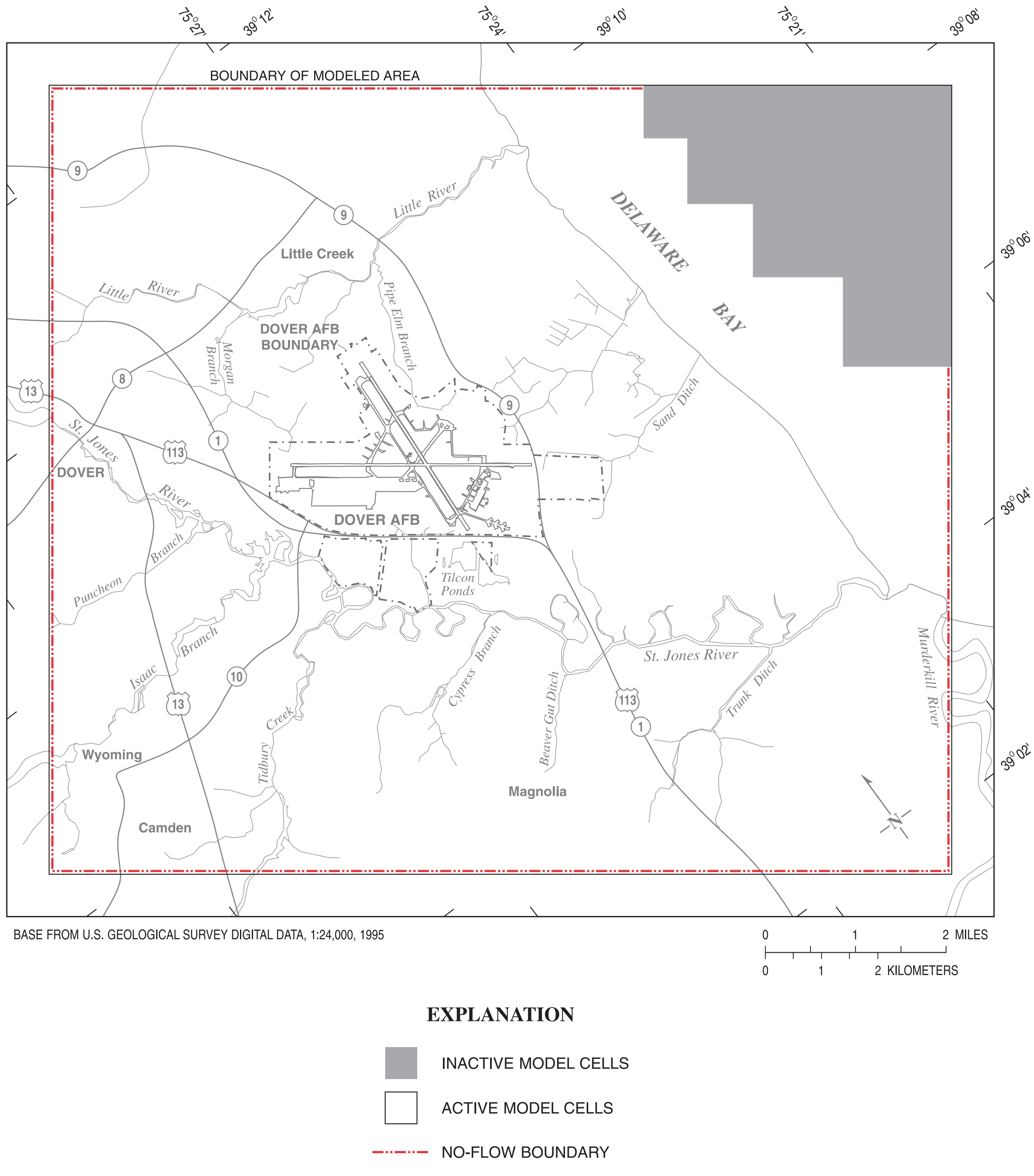


Figure 26. Boundary conditions of layer 2 (lower surficial aquifer), used to simulate ground-water flow in the Dover Air Force Base area, Delaware.

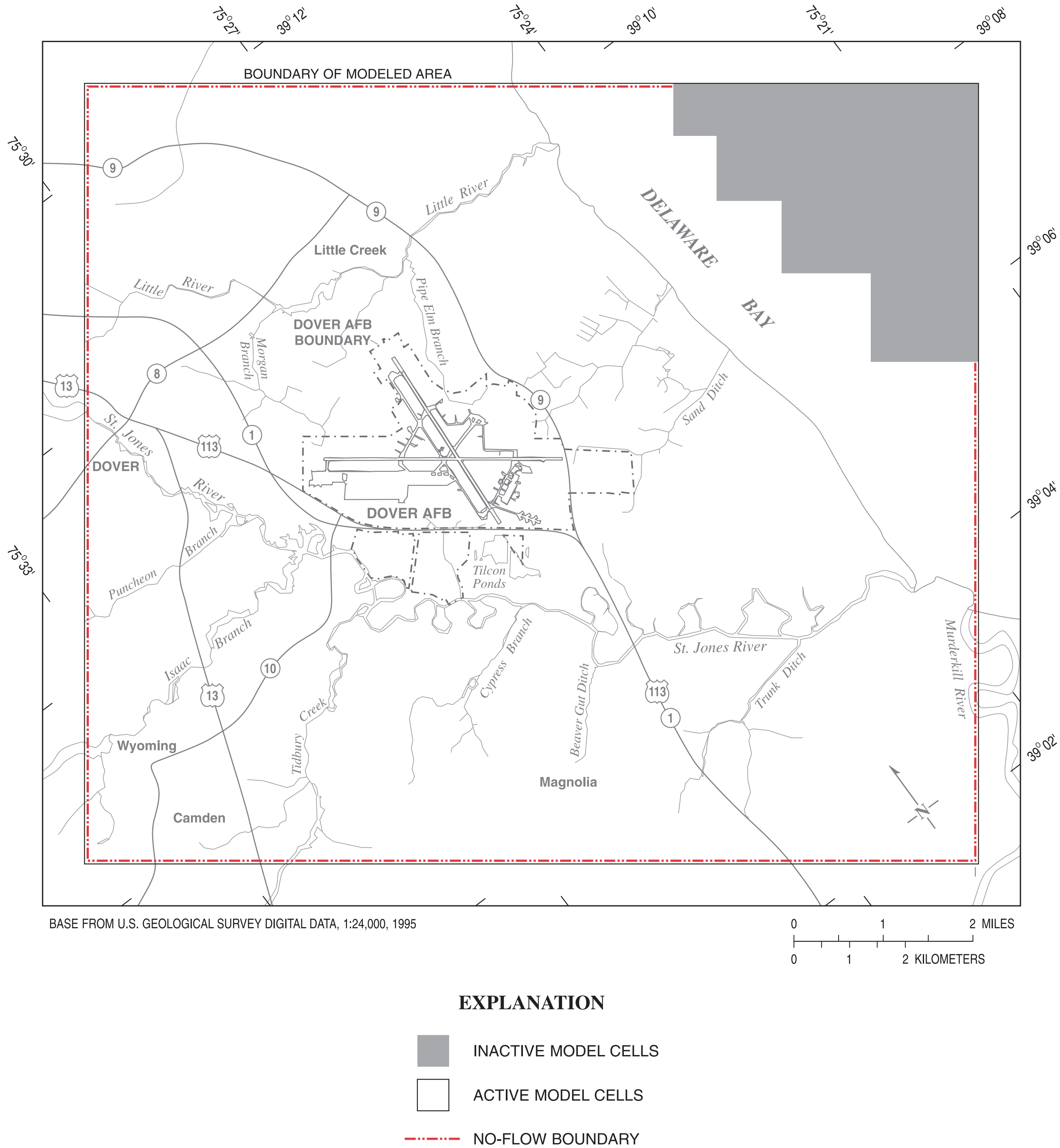


Figure 27. Boundary conditions of layer 3 (upper Calvert Formation), a confining unit used to simulate ground-water flow in the Dover Air Force Base area, Delaware.

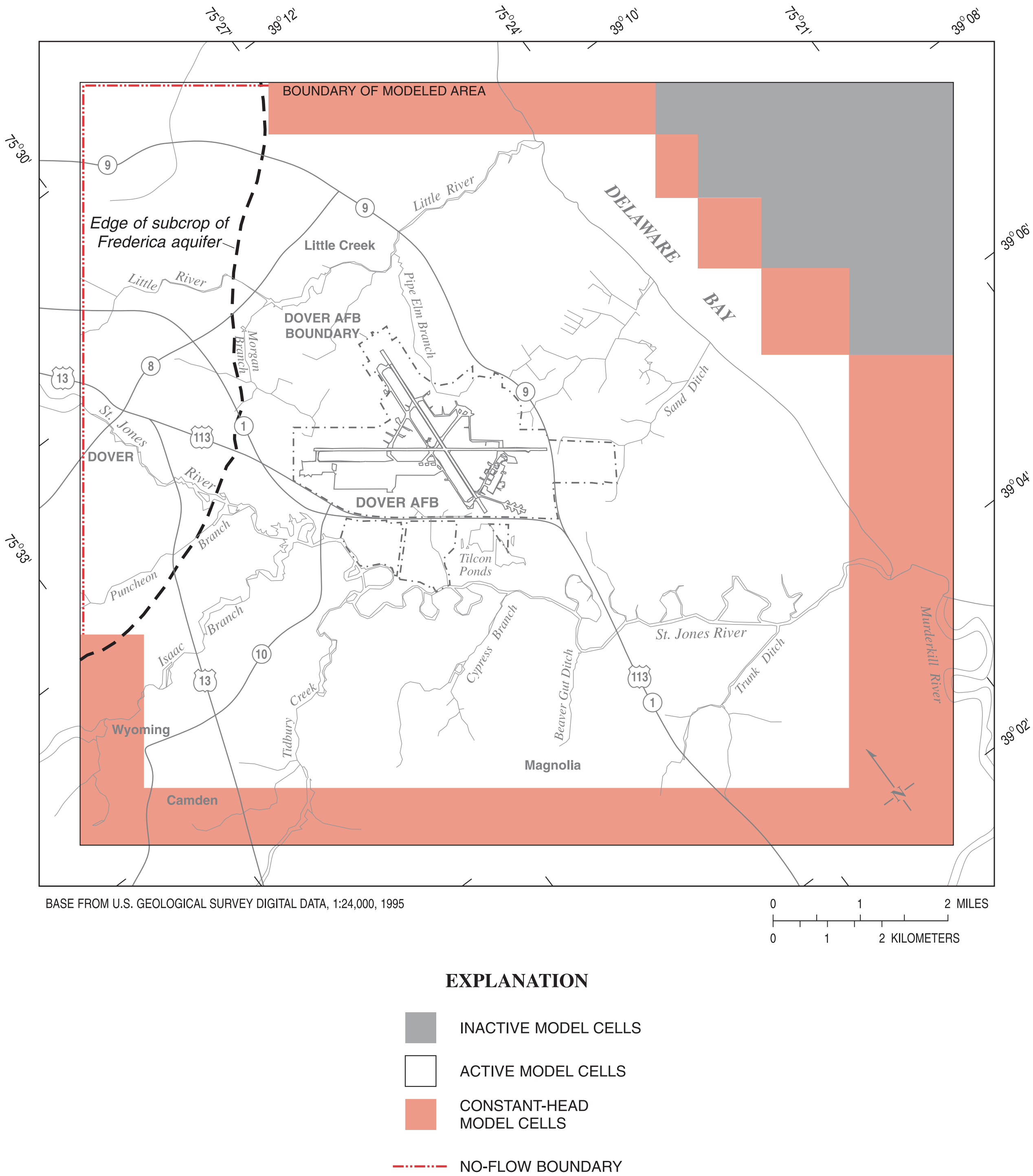
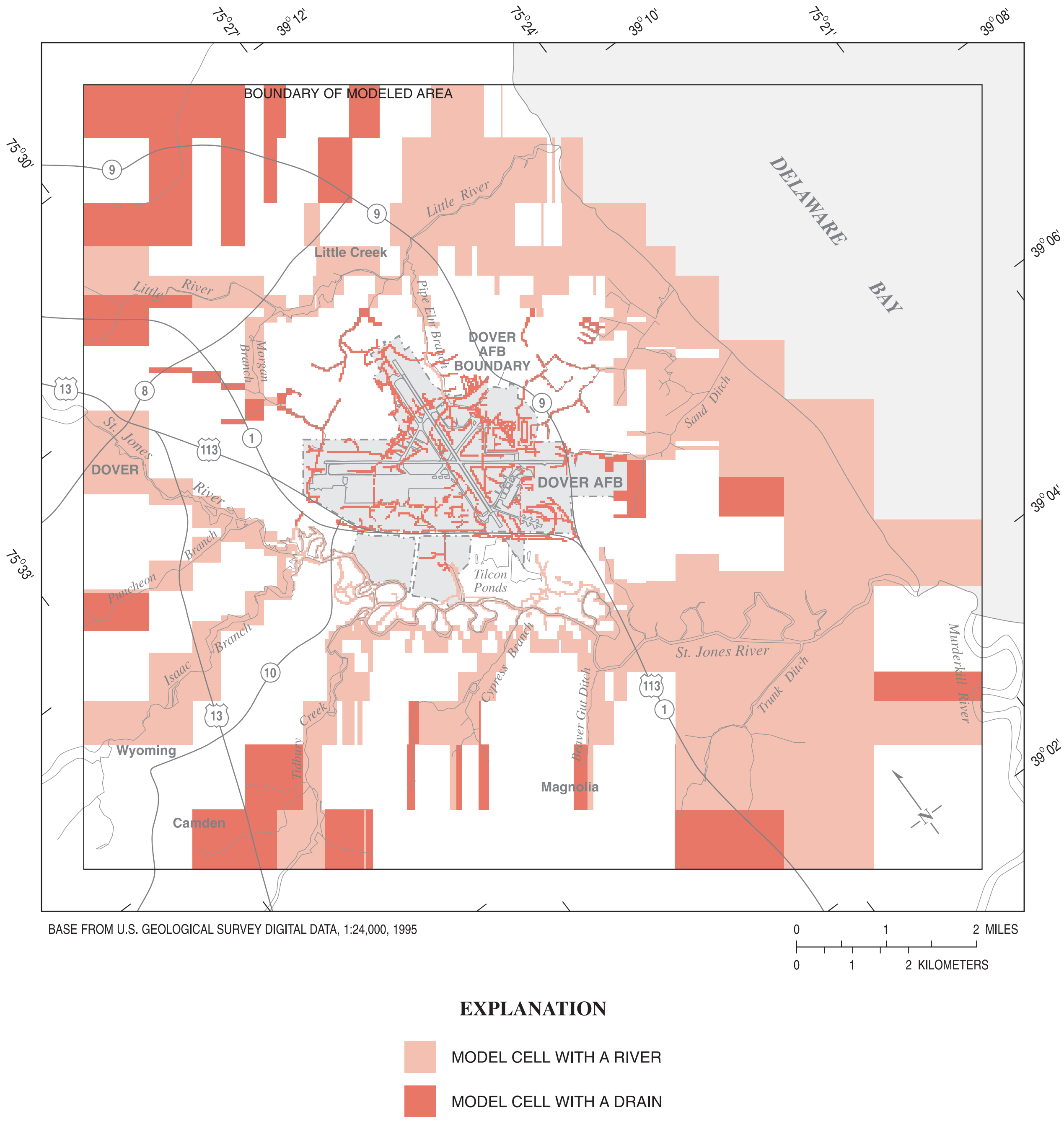


Figure 28. Boundary conditions of layer 4 (the Frederica aquifer), used to simulate ground-water flow in the Dover Air Force Base area, Delaware.



EXPLANATION

Figure 29. Locations of model cells with rivers and drains in layer 1 (the upper surficial aquifer), used to simulate ground-water flow in the Dover Air Force Base area, Delaware.

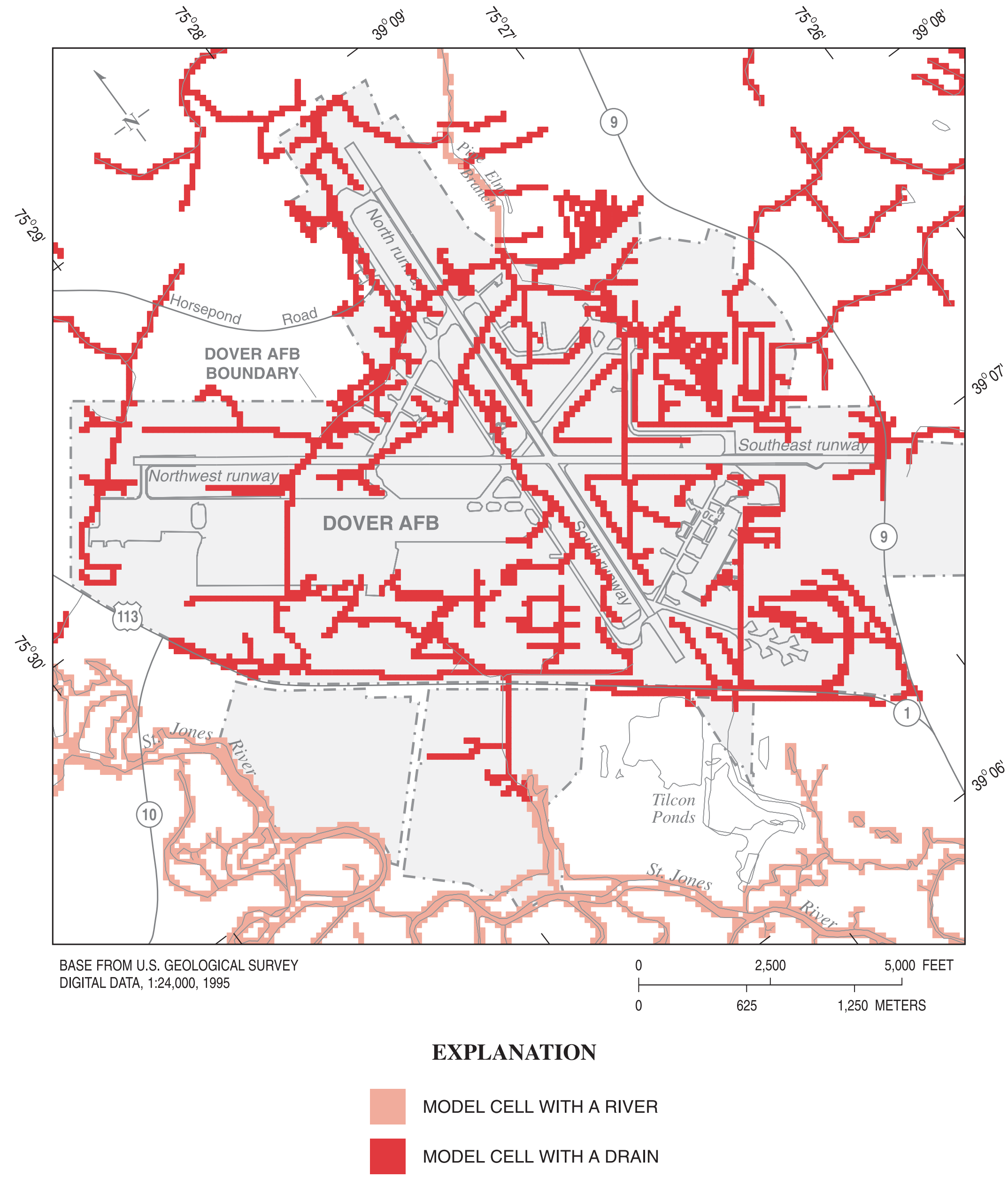


Figure 30. Locations of model cells with rivers and drains in layer 1 (the upper surficial aquifer), used to simulate ground-water flow in the detailed investigation area, Dover Air Force Base, Delaware.

Calibration of the ground-water-flow model was considered complete when the following seven criteria were met:

1. the root-mean-squared error (RMSE) between simulated heads and measured heads in the upper surficial aquifer was minimized;
2. the RMSE between simulated heads and measured heads in the lower surficial aquifer was minimized;
3. head gradients between the upper and lower surficial aquifer at selected well pairs were closely matched;
4. head gradients between the lower surficial aquifer and the Frederica aquifer at selected well pairs were closely matched;
5. the RMSE between simulated head and actual heads in the Frederica aquifer was minimized;
6. simulated ground-water discharge to Pipe Elm Branch of the Little River closely matched the measured ground-water discharge; and
7. the shape and magnitude of simulated off-Base contours of head for the lower surficial aquifer were consistent with the shape and magnitude of off-Base contours of head for the lower surficial aquifer measured in October 1959.

Details of the calibration methods and the degree to which the objectives were met are discussed below.

Calibration of this model was a highly iterative process that used a trial-and-error method with sensitivity analyses as a guide. The objective was to construct an initial ground-water-flow model with appropriate boundary conditions, layering, node spacing, and estimated values of the hydrologic parameters. The following hydrologic parameters were adjusted during calibration: horizontal hydraulic conductivity of the upper surficial aquifer, horizontal hydraulic conductivity of the lower surficial aquifer, horizontal hydraulic conductivity of the semi-confining unit in the surficial aquifer, horizontal hydraulic conductivity of the Calvert Formation confining unit, horizontal hydraulic conductivity of the Frederica aquifer, and recharge rate. Reasonable ranges for these parameters were determined from available data or from literature sources. The hydrologic parameters were then adjusted one at a time to determine values that produced the simulation that most carefully represented flow and head conditions in the ground-water-flow system at DAFB.

The model had several calibration targets. One target was to produce simulated heads that were consistent with observed heads of September 1997, with an RMSE of less than 10 percent of the range of observed heads for the upper and lower surficial aquifer. Another objective was to have less than a 10-percent error between the observed September 1997 base-flow discharge from the aquifer to Pipe Elm Branch and the simulated discharge to Pipe Elm Branch. The hydraulic properties were determined from the quantitative calibration. This calibration was based on observed data from DAFB. To determine if the model was valid outside the boundaries of DAFB, the model was compared to October 1959 heads, for which there are regional data for both head and interpreted contours.

The horizontal hydraulic conductivity of the upper part of the surficial aquifer was adjusted between 1 ft/d and 50 ft/d. The horizontal hydraulic conductivity of the clay in the surficial aquifer was adjusted between 0.001 ft/d and 0.00001 ft/d. The horizontal hydraulic conductivity of the lower part of the surficial aquifer was adjusted over a range of 50 ft/d to 200 ft/d. For each of the hydraulic conductivities of the lower surficial aquifer, recharge to the model was adjusted between 4 in/yr and 20 in/yr.

The next step was to calibrate the hydraulic conductivity of the confining unit in the upper Calvert Formation. The calibration target was to closely match the head in the Frederica aquifer. During these analyses, the values of recharge and horizontal hydraulic conductivity of the surficial aquifer were held constant, and the horizontal hydraulic conductivity of the confining unit was adjusted from values just above to below values reported in the previously published literature. The heads in the Frederica aquifer were compared to measured values of September 1997, and an RMSE was calculated.

Figure 31 shows scatter plots of calculated and observed heads for the upper and lower surficial aquifers for September 1997. For these layers, the agreement is good throughout the range of values. For September 1997 conditions, the RMSE of the upper and lower surficial aquifers were 1.47 ft and 1.10 ft, respectively. The percentage of the total range of observed heads was 9.4 percent of the range of 2.48 ft to 18.12 ft and 8.6 percent of the range of 3.02 ft to 14.96 ft, respectively. The RMSE for the Frederica aquifer was not as good at the value of 1.57 ft, which represents an error of 53 percent, however, there were only four observation points and the total range in head was only 2.95 ft.

The model was calibrated against observed ground-water discharge to Pipe Elm Branch because ground-water discharge to this stream is much greater than that to the other surface-water bodies and because ground-water discharge in Pipe Elm Branch is derived from a larger part of the Base than any other stream or drainage ditch (table 7). The difference between simulated ground-water discharge and observed ground-water discharge for September 1997 for all of the reaches is given in table 7. The error difference between measured and simulated ground-water discharge to Pipe Elm Branch is about 3 percent, which is acceptable because it is below the 10-percent criteria for acceptable error in ground-water discharge. Some of the other errors are quite large, such as the simulated ground-water discharge to Morgan Branch, which in actuality had no ground-water discharge. But the amount of ground-water discharge is small. The error of all of the measured ground-water discharge compared to the simulated ground-water discharge is 5 percent, which is less than the 10-percent error criteria for an acceptable model calibration.

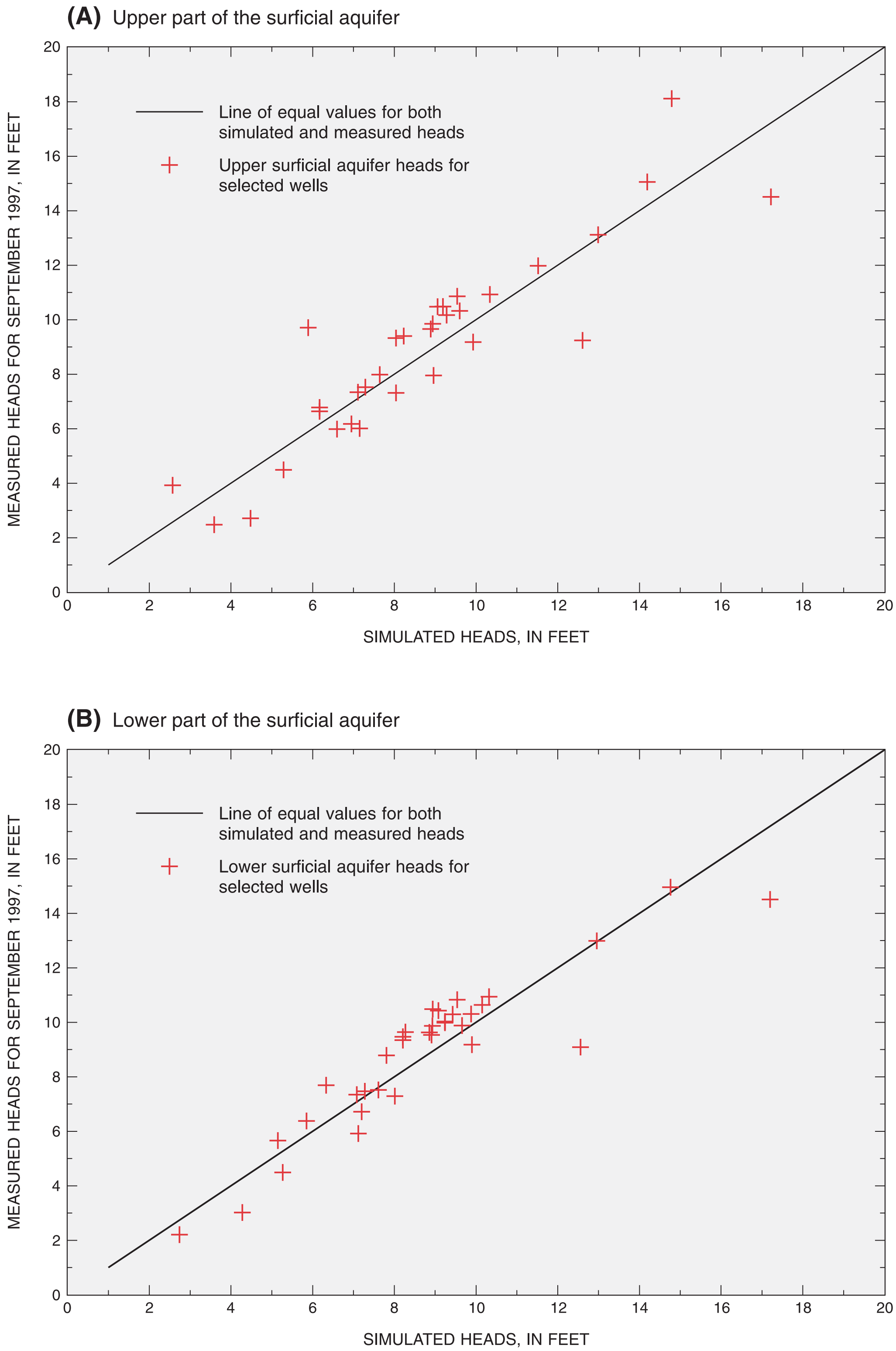


Figure 31. Relation between measured heads (September 1997) and simulated heads in the **(A)** upper part of the surficial aquifer, and **(B)** lower part of the surficial aquifer, Dover Air Force Base, Delaware.

Table 7. *Observed and simulated ground-water discharge to stream reaches in the Dover Air Force Base area, Delaware*

[nc, not calculated because of a division by zero]

Stream or drainage reach	Observed flow Sept. 16, 1997 (cubic feet per day)	Simulated flow (cubic feet per day)	Absolute difference (in percent)
SW1	5,184	8,005	54
Morgan Branch	0	480	nc
Pipe Elm Branch	39,744	38,567	3
Sand Ditch	0	0	nc
Upper Golf Course Tributary	864	1,128	31
Total	45,792	48,180	5

Table 8. *Water budget for simulation of ground-water flow in the Dover Air Force Base area, Delaware*

[ft^2, square feet; in/yr, inches per year; ft/d, feet per day; ft^3/d, cubic feet per day; %, percent]

Type	Recharge area (ft^2)	Average precipitation (in/yr)	Average recharge (in/yr)	Average overland flow and evapotranspiration (in/yr)	Recharge (ft/d)	Recharge into the investigation area (ft^3/d)	Discharge from the ground-water system to surface-water bodies (ft^3/d)
Estimated from map	1.5E + 09	46	12	34	2.74×10^{-3}	4,091,292	4,091,292
Simulated	–	–	12	–	2.74×10^{-3}	4,004,603	4,148,392
Error	–	–	–	–	–	86,689	-57,100
Percent error	–	–	–	–	–	2%	-1%

Regionally, for the lower surficial aquifer, contours of head for both the average observed head and the simulated head show generally good agreement with the general shape of the potentiometric surface of the lower surficial aquifer (fig. 32) and the upper surficial aquifer (fig. 33). A similar relation is also seen between contours of observed head in the Frederica aquifer and simulated heads in the Frederica aquifer (fig. 34).

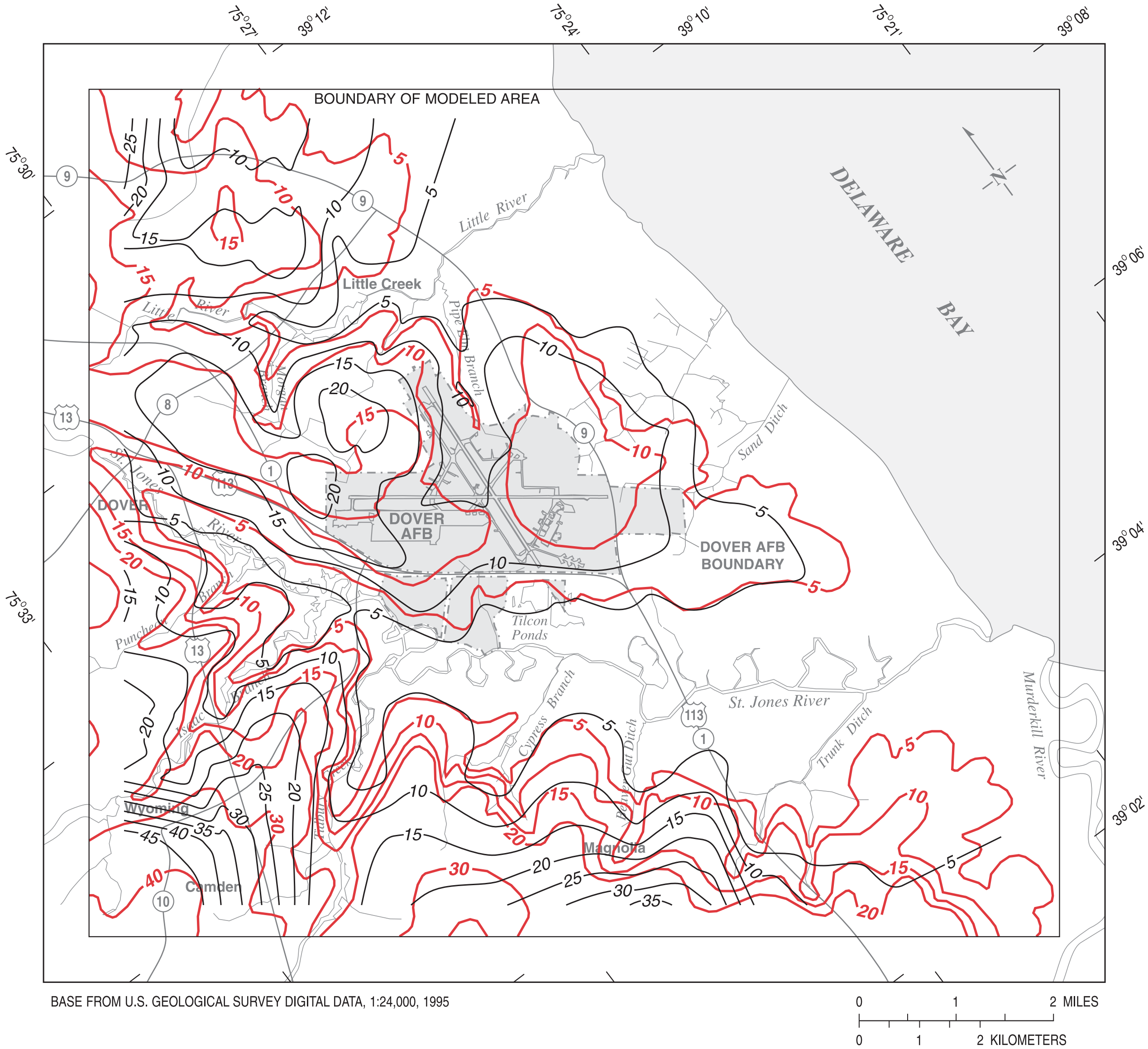
Simulated Water Budget

The simulated water budget for the DAFB area is consistent with the estimated water budget (table 8). Simulated recharge into the system, however, does not exactly match the discharge. Table 8 does not show two other sources of water into the system in the simulation: One is a modest flow, 34,295 ft^3/d (cubic feet per day), from river cells into the ground-water system. Another source of flow is from constant-head cells where there is some minor flow, 109,485 ft^3/d, into the system. Overall, these two sources contribute a 3-percent error of flow into the system.

Sensitivity of the Model

A sensitivity analysis was used to help calibrate the model. The purpose of this analysis was to determine how sensitive the model, or, in other words, the results of the simulation, were to changes in each input parameter. If a small change in an input parameter resulted in a large change in either calculated head or ground-water discharge, then the model was considered sensitive to that parameter. Conversely, if a large change in the parameter resulted in only a small change in either calculated head or calculated ground-water discharge, then the model was less sensitive to that parameter. The sensitivity analysis was performed on the initial model prior to calibration. Thus, in some instances, an increase or decrease of the tested parameter resulted in an improved fit.

It should be noted that the sensitivity analysis described above assumes no changes in the parameters not being tested. If two parameters were tested at the same time, however, the sensitivity results could be different. For example, if, as recharge was increased, the hydraulic conductivity was increased at the same corresponding rate,

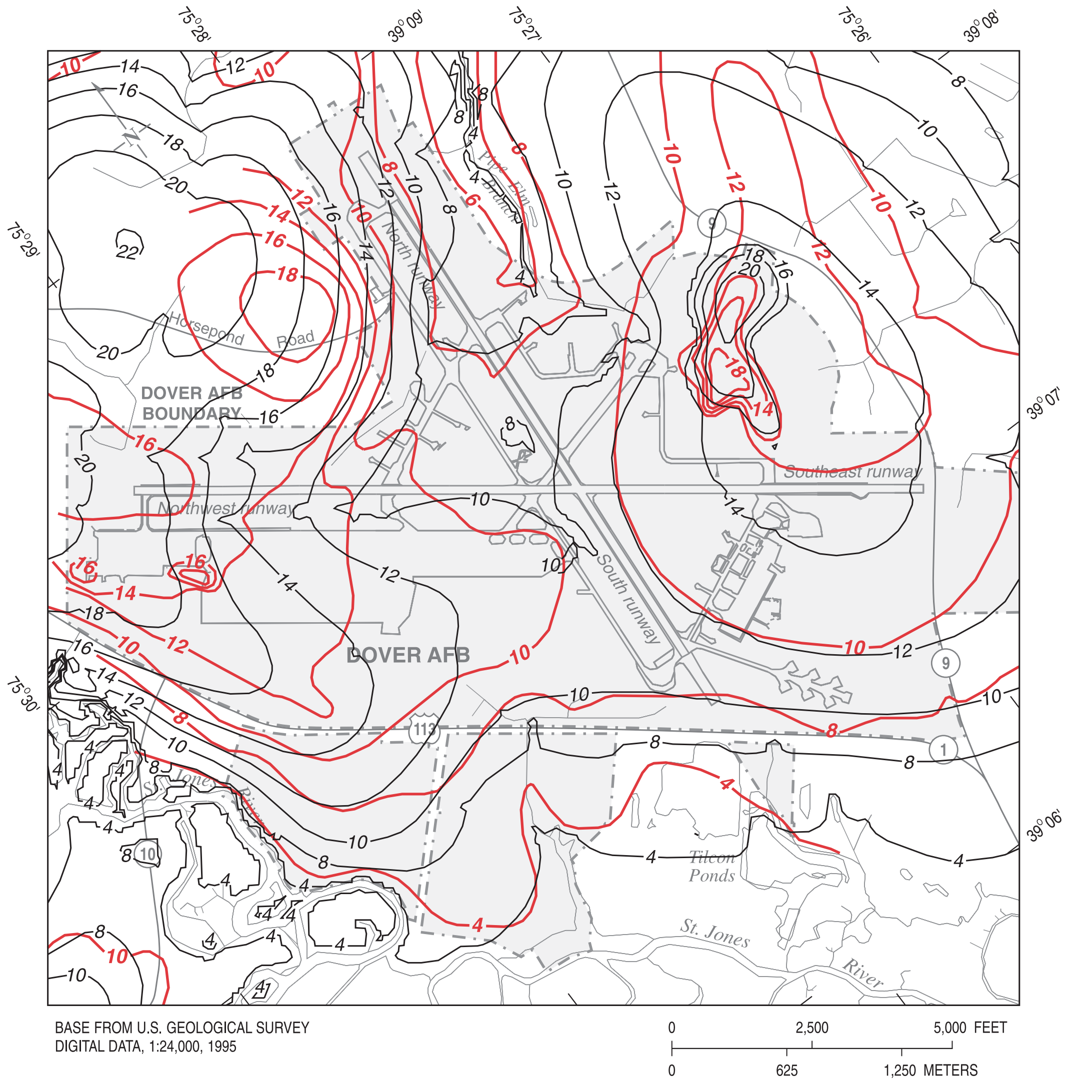


EXPLANATION

—10— ALTITUDE OF WATER TABLE UNDER AVERAGE RECHARGE CONDITIONS (October 1959), IN FEET (Datum is sea level.) (Regional data from Adams and others, 1964; Boggess and Adams, 1965; Boggess and others, 1965; Davis and others, 1965)

—10— SIMULATED HEADS IN LOWER SURFICIAL AQUIFER (Datum is sea level.)

Figure 32. Simulated heads and average heads in the lower part of the surficial aquifer, Dover Air Force Base area, Delaware.



EXPLANATION

—10— ALTITUDE OF WATER TABLE UNDER AVERAGE RECHARGE CONDITIONS (October 1959), IN FEET (Contour interval variable) (Datum is sea level.) (Regional data from Adams and others, 1964; Boggess and Adams, 1965; Boggess and others, 1965; Davis and others, 1965. Estimate of local water-table high near eastern Base boundary from U.S. Geological Survey observations of water levels, 1995-1999.)

—10— SIMULATED HEADS IN UPPER SURFICIAL AQUIFER (Datum is sea level.)

Figure 33. Simulated heads and average heads in the upper part of the surficial aquifer, Dover Air Force Base area, Delaware.

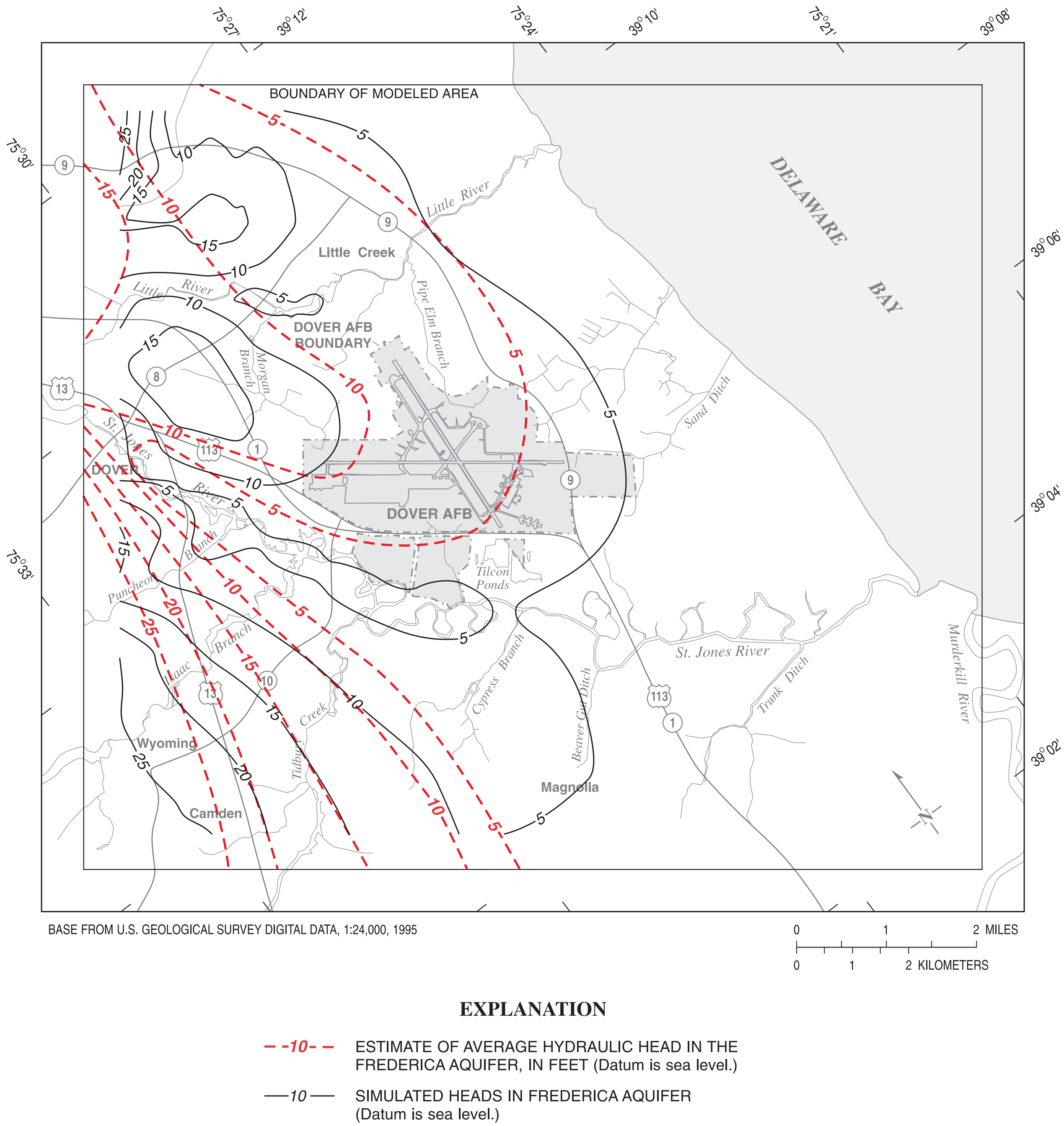


Figure 34. Simulated heads and average heads in the Frederica aquifer, Dover Air Force Base area, Delaware.

then the net change in the head distribution would be negligible. In this case, although the change in head distribution may be negligible, the change in ground-water discharge would not be negligible. These linkages between model parameters, head distribution, and ground-water discharge are the motivation behind measuring ground-water discharge. Even with this linkage of parameters and results, the sensitivity analysis is important in assessing the significance of each of the model-input parameters in order to obtain a reasonable calibration.

In the following discussion, it should be noted that a change in the horizontal hydraulic conductivity means that the vertical conductance between the two layers was also changed. As discussed earlier in this report, it is assumed that the vertical hydraulic conductivity is 10 percent of the horizontal hydraulic conductivity. Thus, if the horizontal hydraulic conductivity changes, the vertical hydraulic conductivity changes, and there is a resulting change to the calculated conductance between the two layers. In the following sensitivity analysis, the vertical hydraulic conductivity was not studied separately. Therefore, the use of the term "horizontal hydraulic conductivity" includes the effects of the change to the conductance between the two layers.

The simulated heads in the upper surficial aquifer are most sensitive to recharge and the horizontal hydraulic conductivity of the underlying lower surficial aquifer (fig. 35). Following these two parameters, the simulated heads in the upper surficial aquifer are moderately sensitive to the horizontal hydraulic conductivity of the upper surficial aquifer. Finally, they are least sensitive to the horizontal hydraulic conductivity of the clays in the surficial aquifer.

For the lower surficial aquifer, the simulated heads are almost equally sensitive to changes in recharge and to the horizontal hydraulic conductivity of the lower surficial aquifer (fig. 36). Next, the heads are sensitive to the horizontal hydraulic conductivity of the upper surficial aquifer. Following these parameters, they are almost equally sensitive to the horizontal hydraulic conductivity of the Frederica aquifer and to the horizontal hydraulic conductivity of the upper Calvert Formation. They are least sensitive to the horizontal hydraulic conductivity of the clays in the surficial aquifer.

Simulated heads in the Frederica aquifer are most sensitive to changes in the horizontal hydraulic conductivity of the overlying confining unit, are sensitive to recharge (fig. 37), and are sensitive to the horizontal hydraulic conductivity of the Frederica aquifer. They are moderately sensitive to the horizontal hydraulic conductivity of the upper surficial aquifer and to the horizontal hydraulic conductivity of the lower surficial aquifer. The heads in this aquifer are least sensitive to the horizontal hydraulic conductivity of the clays in the surficial aquifer. Although the error decreases as the horizontal hydraulic conductivity of the Frederica aquifer is increased to a very high value, this high horizontal hydraulic conductivity was not used because horizontal hydraulic conductivities in the range of 250 ft/d are not supported by any measured values of the horizontal hydraulic conductivity. Similarly, the error decreases as the horizontal hydraulic conductivity decreases to 2.5 ft/d, but simulated heads for normal recharge conditions are too high. The low error on the sensitivity plot for other horizontal hydraulic conductivities of the Frederica aquifer may be due to under-sampling of the potentiometric field by the four measured values of Frederica aquifer head.

Ground-water discharge in the model is most sensitive to recharge and is moderately sensitive to the horizontal hydraulic conductivity of the lower surficial aquifer (fig. 38). It is least sensitive to the horizontal hydraulic conductivity of the upper Calvert Formation, the horizontal hydraulic conductivity of the upper surficial aquifer, and the horizontal hydraulic conductivity of the Frederica aquifer.

Comparison of Simulated Flow Paths and Ground-Water Recharge Dates

The MODPATH-PLOT program (Pollock, 1994), which takes output from MODFLOW and calculates pathlines and traveltimes of ground-water particles, was used to determine the recharge age of ground water along a flow path in a given simulation. The simulated ages were compared to the recharge ages determined from analyses of CFCs and tritium. The comparison was done by tracing water particles in the model from wells, in which recharge dates had been determined, to their recharge locations and then calculating the amount of time necessary for a ground-water particle to have traveled from the top of the water table to the wells. The resulting simulated age should be approximately the same as the CFCs and tritium-recharge dates, which are the approximate date that the water in the sample became isolated from the atmosphere.

Several factors can affect the ground-water recharge dates calculated in particle-tracking simulations. The most significant is the rate of ground-water movement, which is a function of hydraulic conductivity, hydraulic gradient, and porosity. Another factor is the depth and location at which ground-water particles are placed within the model cell. For the simulations in this investigation, a single particle was placed in the geographical center of the cell nearest the well from which CFC and tritium samples were collected. Initial particle depth within the layer coincided with the screen elevation of the well.

For most wells, the agreement between CFCs and particle-tracking recharge dates is considered reasonable (table 9). In six wells, recharge dates from the simulations are within 10 years of the CFC recharge dates. In other wells where agreement is not as good, the assumption of steady-state conditions may have affected the results. Most of the wells with the larger errors are in areas where there may be transient effects due to expanding and contracting ground-water highs, described in the “Surficial Aquifer” section of this report. To show this effect, the model was run with a recharge of 6 in/yr rather than the 12 in/yr used for the other model runs. At well MWD4B, this change had a dramatic effect, where the simulated age changed from 51 years for a

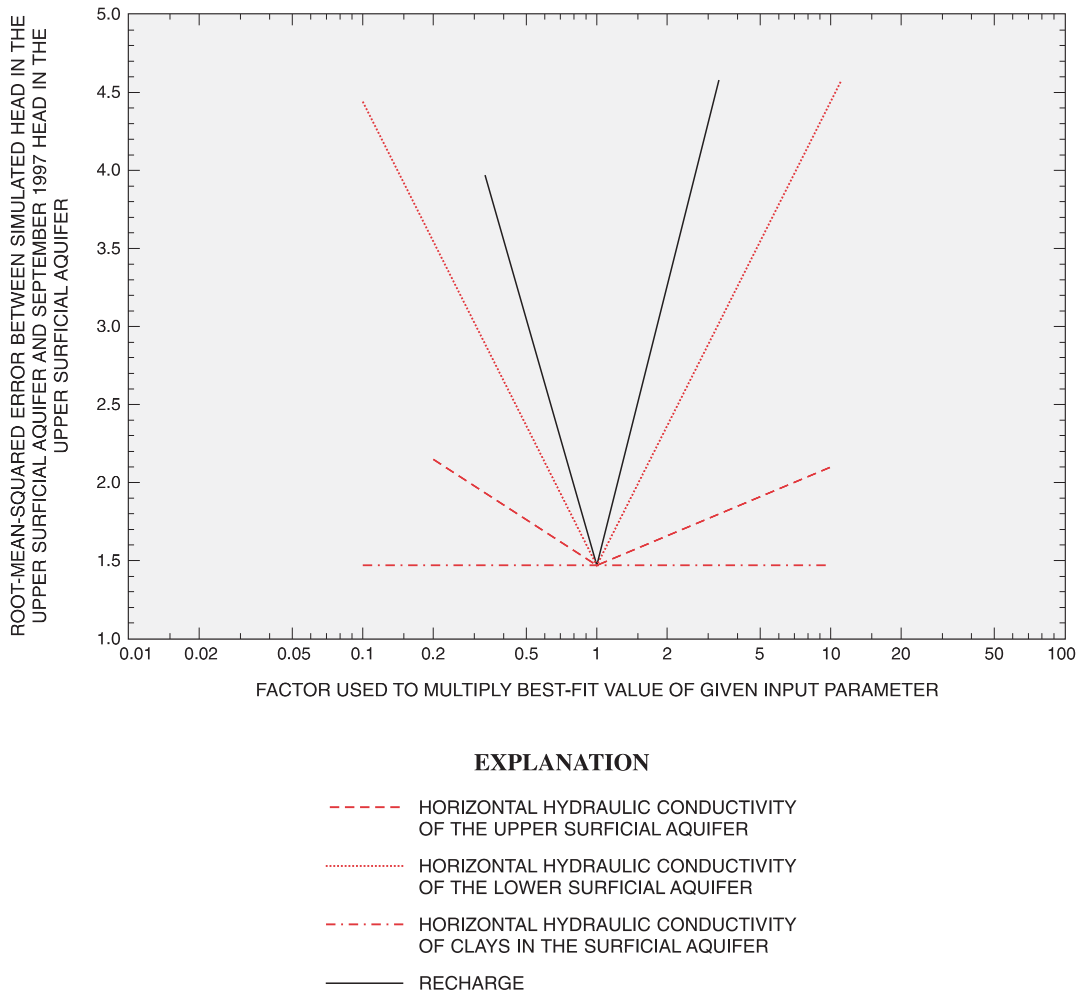


Figure 35. Sensitivity of simulated head in the upper surficial aquifer to changes in recharge, horizontal hydraulic conductivity of the upper surficial aquifer, horizontal hydraulic conductivity of the lower surficial aquifer, and horizontal hydraulic conductivity of clays in the surficial aquifer, Dover Air Force Base, Delaware.

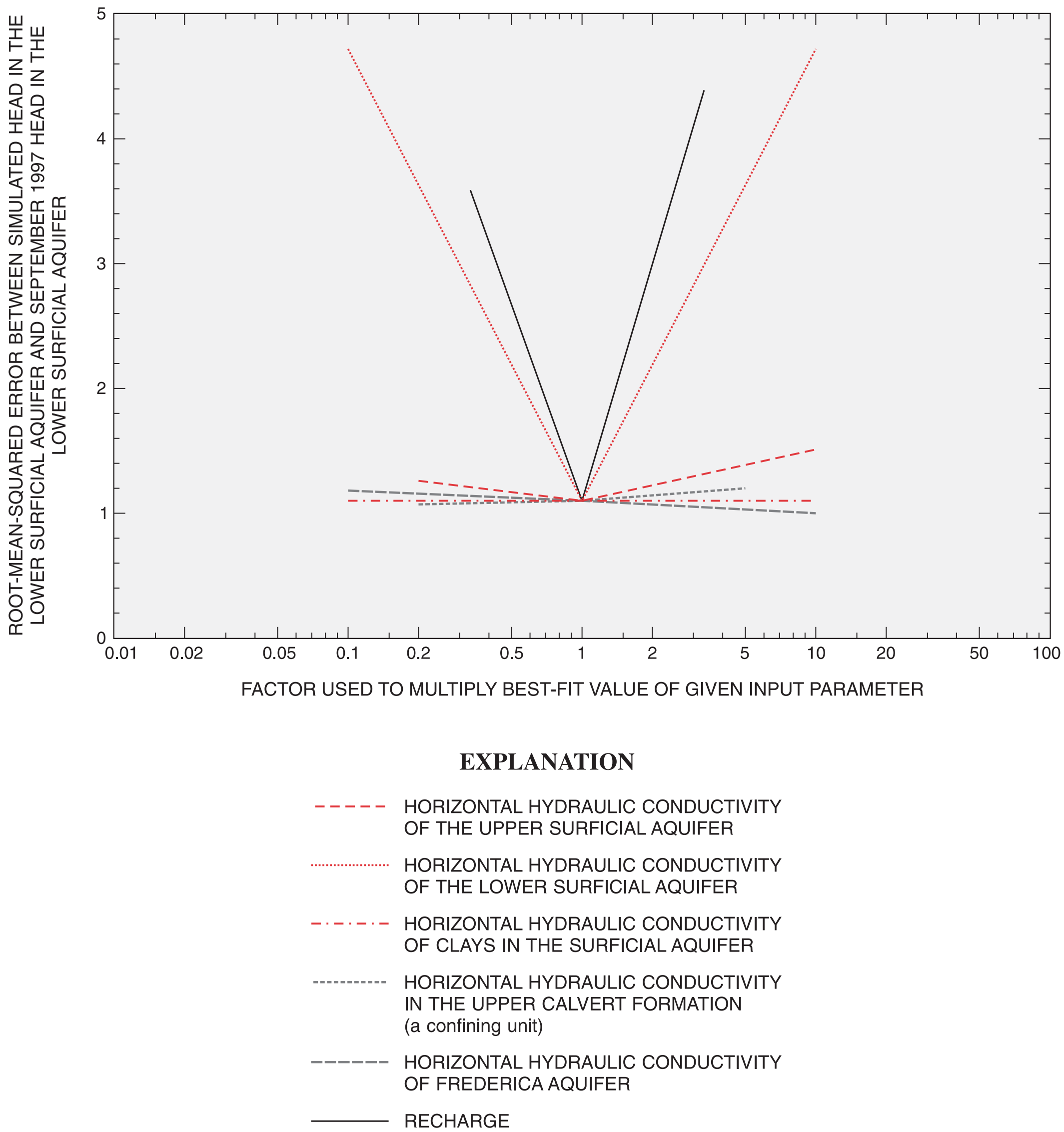


Figure 36. Sensitivity of simulated head in the lower surficial aquifer to changes in recharge, horizontal hydraulic conductivity of the upper surficial aquifer, horizontal hydraulic conductivity of the lower surficial aquifer, horizontal hydraulic conductivity of the upper Calvert Formation confining unit, and horizontal hydraulic conductivity of the Frederica aquifer, Dover Air Force Base, Delaware.

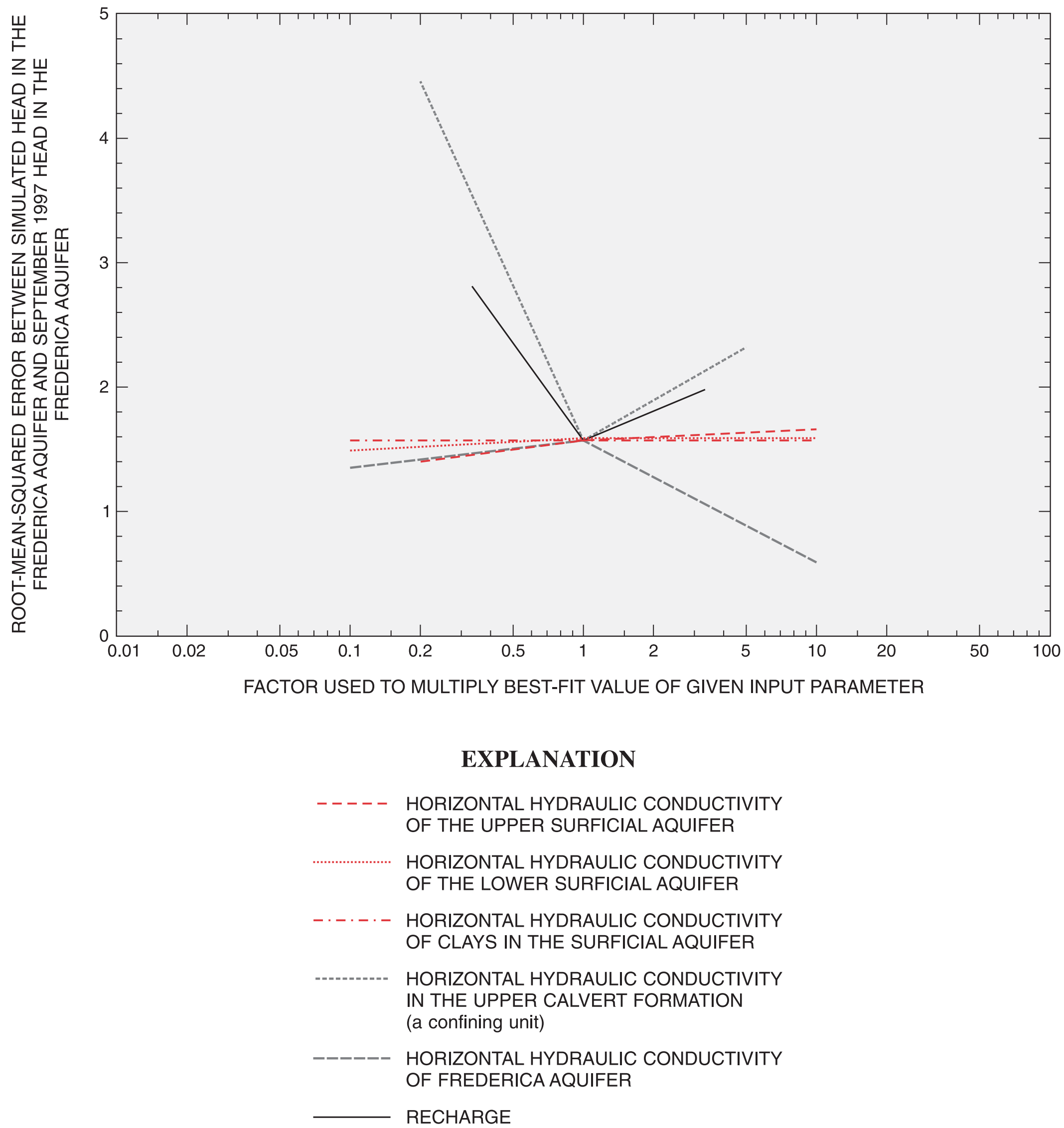


Figure 37. Sensitivity of simulated potentiometric surface of the Frederica aquifer to variation of horizontal hydraulic conductivity of the Frederica aquifer, horizontal hydraulic conductivity of the upper Calvert Formation confining unit, recharge, horizontal hydraulic conductivity of the lower surficial aquifer, and horizontal hydraulic conductivity of the upper surficial aquifer, Dover Air Force Base, Delaware.

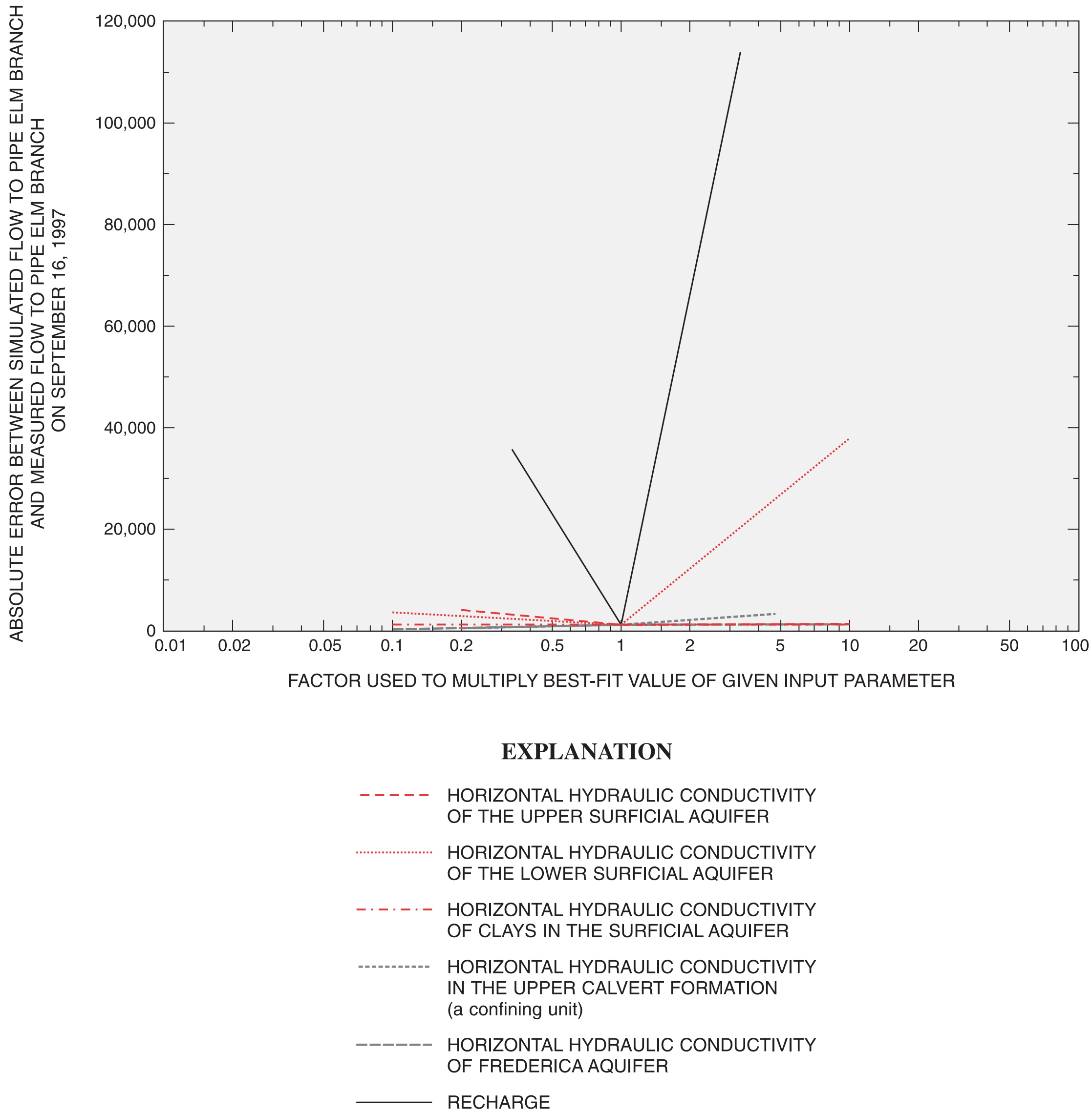


Figure 38. Sensitivity of simulated ground-water discharge to Pipe Elm Branch to changes in recharge, horizontal hydraulic conductivity of the upper surficial aquifer, horizontal hydraulic conductivity of clays in the surficial aquifer, horizontal hydraulic conductivity of the lower surficial aquifer, horizontal hydraulic conductivity of the upper Calvert Formation confining unit, and horizontal hydraulic conductivity of the Frederica aquifer for the Dover Air Force Base area, Delaware.

Table 9. *Comparison of chlorofluorocarbons (CFCs) recharge dates to recharge dates from the ground-water particle-tracking simulations at Dover Air Force Base, Delaware*

[No wells were screened in the upper Calvert Formation and semi-confining unit. The following porosities were used in the MODPATH steady-state flow model—0.3 for the upper surficial aquifer, 0.3 for the lower surficial aquifer, 0.4 for the upper Calvert Formation confining unit, 0.4 for the semi-confining unit, and 0.3 for the Frederica aquifer. A, simulated recharge age; B, traveltime in years; C, error between simulated recharge age and CFC recharge age]

Well no.	CFC recharge date	CFC traveltime (years)	GROUND-WATER PARTICLE-TRACKING SIMULATIONS											
			Recharge rate = 12 inches per year									Recharge rate = 6 inches per year		
			Bottom of screen			Level of pump			Top of screen			Level of pump		
			A	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
UPPER SURFICIAL AQUIFER														
DM102S	1983	13.5	1993	4.0	10	1993	3.5	10	1996	0.5	13	1992	4.7	9
DM342S	1985	11.5	1992	5.0	7	1995	1.5	10	1995	2.0	10	1994	3.0	9
DM367S	1989	7.5	1996	0.3	7	1996	0.5	7	1996	0.5	7	1996	1.0	7
MW40S	1982	14.5	1993	4.0	11	1994	3.0	12	1994	2.5	12	1992	4.5	10
MWD4B	1985	11.5	1945	51.5	-40	1945	51.5	-40	1945	51.5	-40	1991	5.5	6
LOWER SURFICIAL AQUIFER														
DM102D	1972	24.5	1951	46.0	-21	1974	22.5	2	1974	22.5	2	1955	42.0	-17
DM206D	1970	26.5	1968	28.5	-2	1986	10.5	16	1986	10.5	16	1966	30.5	-4
DM342D	1987	9.5	1976	20.5	-11	1979	18.0	-8	1990	6.5	3	1977	20.0	-10
DM405D	1975	21.5	1934	63.0	-41	1962	34.5	-13	1969	27.5	-6	1923	74.0	-52
MW206D	1970	26.5	1935	61.5	-35	1944	53.0	-26	1944	53.0	-26	1951	45.5	-19
MW40D	1975	21.5	1967	29.5	-8	1967	30.0	-8	1967	30.0	-8	1959	38.0	-16

recharge rate of 12 in/yr to about 5 years for a recharge rate of 6 in/yr. This example shows that for some parts of the Base, a transient model would simulate ground-water-flow pathways and traveltimes more accurately than does the steady-state model used here.

Results of Selected Particle-Tracking Analyses

This model can be used for advective-transport analysis at individual sites at DAFB. This section of the report presents forward-tracking analyses for three remediation areas at DAFB. The main objective of these analyses is to determine the ground-water-flow pathlines and traveltimes of water particles traveling in specific areas of DAFB. The results of the following particle-tracking analyses are based on average steady-state conditions and generalized aquifer characteristics. Transient conditions and local variations in aquifer characteristics at specific sites could significantly affect these results.

Natural Attenuation Project Area The Natural Attenuation Project Area (fig. 1c) is an area in which natural attenuation was investigated as a remedial option for contaminated ground water. Bachman and others (1998) used a one-dimensional reactive solute-transport model to assess the breakdown of chemical contaminants along a flow path. Because the model was one-dimensional, questions were raised as to whether the simulated ground-water-flow path matched the actual flow path in the investigation area. In addition, it was not known whether some of the flow paths in the area extended beyond the DAFB boundary. As a consequence, it was apparent that there was a need for additional monitoring wells in the area, and it was anticipated that particle tracking could be used to suggest well placement.

Particle-tracking results show the effects of local ground-water highs (fig. 39) at a landfill, LF13. The water particles initially flow radially away from the local high, and then enter the lower part of the surficial aquifer. The ground-water particles change flow direction where the hydraulic gradient of the lower surficial aquifer is different from that of the upper surficial aquifer. All four ground-water particles placed within LF13 begin their flow paths in a radial pattern away from the ground-water high in the upper surficial aquifer. Once they move downward into the lower surficial aquifer, however, they all move toward Pipe Elm Branch. This suggests that contaminated ground water in LF13 does not migrate toward the adjacent Base boundary. Under the steady-state conditions of the model, water recharging at LF13 can take from 10 to 50 years to reach Pipe Elm Branch.

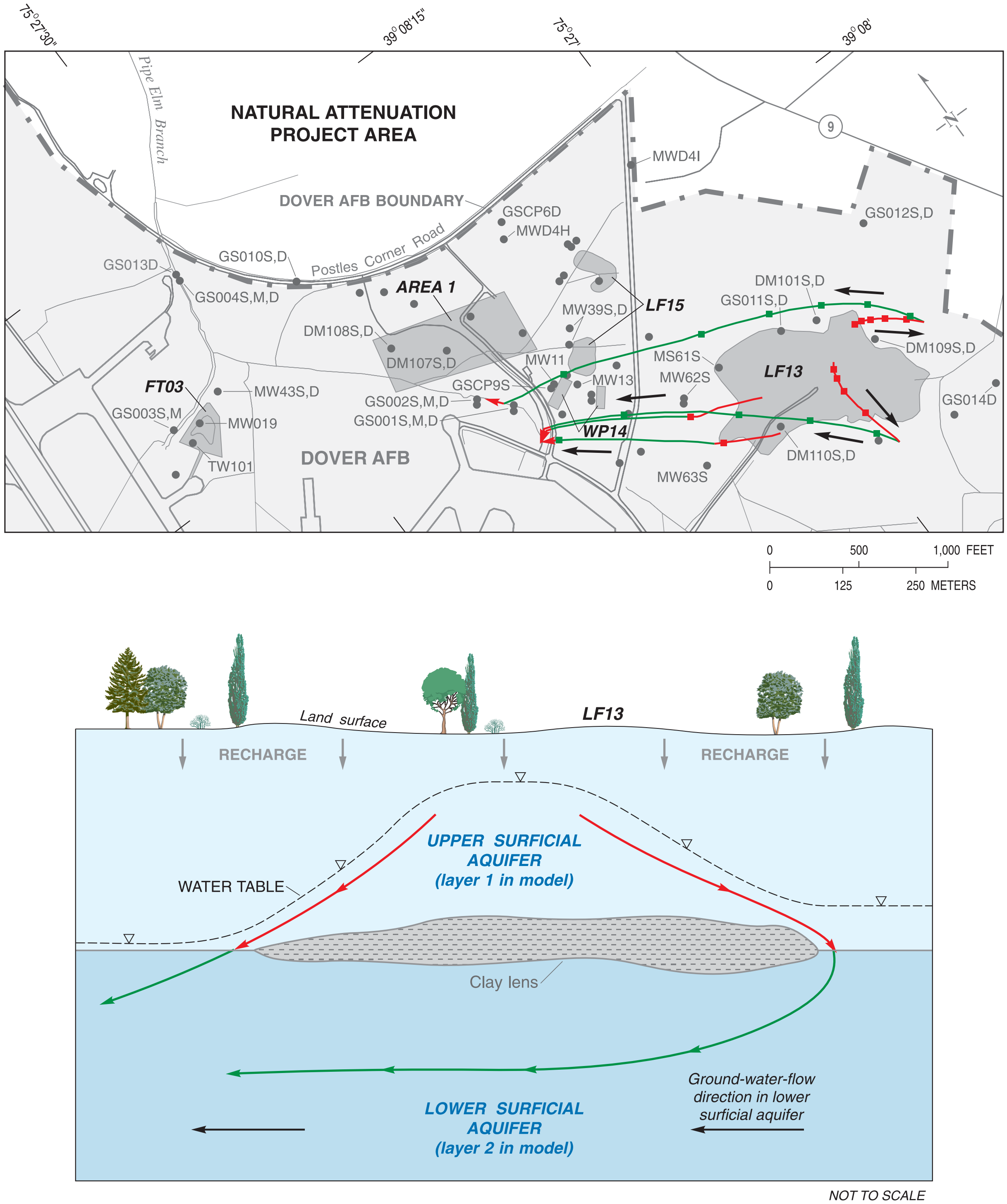
Similarly, water particles placed in the WP14/LF15 areas, which are former locations of a liquid-waste disposal pit and landfill, also move toward Pipe Elm Branch and away from the Base boundary (fig. 40). Traveltimes are generally less than 5 years at these sites.

Long-Term Monitoring at OT-40 The ground-water-flow simulation can also be used to assist in the implementation of long-term monitoring at specific sites. One of these sites is OT-40, an oil-water separator, where long-term monitoring will be implemented (fig. 1c). Particle tracking was used to determine ground-water-flow paths from this site. Monitor wells were installed along these paths.

In this analysis, the ground-water particles were added at the top of the water table. It takes about 4 years for the particles to move through the upper surficial aquifer and enter the lower surficial aquifer (fig. 41). Once the particles enter the lower surficial aquifer, they move at a faster rate, as is seen by the distance between the boxes in figure 41. The particles take about 9 years to reach the Base boundary, which is not shown on figure 41. The final discharge location for these particles is the St. Jones River.

Contaminant Plume at Area 6 Area 6 (fig. 1c) is the location of a large ground-water contaminant plume consisting mainly of chlorinated solvents (U.S. Army Corps of Engineers and Dames & Moore, 1994). Particle tracking was used to define ground-water-flow paths in this area. The pathways (fig. 42a) show that the flow diverges as it moves under Base housing towards the St. Jones River. At the left side of figure 42a, particles take about 10 years to reach the St. Jones River, while near the center of the figure, some of the particles would take about 25 years to reach the St. Jones River, while other particles, which enter into layer 3 and layer 4 of the model, take much longer to reach the St. Jones River. On the right side of the figure, the particles flow to the golf course tributary that crosses under Route 113 and then move towards the St. Jones River.

Figure 42a also shows ground-water particles that enter the confining unit and then the Frederica aquifer. Figure 42 b-e shows the flow in each model layer. Most of the particles released at the top of the water table flow vertically down through layer 1 and into layer 2 (the lower surficial aquifer) (fig. 42b). In layer 2, the particles flow mainly horizontally (fig. 42c). Some of the particles reach the St. Jones River or the Golf Course Tributary (locations given in figure 42a and figure 1c) without entering lower layers in the model. Other particles enter layer 3, which is the upper Calvert confining unit (fig. 42d). Except for the left most part of the figure, the particles travel almost totally vertically. What is not shown well on this figure is that for this vertical flow, many boxes are superimposed. In the left most part of the figure, one of the particles in this layer has a large horizontal component in its flow. This area is where layer 3 has a high hydraulic conductivity and it is thought that in this area the sediments of the upper Calvert confining unit are missing. Figure 42e shows the flow in layer 4, which represents the Frederica aquifer. This flow has a large horizontal component. The distance between boxes is less than the distance between boxes for layer 2 (fig. 42c) because the horizontal gradient is less. In cross section (not shown), the flow in this layer would start to have a downward component then, as it approached the St. Jones River, it would have an upward component of flow. Finally, the particles would enter layer 3 and go up towards the St. Jones River. This flow is in response to the vertical head gradient.



EXPLANATION

PATHLINE IN LAYER 1 (UPPER SURFICIAL AQUIFER)
PATHLINE IN LAYER 2 (LOWER SURFICIAL AQUIFER)
Distance between boxes represents 5-years traveltime.

GENERAL DIRECTION OF GROUND-WATER FLOW

GS013D ● MONITOR WELL AND IDENTIFICATION NUMBER

Figure 39. Pathlines and traveltimes for advective transport of ground-water particles starting at LF13 in the Natural Attenuation Project Area (location shown in figure 1c), Dover Air Force Base, Delaware. (Schematic shows a cross-sectional view of flow off of the local ground-water high at LF13.)

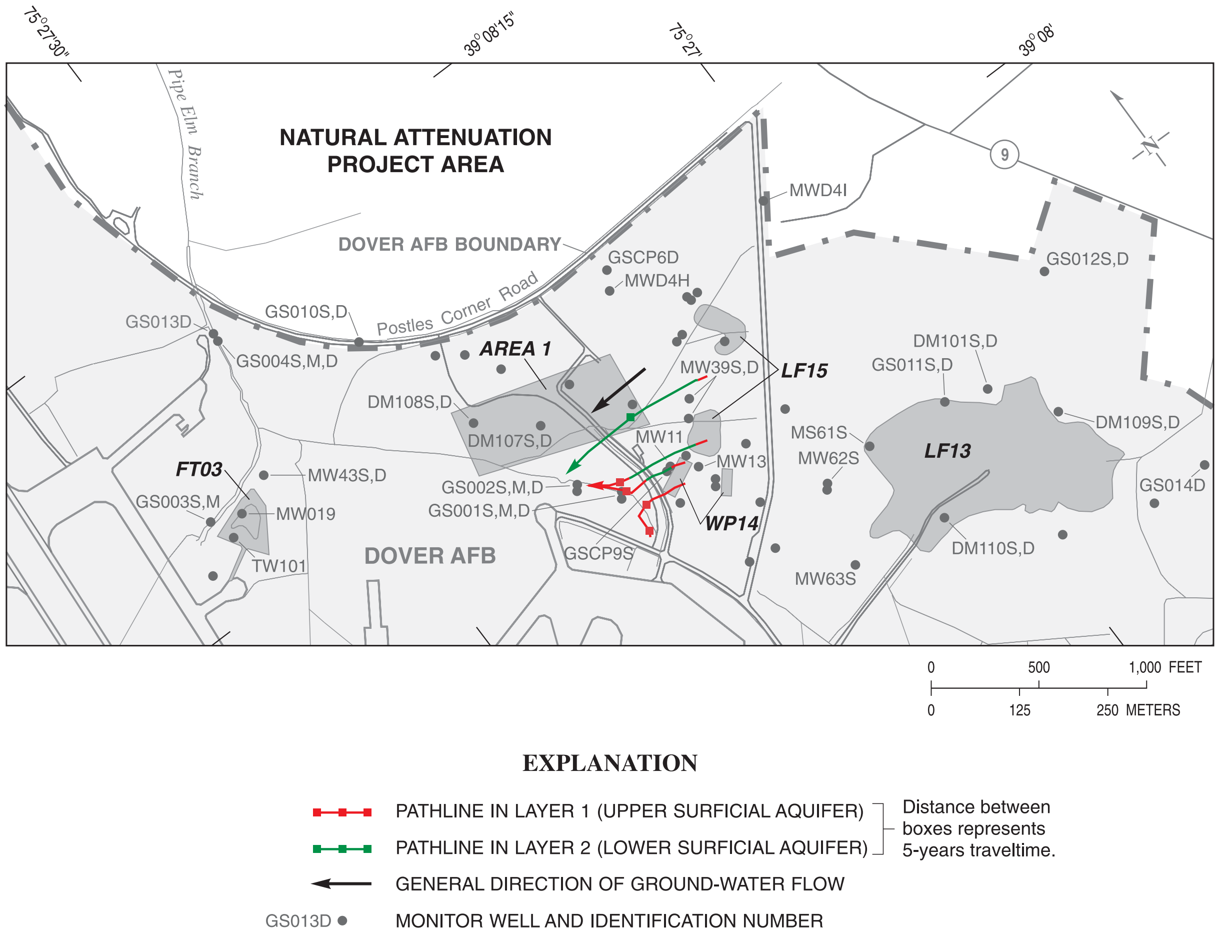


Figure 40. Pathlines and traveltimes for advective transport of ground-water particles starting at WP14/LF15 in the Natural Attenuation Project Area (location shown in figure 1c), Dover Air Force Base, Delaware.

Near the top of the figure, the vertical head gradient is from the surficial aquifer towards the Frederica aquifer. This direction of the vertical head gradient is maintained until near the St. Jones River, where the vertical head gradient reverses with flow going from the Frederica aquifer upward towards the St. Jones River.

Selected Limitations of the Ground-Water-Flow Model

The numerical model described in this report has limitations that could produce misleading results if not taken into account. Future users of this model need to recognize common limitations of ground-water-flow models in general and of this model in particular.

Model-simulation results are sensitive to stresses on the ground-water-flow system. If new, large stresses are added in the DAFB area, such as pumping from new wells in the surficial aquifer, then the model should be recalibrated. Franke and Reilly (1987, p. 11) discuss this issue for ground-water models in general.

Appropriate applications of the model are constrained by the cell size of the model grid. An inappropriate application of the model would be to put a small discharge well in a large model cell, the effect of which is to create a weak sink, which occurs when the well does not discharge at a rate that consumes all of the water entering the cell (Pollock, 1994). A weak sink can allow particles to flow past an area where they should be captured by a pumping well. Weak sinks are caused by using a spatial discretization that is too coarse (Pollock, 1994). Determining the appropriate discretization before the model is assembled can be a difficult decision. Once the grid discretization is selected, the ZONEBUDGET (Harbaugh, 1990) or MODPATH (Pollock, 1994) codes could be used to determine the flow to and from a model cell. Flow to or from the model cell could subsequently be compared to the discharge of the well within the cell. If the well discharge is smaller than the flow to or from the model cell, then that model cell is a weak sink and the cell size should be reduced.

The particle-tracking simulations presented in this report represent advective transport—that is, they do not take into account the decay, retardation, or dispersion of manmade chemicals in the ground-water-flow system. These chemical and mechanical processes are not simulated by the particle-tracking routines, so that actual chemical transport may be

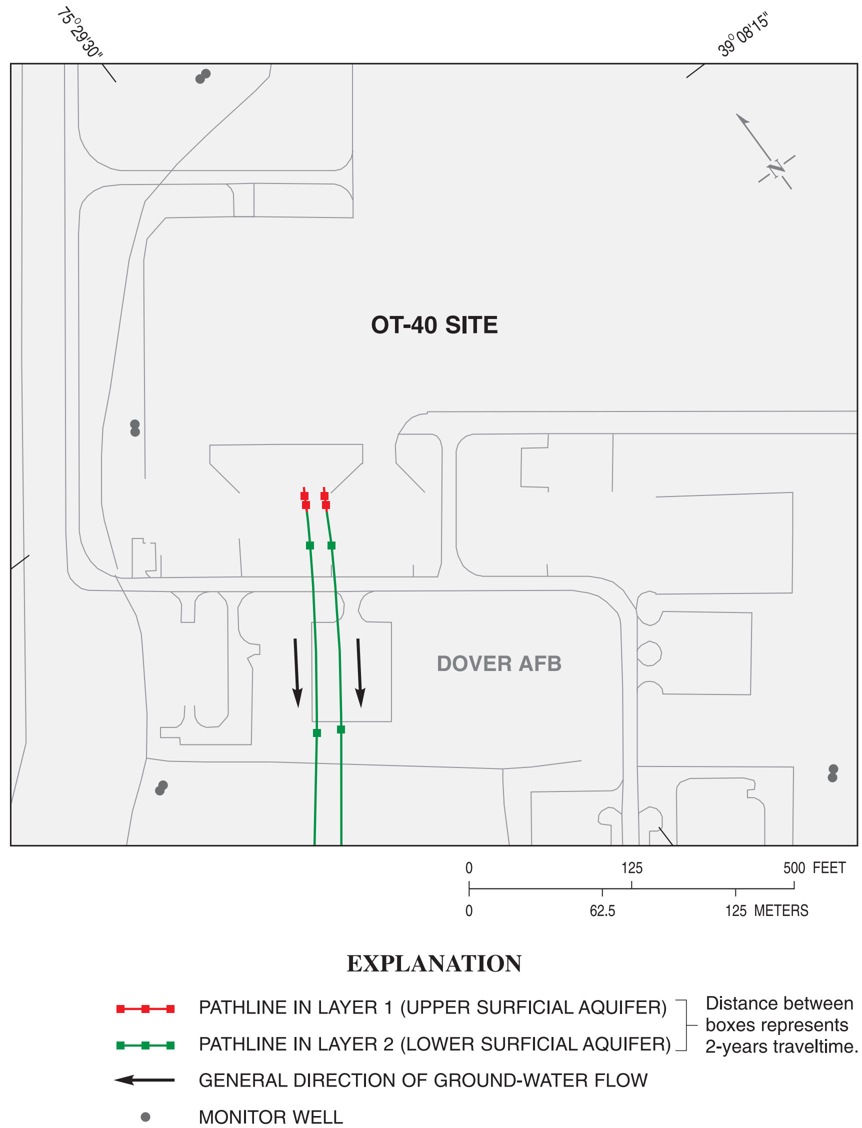
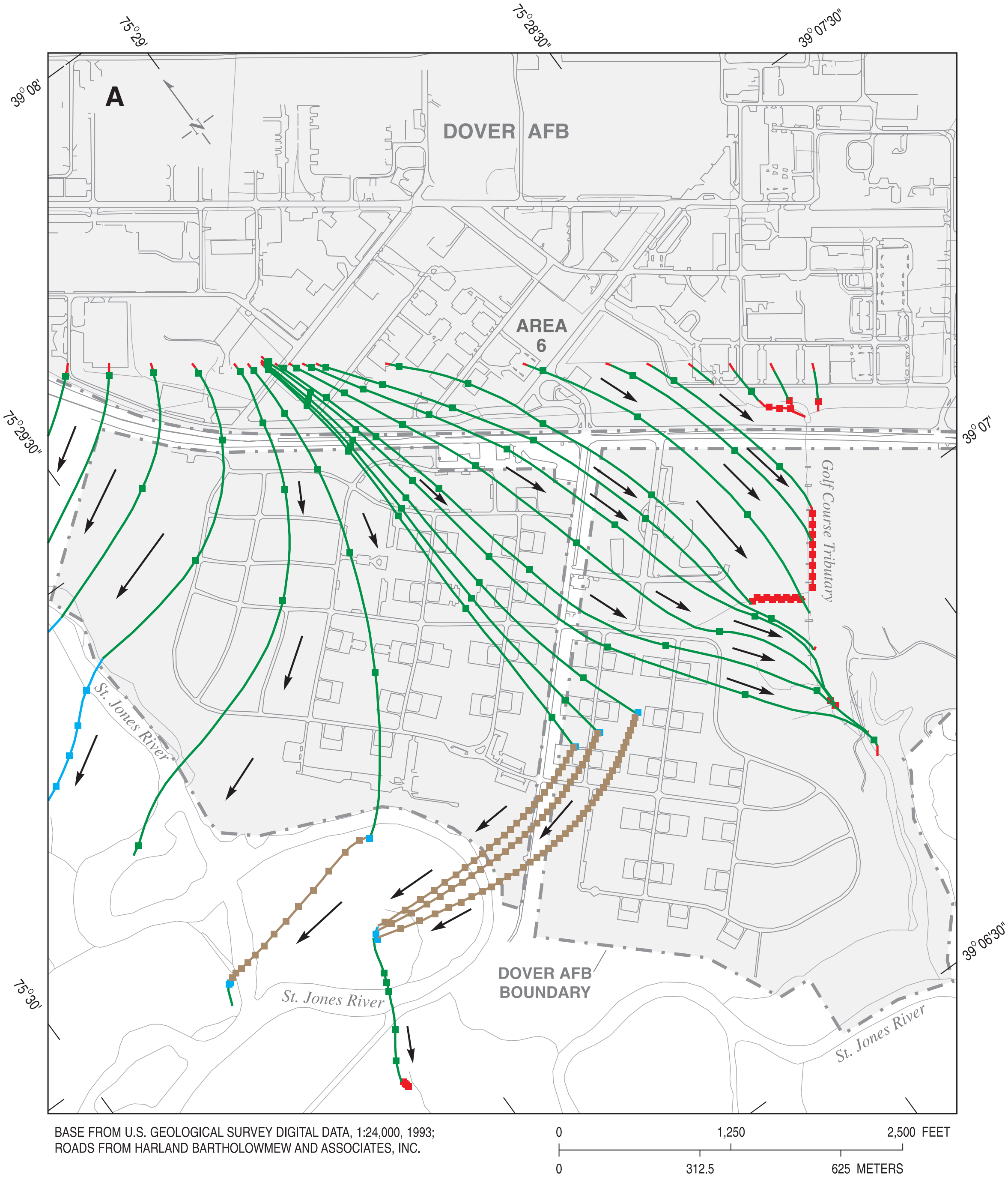


Figure 41. Pathlines and traveltimes for ground-water particles starting at the OT-40 site (location shown in figure 1c), Dover Air Force Base, Delaware.

faster or slower than the advective-transport predictions. The particle-tracking results, therefore, give only the average distance a particle of water would travel in the ground-water-flow system over a given time period, and should be considered approximate. Because certain aspects of the ground-water-flow system, such as the variable distribution of hydraulic conductivity, are not fully characterized or represented in the model, the model should not be used to provide answers to questions that depend upon the details of the simulated heads and pathlines. Simulation results of an adequately calibrated model should generally provide a good approximation of heads and flow direction in a ground-water system, but the complexity of the these systems means that complete accuracy is impossible. Some of this uncertainty is indicated by discrepancies between calculated and observed results. Limitations of the use of ground-water-flow models are discussed in Konikow (1988a, 1988b), Konikow and Bredehoeft (1992), and Bredehoeft and Konikow (1993).



EXPLANATION

PATHLINE IN LAYER 1 (UPPER SURFICIAL AQUIFER)
PATHLINE IN LAYER 2 (LOWER SURFICIAL AQUIFER)
PATHLINE IN LAYER 3 (UPPER CALVERT FORMATION)
PATHLINE IN LAYER 4 (FREDERICA AQUIFER)

Distance between boxes represents 5-years traveltime.

GENERAL DIRECTION OF GROUND-WATER FLOW

Figure 42a. Composite pathlines and traveltimes for ground-water particles released in Area 6 (location shown in figure 1c), Dover Air Force Base, Delaware.

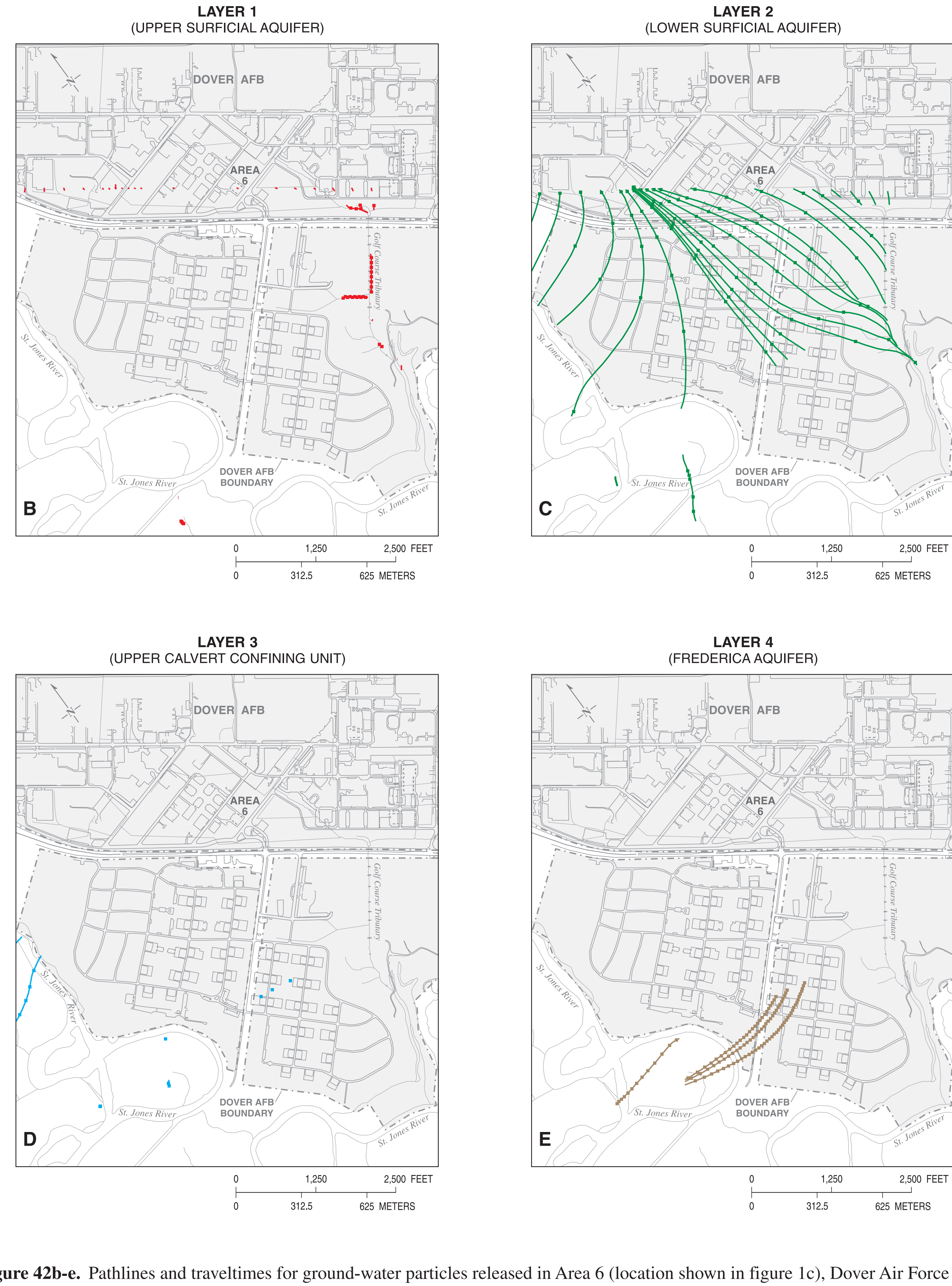


Figure 42b-e. Pathlines and traveltimes for ground-water particles released in Area 6 (location shown in figure 1c), Dover Air Force Base, Delaware, for the following layers: **(B)** layer 1 (the upper surficial aquifer), **(C)** layer 2 (the lower surficial aquifer), **(D)** layer 3 (the upper Calvert confining unit), and **(E)** layer 4 (the Frederica aquifer).

Summary

Dover Air Force Base is underlain by unconsolidated sediments of the Atlantic Coastal Plain. The uppermost sand unit in the Calvert Formation at Dover Air Force Base is the Frederica aquifer, which is the deepest unit investigated in this report. A confining unit of clayey silt in the upper Calvert Formation separates the Frederica aquifer from the lower surficial aquifer, which is the basal Columbia Formation. North and northwest of Dover Air Force Base, the Frederica aquifer subcrops beneath the Columbia Formation and the upper Calvert Formation confining unit is absent. The Calvert Formation dips to the southeast. The Columbia Formation consists predominately of sands, silts, and gravels, although in places clay layers separate the surficial aquifer into an upper and lower surficial aquifer.

The shape of the water table at Dover Air Force Base is controlled by the amount of recharge and the distance to discharge areas. The main ground-water discharge areas are the Little River, the St. Jones River, and the Delaware Bay. If there were no secondary drainage, then the water table would form a broad high centered near the Base; however, there are several secondary discharge areas, such as Pipe Elm Branch, Morgan Branch, and the Golf Course Tributary. These secondary discharge areas create a series of ground-water highs and divides in the area of the Base, two of which are termed, in this report, the Northwest Runway Divide and the Southeast Runway High. The potentiometric surface of the Frederica aquifer also forms a broad high, which is centered on Dover Air Force Base.

Long-term water-level hydrographs show changes in both seasonal and annual ground-water recharge at Dover Air Force Base. These variations in recharge are related to temporal changes in evaporation, plant transpiration, and precipitation. Differences in water levels in paired wells finished in different depths in the surficial aquifer indicate areas where extensive silts and clays are present in the surficial aquifer. In these areas, a vertical head difference as large as several feet may occur between water levels in wells screened above and below the clays, and local ground-water highs typically form during normal recharge conditions. When drought conditions persist, water drains off these highs, and the vertical gradients decrease. At the south end of Dover Air Force Base, hydrographs of water levels in wells completed in the Frederica aquifer show that off-Base pumping for irrigation of crops can cause the potentiometric surface to decline below sea level during part of the year. During the time of the year with no irrigation (and no pumping), flow is from the surficial aquifer towards the Frederica aquifer, except near the St. Jones River, where heads in the Frederica aquifer are above the heads in the lower surficial aquifer. In this area, flow is from the Frederica aquifer towards the lower surficial aquifer.

A 4-layer, steady-state numerical model of ground-water flow was assembled for Dover Air Force Base and the surrounding area. The upper two model layers represent the upper and lower surficial aquifers, which are in the Columbia Formation. In some areas of the model, a semi-confining unit is used to represent the intermittent clay layer between the upper and lower surficial aquifer. This semi-confining unit causes the local ground-water highs in the surficial aquifer. The third model layer represents the upper Calvert Formation confining unit. The fourth model layer represents the Frederica aquifer. The model was calibrated to hydraulic heads and to ground-water discharge in Pipe Elm Branch, both measured in September 1997. For the calibrated model, the root-mean-squared errors for the hydraulic heads and the ground-water discharge in the Pipe Elm Branch were 9 percent of the range of head and 3 percent of discharge, respectively. Heads simulated by use of the model were consistent with a map based on field measurements that shows average water levels in the region.

The MODPATH particle-tracking program was used to simulate ground-water-flow directions for several areas on the Base. At LF13, one of the Base landfills, this analysis showed the effects of the local ground-water highs. In this area, ground water can flow from the highs and then dramatically change flow direction as it enters the lower surficial aquifer. At Area 6, the pathlines show a divergence of flow, with flow going from the Base towards the St. Jones River and towards the Golf Course Tributary. The pathline analysis also shows that ground water flows from the lower surficial aquifer, through the upper Calvert confining unit, through the Frederica aquifer, then back up through the upper Calvert confining unit and then to the lower surficial aquifer.

The steady-state model has several limitations. The entire ground-water system is under transient conditions, due mainly to seasonal and yearly changes in recharge and withdrawal from irrigation wells. This steady-state model is still an effective tool, however, for understanding the ground-water-flow system underlying the Base for average conditions. If the ground-water system is subjected to new stresses, such as pumping from new wells at or near the Base in the surficial aquifer or in the Frederica aquifer, then the model should be verified for these conditions and, if necessary, recalibrated. Nevertheless, the model can be used to determine ground-water-flow pathlines in areas of the Base where the flow directions are constant. In addition, the steady-state model is a necessary step in the development of transient models and solute-transport models, which are planned for future ground-water monitoring on the Base.

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