ASSESSMENT OF GROUND-WATER CONTAMINATION AT WURTSMITH AIR FORCE BASE, MICHIGAN, 1982-85

By T. R. Cummings and F. R. Twenter

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who may prefer to use metric (International System) units rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	3.785	liter (L)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
cubic foot per second (ft^3/s)	28.32	liter per second (L/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.0386	liter per second per square kilometer [$(L/s)/km^2$]
gallon per minute per foot [(gal/min)/ft]	0.207	liter per second per meter [(L/s)/m]
degree Fahrenheit (°F)	(*)	degree Celsius (°C)

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*Temperature °C = (temperature °F -32)/1.8.

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ABSTRACT

Continued study of ground-water contamination at Wurtsmith Air Force Base, Michigan, defined the movement and distribution of volatile organic compounds in the glacial sand and gravel aquifer at known sites of contamination, and has defined new plumes at two other sites.

The Arrow Street purge system, installed in 1982 to remove contaminants from the Building 43 plume, has lowered concentrations of trichloroethylene in ground water in the central part of the most contaminated area from a range of 1,000 to 2,000 micrograms per liter to about 200 micrograms per liter. Trichloroethylene is not escaping off-Base from this area.

In the southern part of the Base a plume containing principally trichloroethylene and dichloroethylene has been delineated along Mission Drive. Maximum concentrations observed were 3,290 micrograms per liter of trichloroethylene and 1,480 micrograms per liter of dichloroethylene. Hydrologically suitable sites for purge wells are identified in the southern part of the plume using a new ground-water flow model of the Base.

A benzene plume near the bulk-fuel storage area, delineated in earlier work, has shifted to a more northerly direction under influence of the Arrow Street purge system. Sites initially identified for purging the benzene plume have been repositioned because of the change in contaminant movement. JP-4 fuel was found to be accumulating in wells near the bulk-fuel storage area, largely in response to seasonal fluctuations in the water table. It is thought to originate from a spill that occurred several years ago.

A more thorough definition of contaminants in the northern landfill area has permitted a determination of the most hydrologically suitable sites for purge wells. In general, concentrations found in water do not differ greatly from those observed in 1981.

Since 1981, concentrations of trichloroethylene have decreased significantly in the Alert Apron plume. Near the origin of the plume, the concentration of trichloroethylene has decreased from 1,000 micrograms per liter in 1980 to 50 micrograms per liter in 1984. Water from Van Etten Lake near the termination of the plume had only a trace of trichloroethylene at one site.

Benzene detected in water from well AF2 seems to originate near the former site of buried fuel tanks west of the operational apron. During periods of normal purge pumping along Arrow Street, contaminants are drawn to the purge system. During periods when pumping is low, contaminants are drawn toward water-supply wells AF2, AF4, and AF5.

INTRODUCTION

In 1982, the U.S. Geological Survey completed a study of ground-water contamination at Wurtsmith Air Force Base,[1] Michigan. The study defined the rate and direction of ground-water flow, the extent of contamination, and general water-quality conditions. Mathematical models of the ground-water-flow system were developed, and hydrologically suitable sites for installing purge wells were identified. Results of the study, which reported on activities from December 1979 to March 1981, were published as U.S. Geological Survey Water-Resources Investigations Report 83-4002, "Ground-Water Contamination at Wurtsmith Air Force Base, Michigan," by Stark and others (1983). That study should be consulted for a detailed discussion relating to geology, hydrology, mathematical modeling of the ground-water-flow system, and methods of data collection and analysis.

Since completion of the initial study, the U.S. Air Force has requested, from time-to-time, additional data-collection activity in connection with problems previously identified on the Base, or in connection with discoveries of previously undetected contamination. New developments have also required re-evaluation of local ground-water conditions in order that the limited potable-water supplies of the Base can be properly managed.

Purpose and Scope

This report assembles data collected and summarizes the results of work conducted from 1982 through 1985. Its purpose is to describe work performed to improve the delineation of known plumes of contamination, and to define the extent of new plumes detected since completion of the earlier work. Plumes were delineated on the basis of volatile hydrocarbon concentrations. The report also describes the effectiveness of purge wells in removing trichloroethylene from the ground-water system in the central part of the Base.

Description of Area

Wurtsmith Air Force Base is in Iosco County in northeastern Lower Michigan (fig. 1). The Base, which has an area of 7 mi^2 (square miles), is adjacent to the community of Oscoda on the western shore of Lake Huron. The land surface is a 5-mi (mile) wide plain bounded on the west by 80-foot-high bluffs (fig. 2). The elevation of the land surface ranges from 580 to 750 ft above sea level. Several small streams flow from the bluffs and discharge into a swampy area west of the Base. Plate 1 is a detailed map of the Base.

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[1] Referred to as the "Base" in this report.

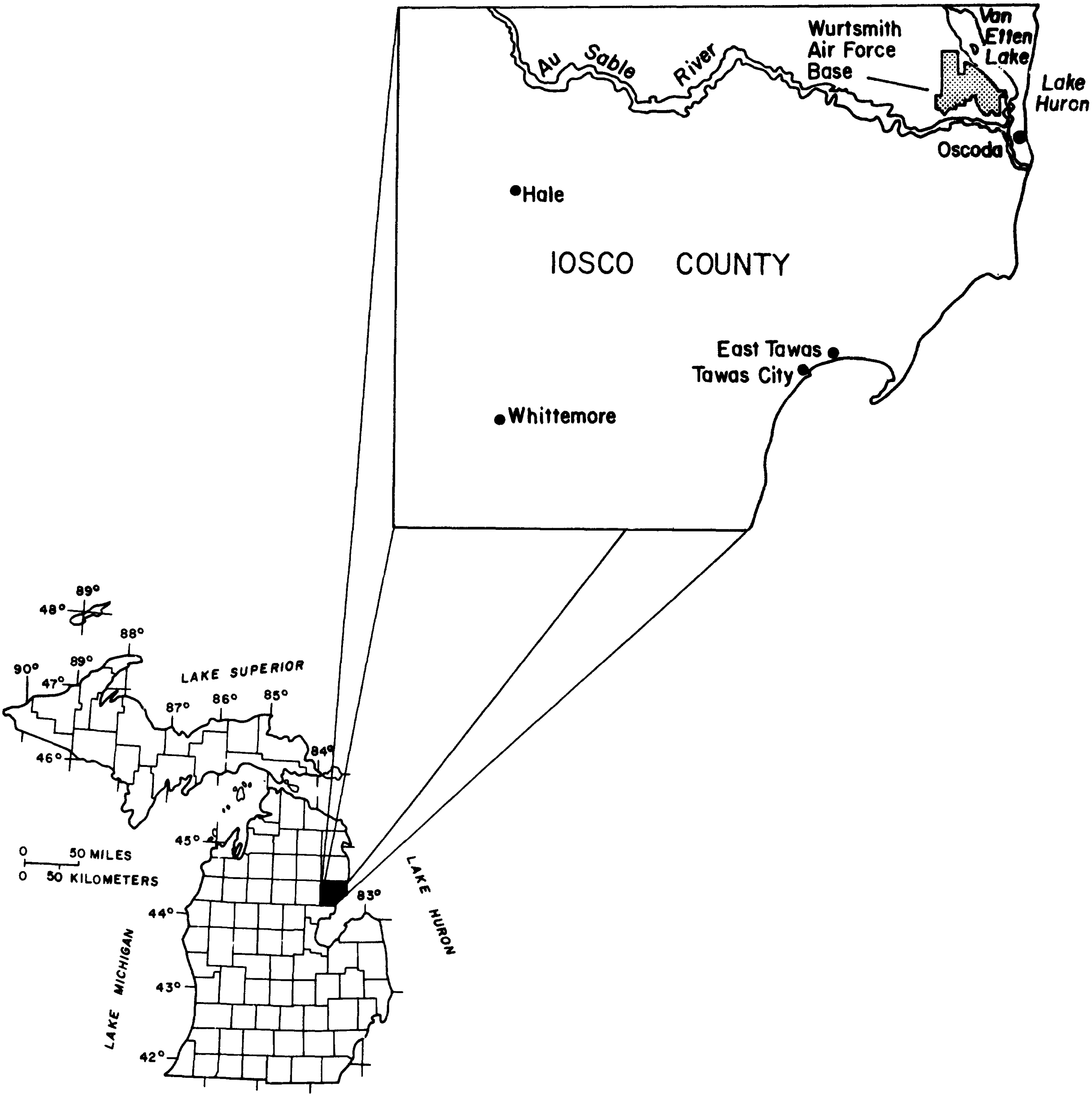


Figure 1.--Location of Wurtsmith Air Force Base in Michigan.

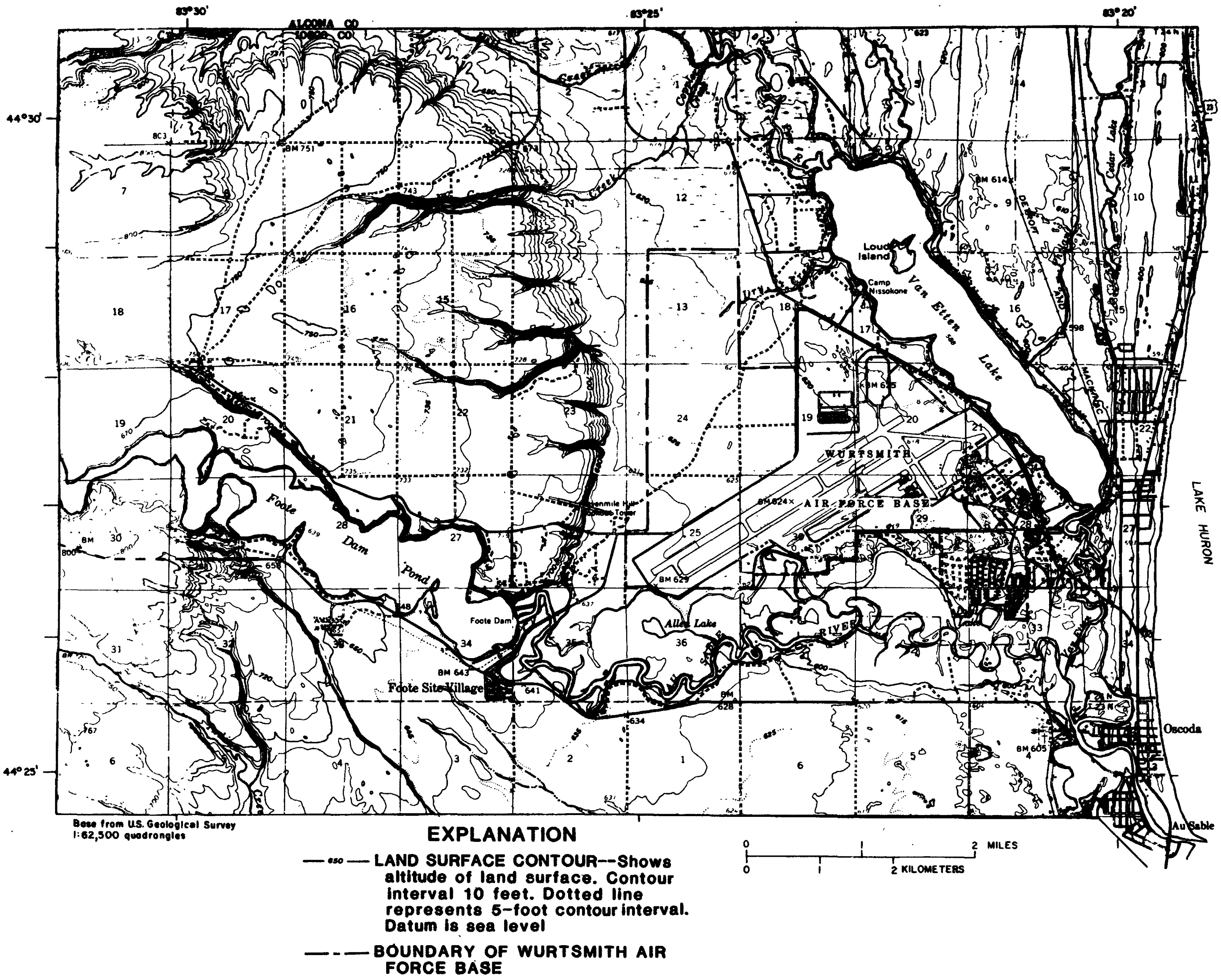


Figure 2.--Physical features in vicinity of Wurtsmith Air Force Base.

The Au Sable River, which flows eastward and discharges into Lake Huron, is half a mile south of the Base. The land between the Base and the river is swampy. From the bluffs and extending 20 mi upstream, flow of the Au Sable River is controlled by a series of dams. Van Etten Lake, northeast of the Base, is 4 mi long and half a mile wide.

Mean monthly temperatures range from 21°F in January to 68°F in July. The lowest recorded temperature is -22°F, the highest 102°F. Average annual precipitation is 30 in.; average snowfall is 44 in.

SUMMARY AND CONCLUSIONS OF 1979-81 STUDY

The principal aquifer in the Wurtsmith Air Force Base area is a sand and gravel unit that extends from land surface to a depth that averages 65 ft. The unit is mostly a medium to coarse sand containing some gravel. Thin beds of clay lie at depths ranging from 5 to 15 ft in the northern part of the Base. Underlying the sand and gravel unit is a bed of relatively impermeable clay. Figure 3 shows the altitude of the top of the clay unit; figure 4 is a generalized geohydrologic section showing the relation of the sand and gravel unit to the clay unit.

The sand and gravel aquifer is mostly under water-table conditions. The depth to water ranges from about 25 ft near Van Etten Lake to less than 10 ft at places along the western part of the Base. Most ground-water flow is eastward toward Van Etten Lake and Van Etten Creek (fig. 5); a small part flows southward to the Au Sable River. In areas influenced by pumping, the natural direction of flow is significantly altered as water moves toward the pumped wells. Water levels fluctuate from 1 to 3 ft annually. The general configuration of the water table, however, does not change significantly.

Two-dimensional finite-difference flow models were used to describe ground-water movement and to simulate water levels. Average flow ranged from 0.8 ft/d in the eastern part of the Base to 0.3 ft/d in the western part. (Work performed during 1982-85 indicated rates as high as 5 ft/d at some locations.) Simulations seemed to indicate that hydraulic conductivity is about 100 ft/d in the eastern part of the Base and about 150 ft/d in the western part.

Trichloroethylene that leaked from a buried storage tank near Building 43 moved northeastward under the influence of the natural ground-water gradient and the pumping of Base water-supply wells (fig. 6). The most highly contaminated water--greater than 1,000 μg/L (micrograms per liter) of trichloroethylene--was found in a band along Arrow Street between well AF57 and well AF3, although that part of the plume having less than 50 μg/L of trichloroethylene was broader and extended northeastward to Perimeter Road. Movement of the most highly contaminated part of the plume seemed to have been arrested by pumping; however, eastward movement of the plume could be prevented only by near-capacity pumping of existing purge wells.

About 580 gal (gallons) of trichloroethylene was purged from the ground-water system between November 1977 and March 1981. Eighty-four percent of that amount was pumped from wells AF3 and AF57 (plate 1). The rate of removal was closely related to the rate of purge pumping.

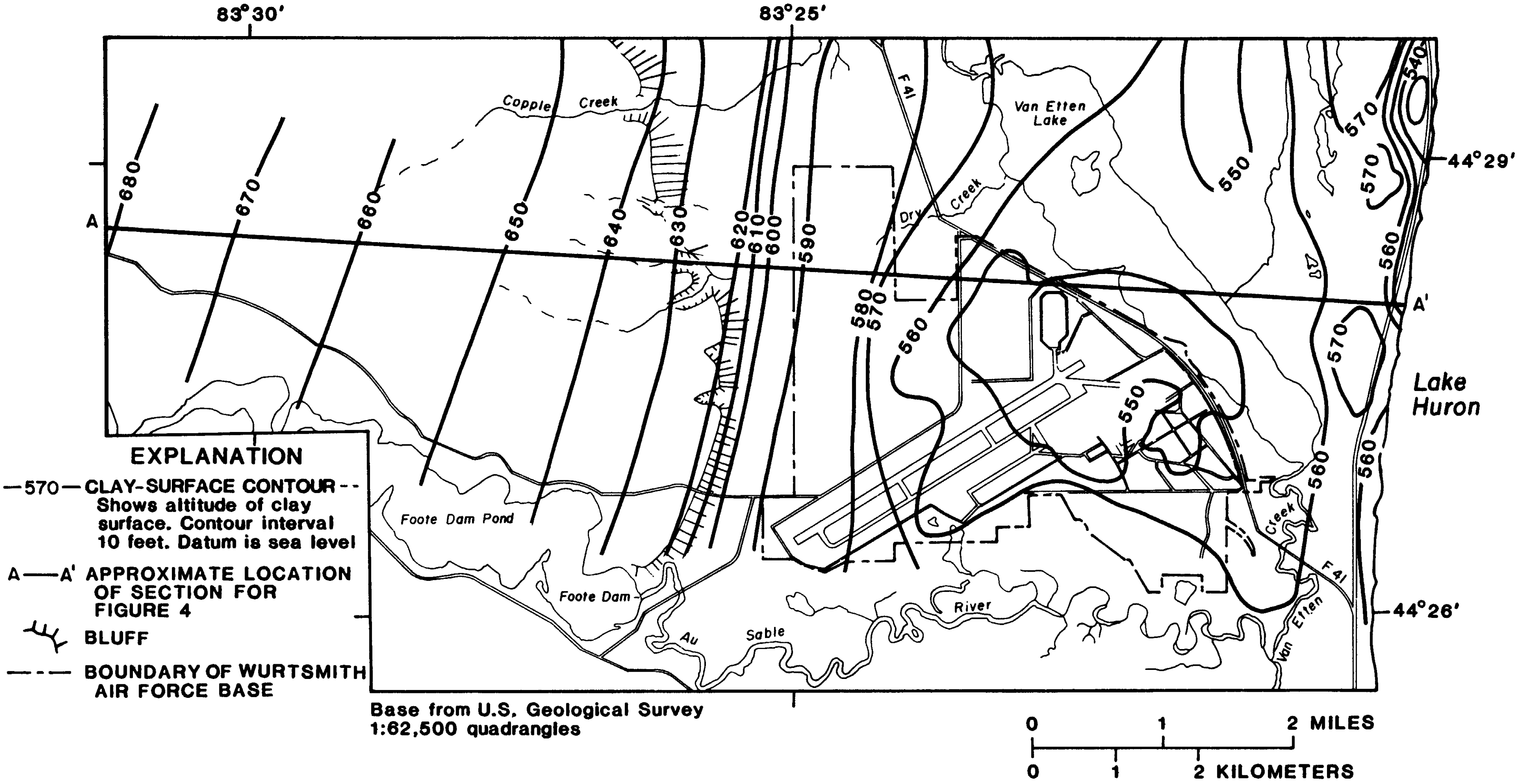


Figure 3.--Altitude of top of clay unit.

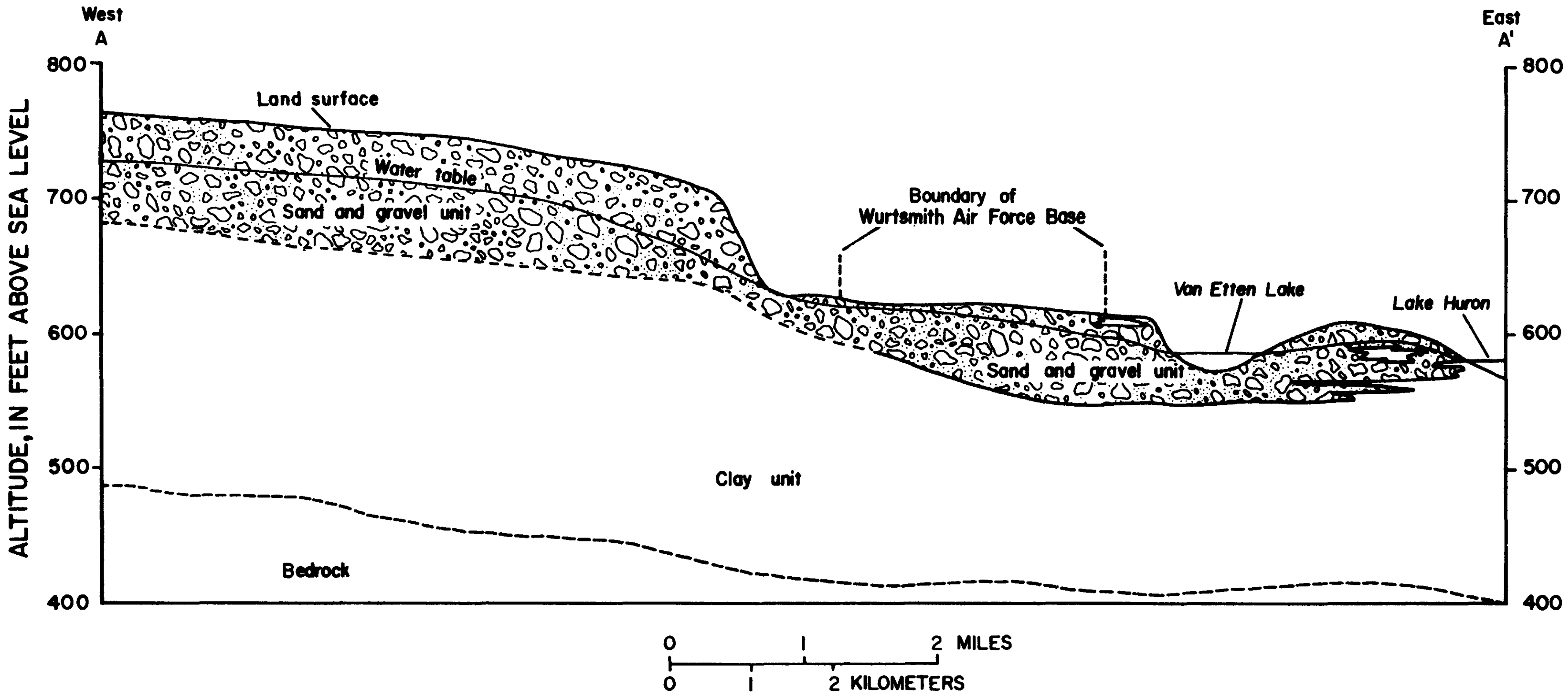
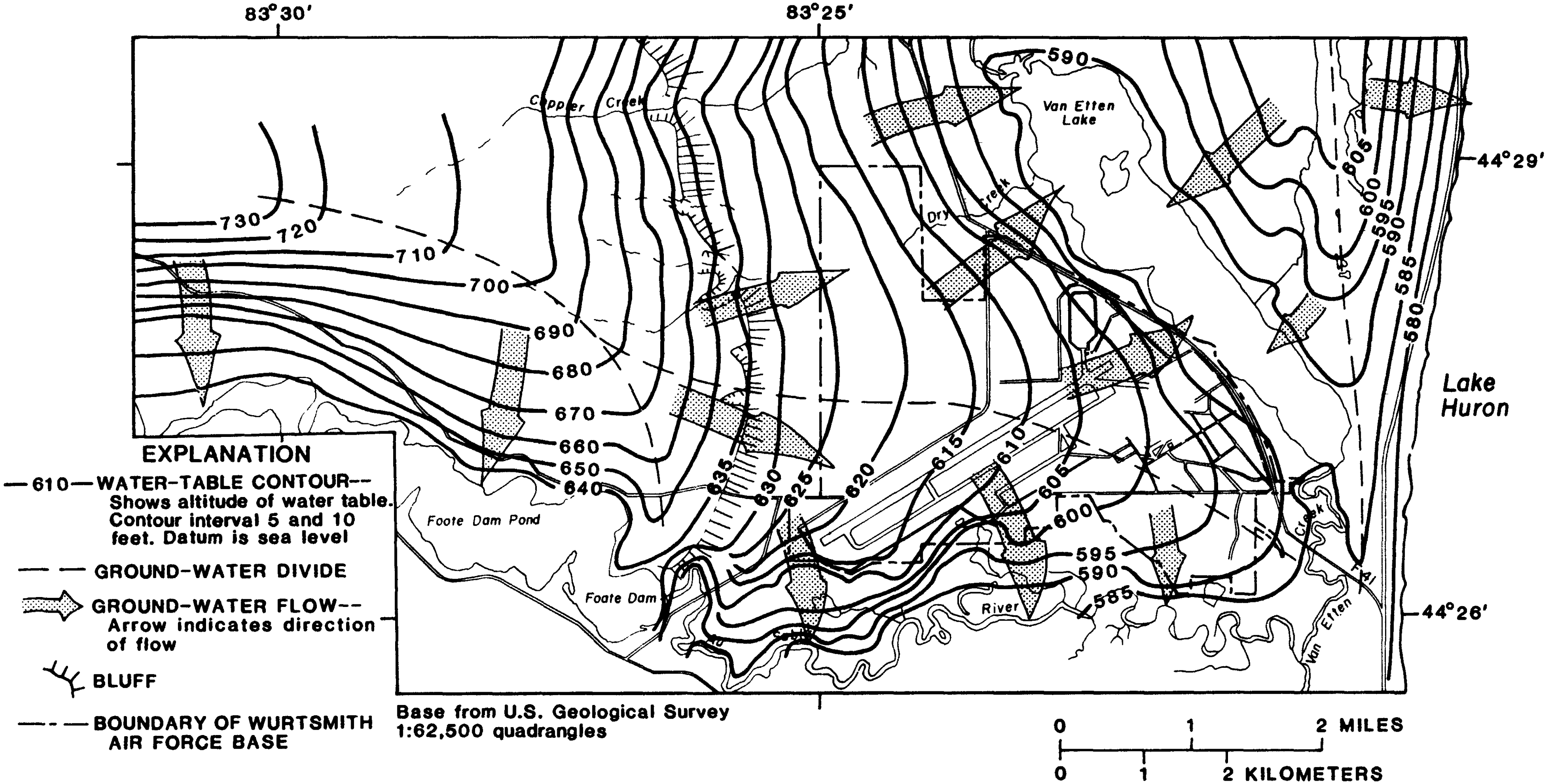
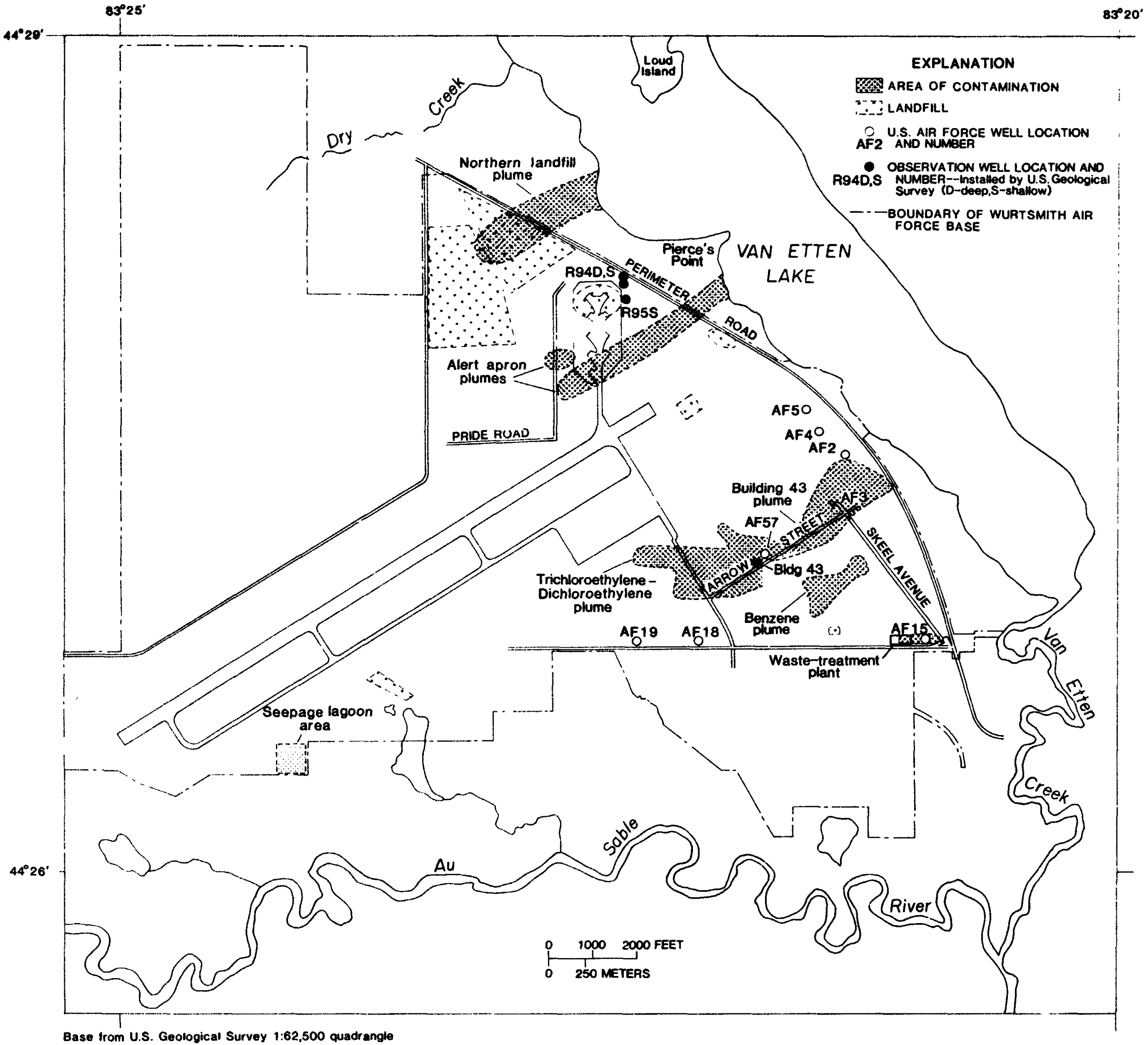


Figure 4.--Generalized geohydrologic section showing relation of sand and gravel unit to clay unit. Line of section shown on Figure 3.



Base from U.S. Geological Survey
1:62,500 quadrangles

Figure 5.--Altitude of water table and direction of ground-water flow, September 1980.



Base from U.S. Geological Survey 1:62,500 quadrangle and Wurtsmith Air Force Base 1:7,200 map

Figure 6.--Areas of ground-water contamination at Wurtsmith Air Force Base, 1979-81.

A model simulation indicated that, with additional purge wells and supply wells pumping, water levels in the most highly concentrated part of the Building 43 plume would be lowered about 15 ft, and trichloroethylene would not escape to Van Etten Lake. Because trichloroethylene is not uniformly distributed in the aquifer, no prediction could be made of the time required to reduce concentrations to specified levels.

Trichloroethylene in water from supply wells AF18 and AF19 in 1978 did not come from the Building 43 spill site (fig. 6). A ground-water divide, which runs northwest diagonally across the Base, indicated that migration of trichloroethylene southwestward from the spill is not possible.

Ground-water contaminated with trichloroethylene was identified in the vicinity of the alert apron (fig. 6). No spill sites were located, but concentrations of about 1,000 μg/L were detected west of the alert apron near Pride Road. Data indicated two plumes exist. The major and southernmost plume extends off Base to the area of Pierce's Point, and trichloroethylene detected in water from a domestic well on the Point probably had its origin on the Base some years ago. A smaller, less well defined plume or area of contamination occurred immediately north of the major plume. The location of the alert apron prevented precise definition of the northeastern boundary of the smaller plume. Water from well R94S, R94D, and R95S, just east of the alert apron, did not contain trichloroethylene; this suggested that the smaller plume terminated under the alert apron.

A simulation of ground-water flow in the area of the Alert Apron plume indicated that 12 small-diameter purge wells, each capable of pumping about 40 gal/min (gallons per minute), were hydrologically suitable for removing trichloroethylene from the system.

Analysis of ground-water-flow data indicated that trichloroethylene detected in water east of the waste-treatment plant did not come from the leakage of the storage tank at Building 43 (fig. 6). Sludge placed in the drying beds at the plant before installation of carbon filtration on the Base was the most plausable origin of trichloroethylene in the water. Trichloroethylene was not found to be adsorbed on soils, cores, or surface sludge material, although other organic compounds were detected.

Ground-water flow from the northern landfill area is northeastward toward Van Etten Lake. Dichloroethylene and benzene were more commonly detected in ground water than was trichloroethylene, although a higher concentration of trichloroethylene was detected. No evidence was found that leakage from buried tankers containing trichloroethylene has contaminated ground water. Dichloroethylene and benzene occurred primarily in the shallow part of the aquifer; the source seemed to be in the western landfill area. The source of trichloroethylene seemed to be in the southwestern landfill area (fig. 6).

Dichloroethylene occurred in ground water in the general area encompassed by the Building 43 trichloroethylene plume (fig. 6). Concentrations were highest, however, approximately 900 ft northwest of the Building 43 spill site. Investigation detected dichloroethylene westward as far as Skyway Street and disclosed traces of trichloroethylene and benzene. Dichloroethylene tended to be in the deeper part of the aquifer; trichloroethylene seemed to be at more shallow depths. Benzene contamination was localized; a JP-4 fuel pump house was the likely source. Under the influence of the natural ground-water gradient and pumping in the vicinity of Arrow Street, contaminants were being drawn eastward to the Building 43 plume area.

Benzene was detected in concentrations exceeding 1,000 μg/L in water east of the bulk-fuel storage tanks (fig. 6). Data indicated that the benzene was primarily in the shallow part of the aquifer and that a plume extended northeastward from the bulk-fuel storage area to the vicinity of the hospital. Its source was likely one or more of the storage tanks or from spillage on the ground in the recent past. Ground-water movement was influenced by pumping of Base supply and purge wells. Based on model simulations, installing and pumping five purge wells, having a total capacity of 150 gal/min, seemed to be the most hydrologically suitable scheme for removal of benzene from the aquifer.

Trichloroethylene, benzene, and dichloroethylene were found in ground water in the immediate vicinity of the seepage lagoons (fig. 6). Concentrations decreased, however, from 1978 through 1981, largely because these substances were no longer contained in water pumped from the treatment plant.

Analyses by the U.S. Geological Survey for a variety of chemical, physical, and biologic characteristics of water were made to evaluate general water-quality conditions, with particular reference to landfills. Concentrations of trace metals, with the exception of zinc, were low at all locations. Water from wells O2S and R29S had nickel concentrations of 100 μg/L. Based on specific conductance measurements, dissolved-solids concentration ranged from 100 to 200 mg/L over much of the Base; on the eastern part of the Base, in an area of concentrated operations and activity, the range was about 200 to 440 mg/L. Levels were similar in the northern landfill area, where seepage from the landfill probably increases dissolved-solids concentration. Concentration was highest in water from well AF15, and the high value was probably related to seepage from sludge drying beds at the waste-treatment plant. In general, chloride concentrations followed a pattern similar to dissolved-solids concentrations. Nitrate plus nitrite concentrations showed less consistent areal distribution than either chloride or dissolved-solids concentrations. Concentrations of nitrate plus nitrite exceeding 5 mg/L were found in water from several wells, some of which were adjacent to landfills. Water from well AF15 contained as much as 28 mg/L--an amount that considerably exceeds recommended drinking-water limits of the U.S. Environmental Protection Agency (1977a). At most locations, biochemical oxygen demand (BOD) and chemical oxygen demand (COD) concentrations were not particularly suggestive of ground-water contamination. However, well R22S in the northern landfill area had a BOD concentration of 13.8 mg/L. Well O2S, south of the seepage lagoons, had a BOD concentration of 14.2 mg/L. With respect to COD, water from wells O6D and R10S contained 39 mg/L and 66 mg/L, respectively. It seemed certain that the higher concentration of COD in R10S was related to benzene detected in the area.

Gross beta activity and gross alpha activity in water did not exceed U.S. Environmental Protection Agency regulations. Regulations were also met when specific analyses for strontium-90 were made.

ASSESSMENT OF GROUND-WATER CONTAMINATION, 1982-85

Investigations during 1982-85 were conducted in the northern landfill area, the bulk-fuel storage area, the Mission Drive-well AF18 area, the Building 43 area, and the well AF2 area. Work was continued along the eastern margin of the Base, where water in an off-Base water-supply well contained traces of trichloroethylene. Analyses of water from wells in the Alert Apron plumes, as well as of water of Van Etten Lake, also were made. An investigation also was conducted to locate a suitable site for a supplemental Base water supply (wells GST1 and GST3, plate 1). Figure 7 shows areas where additional work was performed during 1982-85.

Methods of data collection and analysis during this investigation were the same as those used in the earlier study, and the reader is referred to Stark and others (1983) for their description. Since May 1982, 165 wells[2] have either been drilled to obtain water samples and water-level data, or hand augered just to the water table to obtain water and soil samples. Locations and identifications of drilled wells are given in table 1 (at end of report) and on plate 1. Locations of augered wells are shown on figures at appropriate places in this report. Most laboratory analyses were for volatile hydrocarbons, although water at a few sites was analyzed for base/neutral compounds. Analyses for common dissolved substances and radiochemicals were made at locations proposed for a supplemental Base water supply or at locations where specific substances were of interest.

Some of the work undertaken during 1982-85 required that the previously developed mathematical model of ground-water flow, referred to as the "Base model" in Stark and others (1983), be modified to better define its predictive capability in areas along the margin of the Base. As new geologic and water-level data became available in the investigation, refinement of the Base model eliminated the necessity of using two other previous models--the "Alert Apron" and "Building 43" models. Development of the new model is discussed in Appendix B.

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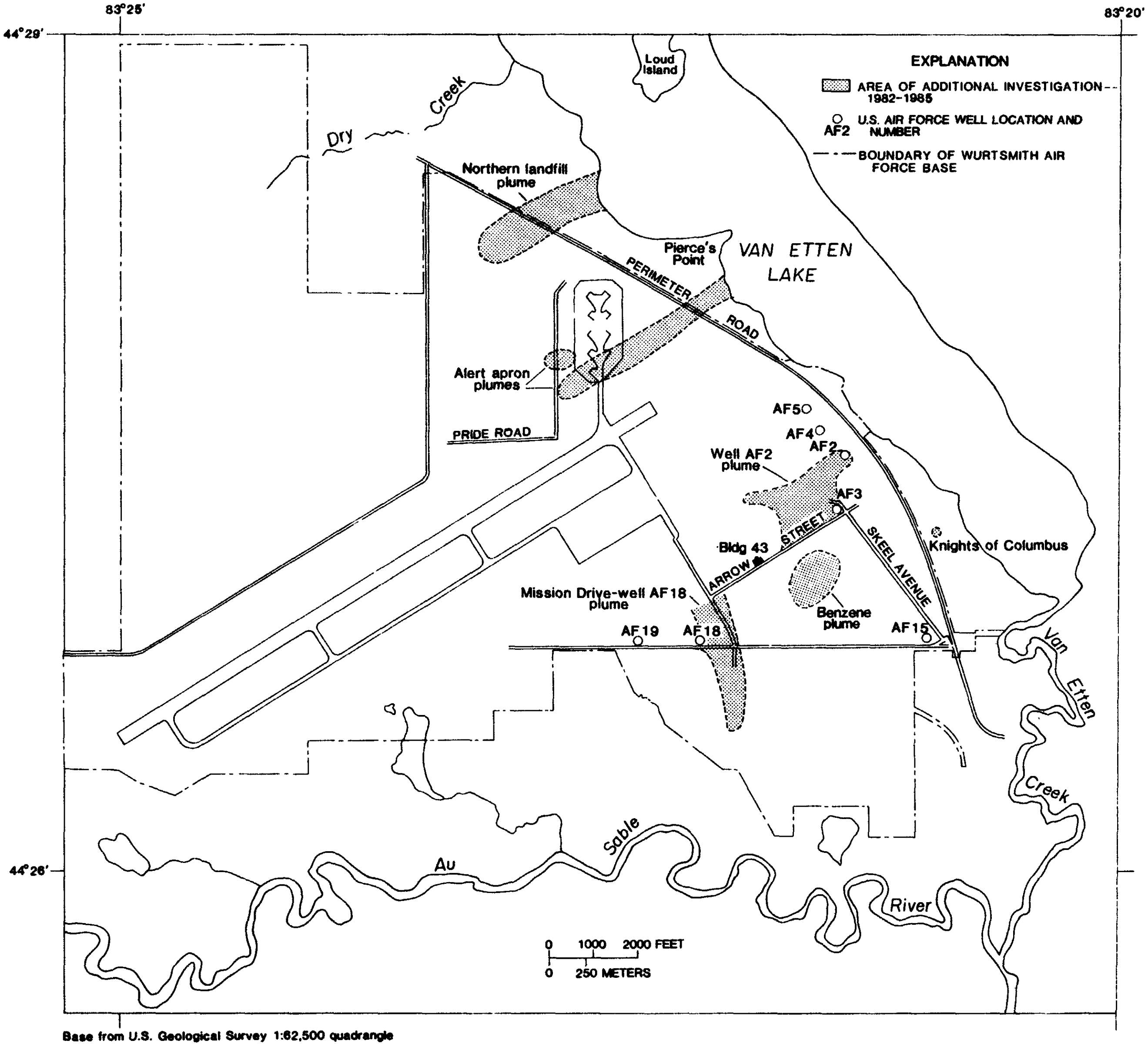
[2] Deep and shallow wells are designated by "D" or "S" following the well number. At a few locations, wells on intermediate depth were also installed. These are designated by "M" following the well number.



Base from U.S. Geological Survey 1:62,500 quadrangle and Wurtsmith Air Force Base 1:7,200 map

Figure 7.--Areas of additional investigation, 1982-85.

Building 43 Plume Area

Purge-Well System

A trichloroethylene purge system along Arrow Street in the Building 43 area went into operation in December 1981. Purge wells PW1, PW2, PW3, and PW4, each capable of pumping about 300 gal/min, were installed at locations shown on plate 1. (The purge wells are 67-70 ft deep and have 30 ft of 20-slot, 10-in. screens. Screen bottoms are set 5 ft above the clay. Existing well AF3 was also to be part of the purge system.) A reduced withdrawal rate of about 400 gal/min was maintained until April 1982, when the system became fully operational. To verify that the system was operating effectively, water samples were collected from purge wells and observation wells on the margin of the plume in April and September 1983, and in January and April 1984 (table 2, at end of report), and water levels in nearby wells were measured. Figure 8 shows the water table on April 28, 1983, and the general direction of ground-water flow. On April 28, pumpage from wells PW1-PW4 was 1,155 gal/min. The position of the ground-water divide and orientation of ground-water flow lines indicated that water was being drawn to the purge system from all surrounding areas; no contaminated water from these areas was moving off-Base.[3] Figure 9 shows a generalized areal distribution of trichloroethylene in April 1983, about a year after the purge system went into full operation. The distribution is based on data collected by the Geological Survey (table 2) and on unpublished data from the U.S. Air Force.

Evaluation of unpublished Air Force analyses of water from wells AF57 and AF3 suggests that concentrations of trichloroethylene in the central part of the plume ranged from 1,000 to 2,000 μg/L in the months immediately preceeding purge-well installation in December 1981. In April 1983, the maximum concentration was 508 μg/L (well PW2, table 2). The greatest change since 1980, however, seems to have occurred in water from well AF3--the most northeasterly well in the major area of contamination. In September and October 1980, water from well AF3 had concentrations of 4,300 μg/L and 3,000 μg/L. In April 1983, the concentration was 83 μg/L. This suggests that the purge system is operating as intended.

Figure 10 is a generalized section of the plume in April 1983, showing that the lateral extent of the plume has been narrowed. Water from well R17S, which contained 2,100 μg/L of trichloroethylene in September 1980, had only 18 μg/L in April 1983. The concentration of water from well R17D, however, had increased from "not detected" in 1980 to 90 μg/L in April 1983. It is likely that this increase was the result of water being drawn downward by pumping nearby purge wells, causing contaminated water in the shallow part of the aquifer to mix with the deeper water.

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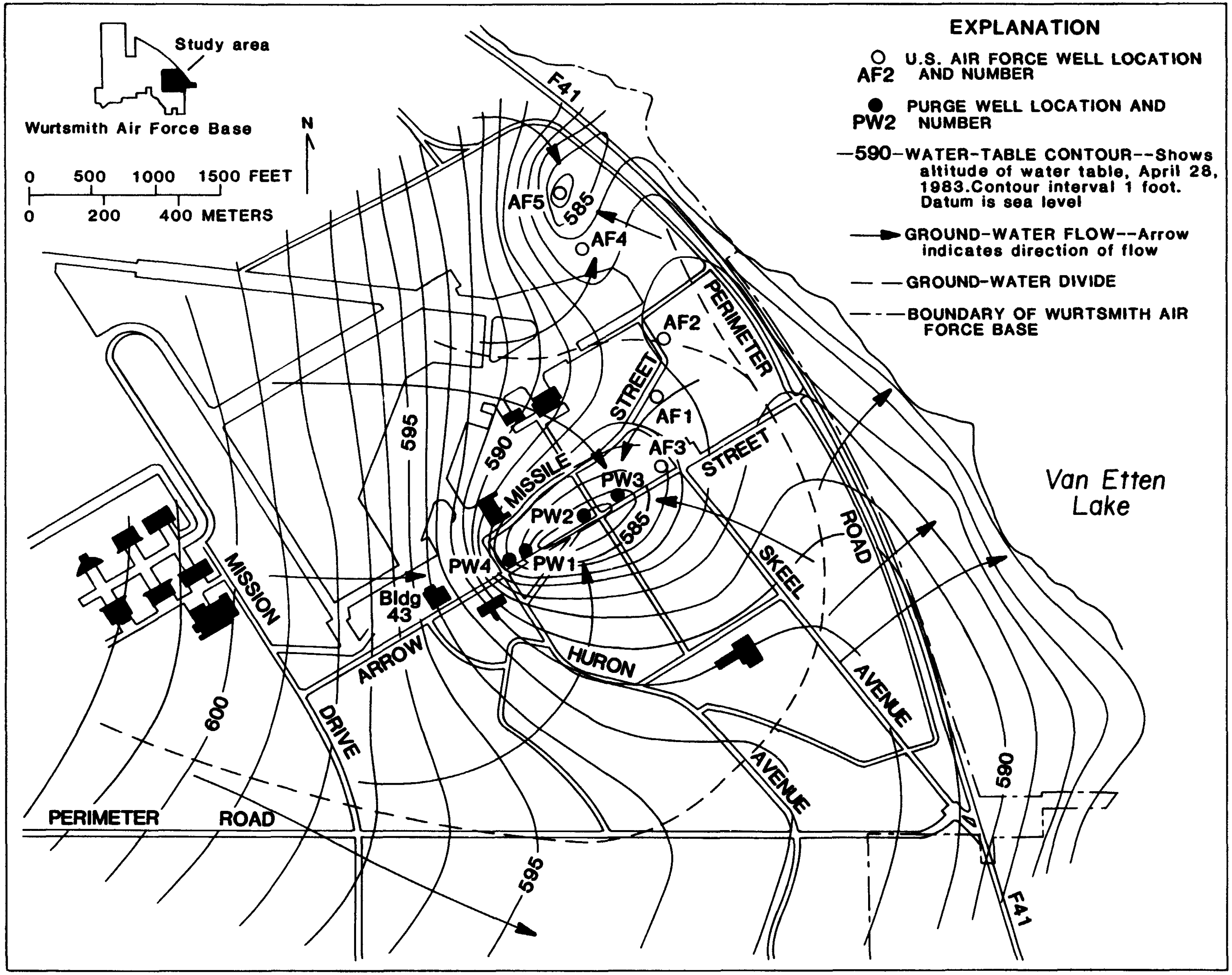
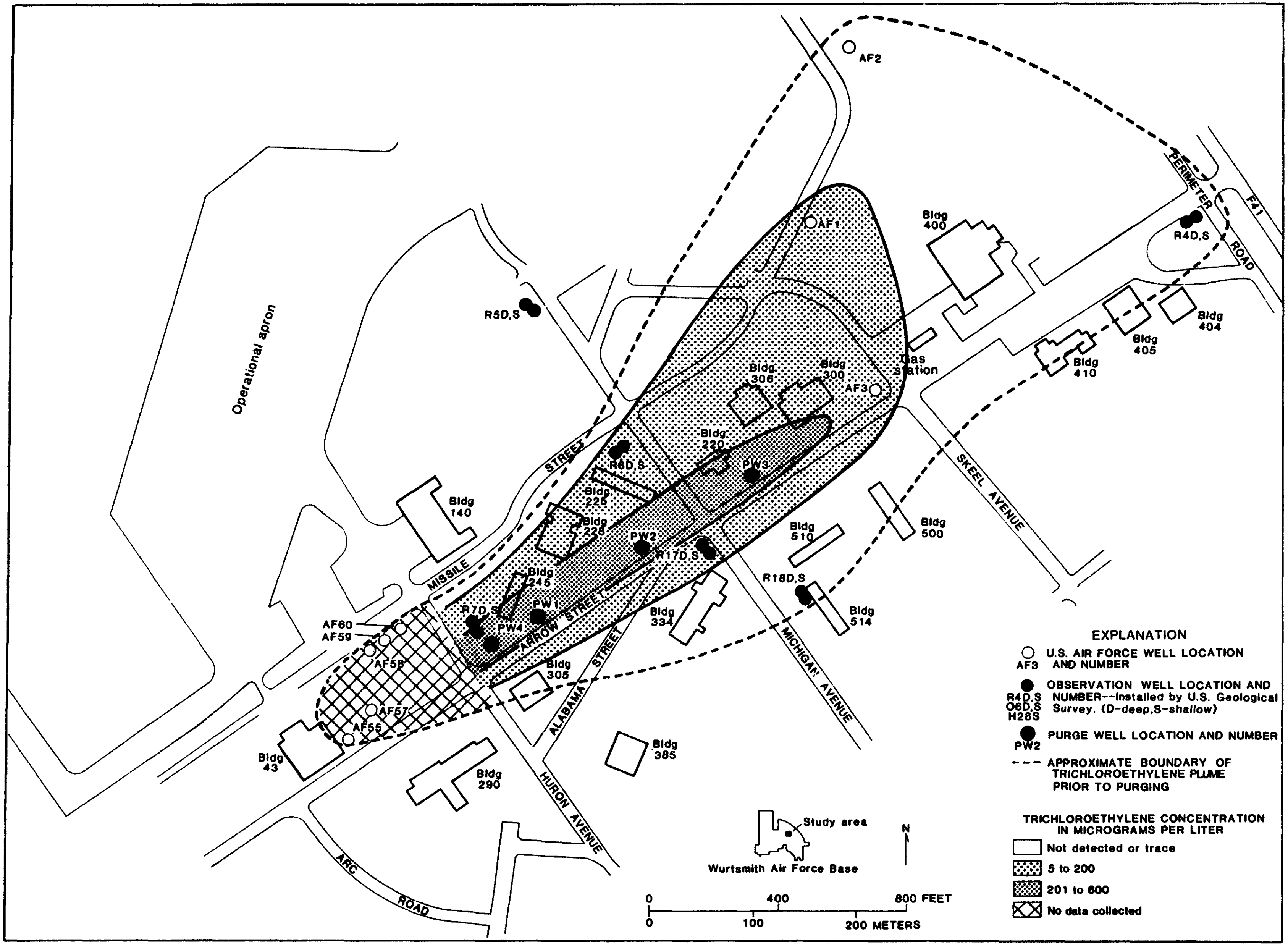
[3] Base model simulations in November 1984 indicated that a minimum purge rate of 600 gal/min was necessary to prevent contaminants from moving off-Base or to water-supply wells, and that well AF1, in lieu of AF3, should continue to be part of the purge system.



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 8.--Altitude of water table and direction of ground-water flow, April 28, 1983.



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 9.--Generalized Building 43 trichloroethylene plume, April 1983.

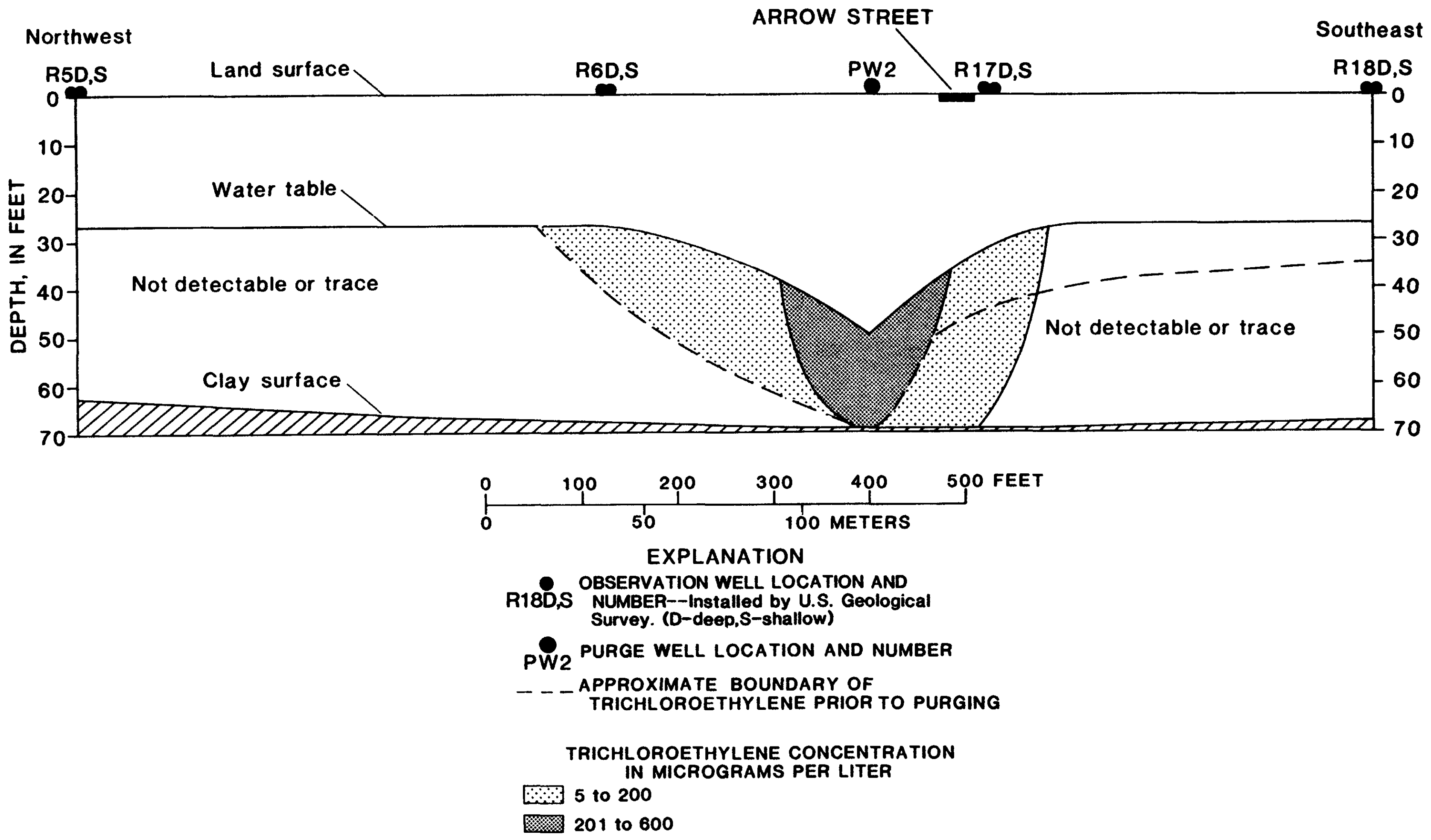


Figure 10.--Generalized vertical distribution of trichloroethylene in Building 43 plume between wells R5D,S and R18D,S, April 1983.

On September 27, 1983, additional samples were collected from the purge wells and well R17D. The maximum concentration of trichloroethylene in the most highly contaminated part of the plume was 206 μg/L (well PW2). The concentration of water from well R17D was 25 μg/L, a decrease from 90 μg/L in April. The concentration of trichloroethylene in water from well AF3 decreased from 83 μg/L in April to 38 μg/L in September.

Data collected by the Air Force also show the effectiveness of the purge system. Figure 11 shows changes in the trichloroethylene concentration of water based on analyses of a composite[4] of water from wells PW1-PW4 during May 1982 to December 1984. A trend of decreasing concentration is evident, although substantial variations in concentration occur during a single month or even shorter period.

In January and April 1984, concentrations of trichloroethylene in water from purge wells were higher than in September 1983. Water from well PW4 contained 388 μg/L. Increases in trichloroethylene were accompanied by proportionally larger increases in dichloroethylene. For example, a purge-well composite (Pc) contained 108 μg/L of dichloroethylene. Observed increases in concentrations of trichloroethylene and dichloroethylene suggest that contaminated water from a source west of Building 43 (fig. 30, Stark and others, 1983) may have reached the Arrow Street purge system in greater amounts during 1984. West of Building 43, water from well 07D had a dichloroethylene concentration of 266 μg/L in December 1979; water from well H6S had a trichloroethylene concentration of 821 μg/L in March 1981. Water from well AF57, near the western margin of the Building 43 plume, had a dichloroethylene concentration of 187 μg/L in January 1980.

Water from well H29S (plate 1), which is 450 ft south of Arrow Street and lies outside the plume delineated on figure 9, contained 4.3 μg/L of trichloroethylene in April 1983. It is believed that this is related not to the Building 43 spill, but to trichloroethylene detected farther west in earlier work, and possibly to an area of contamination along Mission Drive discussed in a following section of this report. This is supported by the fact that water from H28S, about 200 ft west of well H29S, contained dichloroethylene (22 μg/L), which was initially detected in the area west of Building 43.

Accurate prediction of the levels to which contaminants may be reduced by purging is not possible. The fact the aquifer is sandy and has a low organic-matter content suggests that further reduction is very likely. A continued decrease in concentration also is suggested by the fact that trichloroethylene is no longer detected in some areas where it once was present. Because trichloroethylene and dichloroethylene are probably being drawn to the purge system from an area west of the Building 43 spill site, purge water may contain these contaminants for a longer period than otherwise expected.

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[4] Analyses are identified as "Pc" in table 2; collection site shown as "+" on plate 1.

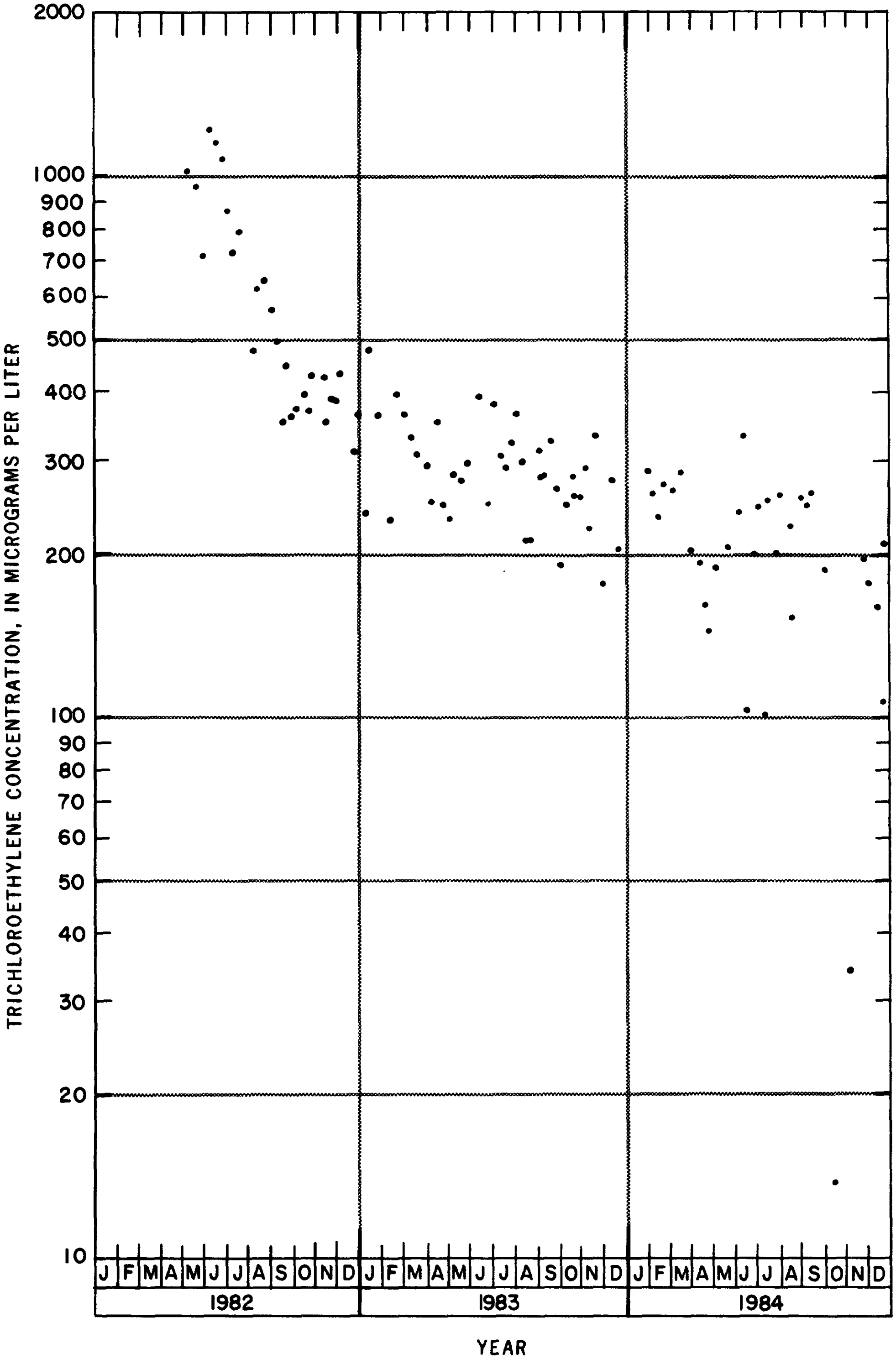

Figure 11.--Changes in trichloroethylene concentration of composite (Pc) of purge well withdrawals.

Estimates of future concentrations of contaminants in the plume may be obtained from data that have been collected, if it is assumed that purge pumping rates, as well as hydrologic factors, remain similar. To make such estimates, regression equations relating trichloroethylene concentration and time were developed in both linear and exponential forms. Concentration data collected by the U.S. Air Force during the period April 1983 through June 1985 were used in developing the equations. Because only small incremental changes in concentration with time occur, both equation forms seemed equally valid when compared to actual data; correlation coefficients of the equations did not differ appreciably. Predictions with each equation, however, differed significantly. For example, a mean concentration of 50 μg/L for purge-well-composite Pc was predicted to occur in September 1986. Using the exponential equation, a level of 50 μg/L was predicted in May 1988. To test if one form of the equation had better long-term predictive capability, U.S. Air Force data for the period April 1983 to December 1984 were used to develop both linear and exponential regression equations, and concentrations during the period January through June 1985 were predicted. Concentration change during the 6-month period was small enough, and predictions were similar enough, to prevent a judgement as to which type of equation might have the best long-term validity.[5]

Relation of Purge Pumping to Trichloroethylene Removal

From November 1977 through June 1985, about 900 gallons of trichloroethylene were removed from the aquifer. Figure 12 shows the relation of pumping to trichloroethylene removal. About 2.2 billion gallons of water were withdrawn from the aquifer from 1977 to mid-1985, and thus, for each gallon of trichloroethylene removed, about 2.45 million gallons of water have been withdrawn. During the first 6 months of 1985, the rate was much lower--about 9.6 million gallons of water for each gallon of trichloroethylene removed.

Knights of Columbus Area

Continued detection of trichloroethylene in water from a well off-Base at the Knights of Columbus hall (well KC, plate 1) prompted further investigation of ground-water flow and trichloroethylene concentrations in water in the area. In April 1983, two additional wells (H30S and H31S) were installed at locations shown on figure 13. Locations were chosen after reviewing previously collected water-level data and chemical analyses. Samples were collected and analyzed from the two new wells, from the Knights of Columbus well, and from wells R79S, R80S, R81S, R83S, and R84S. The Knights of Columbus well contained 4.2 μg/L of trichloroethylene; upgradient about 400 ft, water from H30S contained 27 μg/L. Water of well H31S contained 4.2 μg/L of trichloroethylene. Trichloroethylene was not detected in water from other wells in the area.

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[5] Analyses of water samples collected in mid-1986 indicated that a level of 50 μg/L would not be achieved by September 1986.

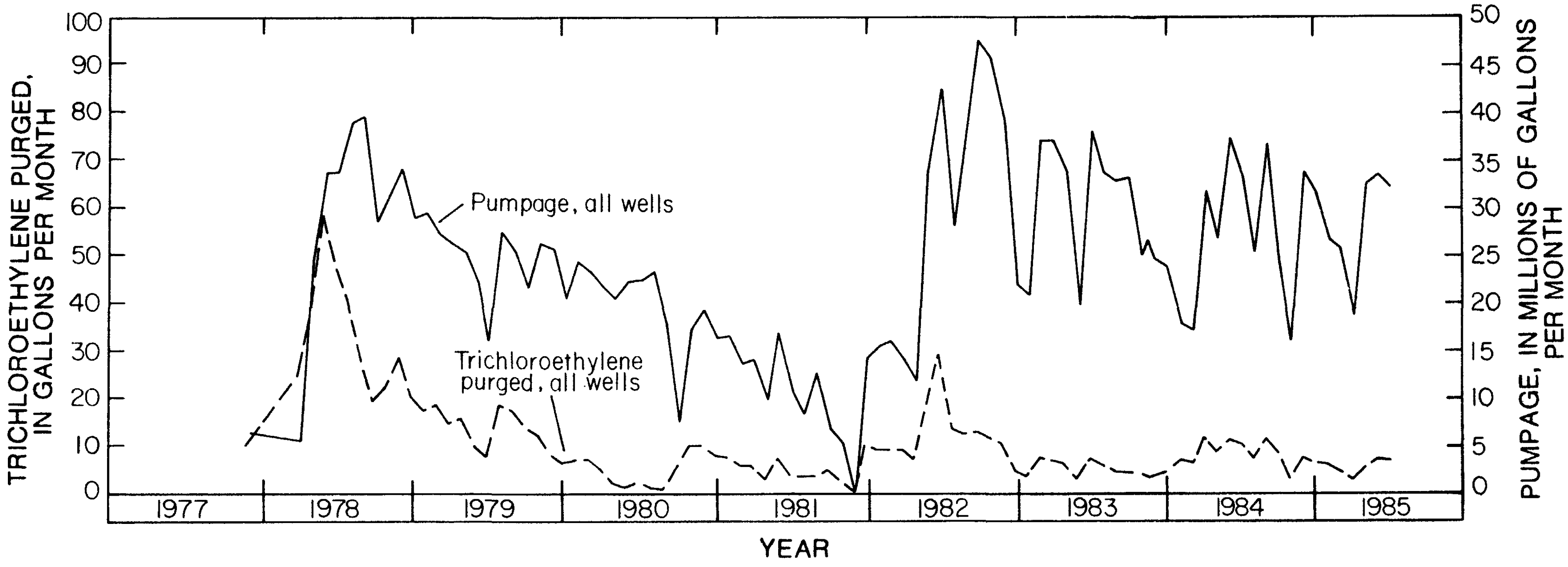
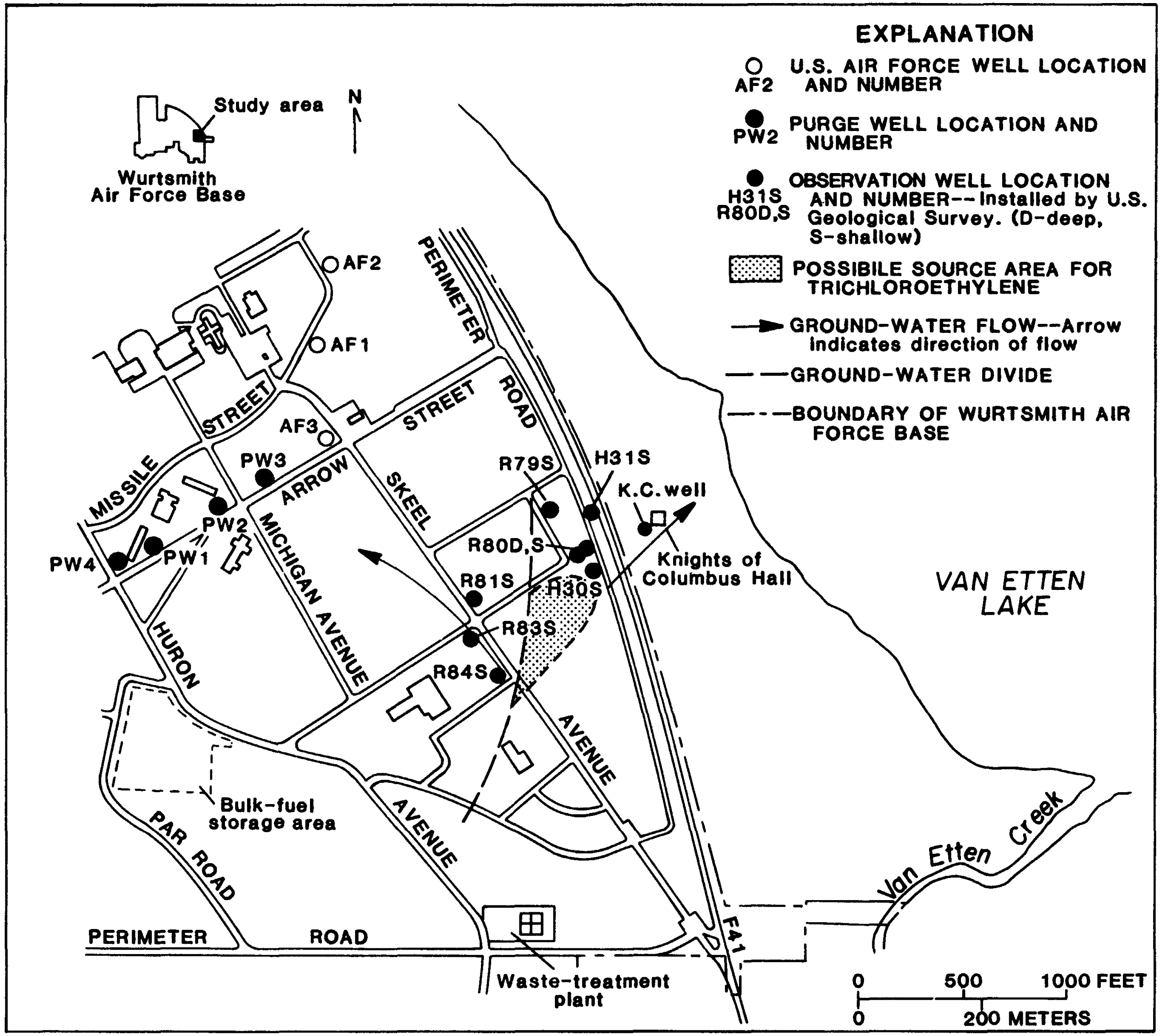


Figure 12.--Relation of purge pumping to trichloroethylene removal.



Base from U.S. Geological Survey 1:7,200 map

Figure 13.--Ground-water flow near Knights of Columbus hall, April 28, 1983.

Since installation of the Arrow Street purge system, a ground-water divide has developed and the direction of flow has changed in the area. Flow to the Knights of Columbus well is only from a small area east of Skeel Avenue. The shaded area on figure 13 seems to be the only place where a source of trichloroethylene may exist. It is possible that trichloroethylene reached this general area from the Building 43 spill several years before the Arrow Street purge system went into operation, and continues to move off-Base in low concentration east of the ground-water divide. In December 1980, water from wells R80S, R81S, R83S, and R84S contained trichloroethylene. Well R84S had the highest concentration of the four wells--54 μg/L. Prior to purge pumping, ground water had moved from the vicinity of R84S toward the Knights of Columbus well.

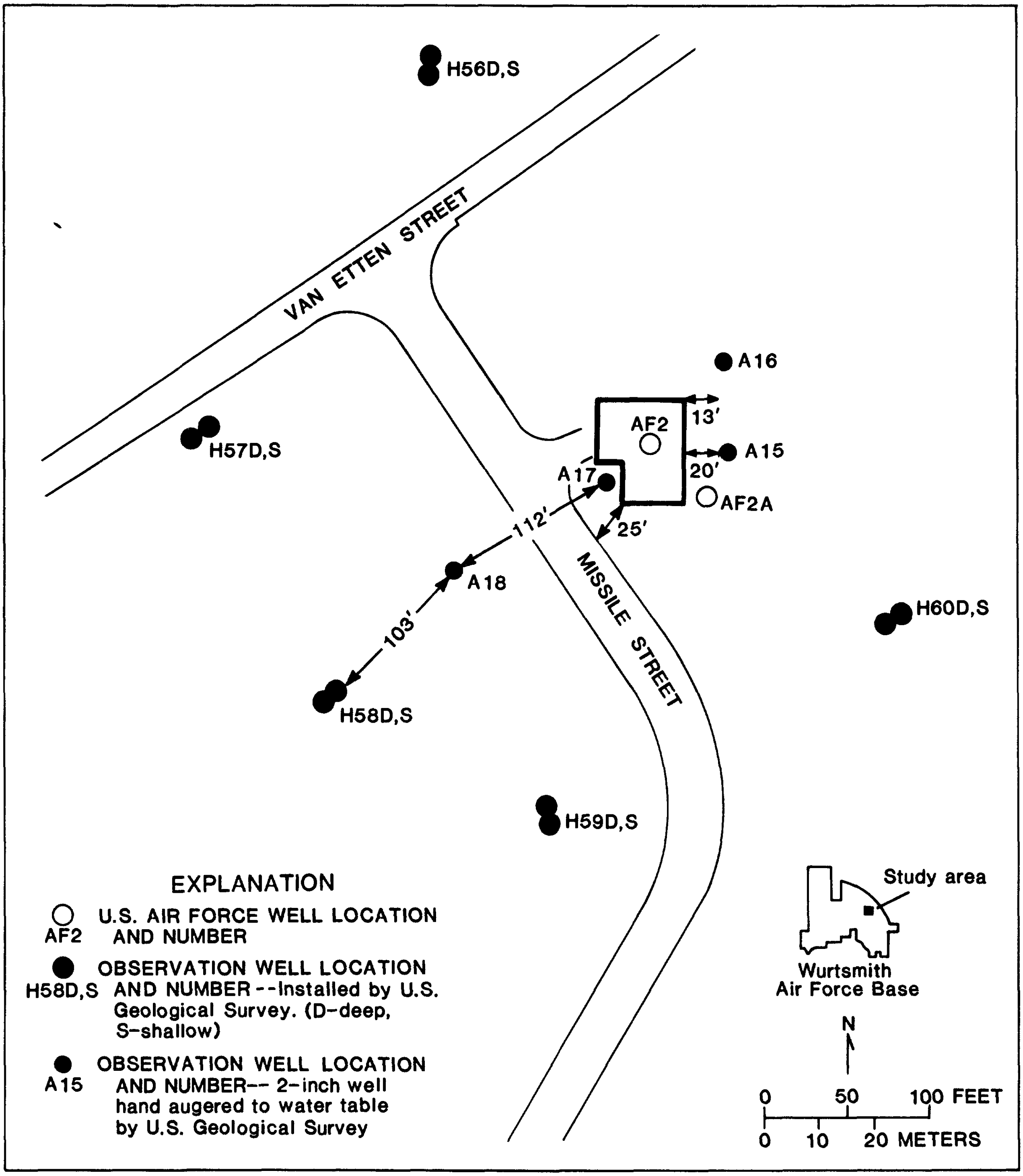
Well AF2 Area

Detection of benzene in water-supply well AF2 in late 1983 by the Air Force prompted an investigation of the problem. Previous analyses of water from wells in the area had not detected benzene. In January 1984, four 2-inch wells (A15 to A18) were hand augered to the water table in the immediate vicinity of well AF2 (fig. 14). Table 3 shows that benzene was not detected when analyses of water were made. To expand the search for a source, deep

Table 3.--Analyses of water at the surface of the water table north of Arrow Street
[Analyses by U.S. Geological Survey, Results in micrograms per liter (μg/L). ND means not detected.]

Well number	Date	Tri-chloro-ethylene	1,2 Di-chloro-ethylene	Benzene	Toluene	Xylene	Ethyl benzene	Tetra-chloro-ethylene	Methylene chloride	Other
A15	January 25, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
A16	January 25, 1984	ND	ND	ND	ND	ND	ND	ND	ND	(a)
A17	January 25, 1984	ND	ND	ND	3.5	ND	ND	ND	ND	ND
A18	January 25, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
A42	April 18, 1985	ND	ND	ND	ND	5,520	364	ND	ND	ND
A43	April 18, 1985	ND	ND	ND	ND	1,240	ND	ND	ND	ND
A44	April 18, 1985	ND	ND	ND	ND	2,020	ND	ND	ND	ND
A45	April 18, 1985	ND	ND	ND	327	5,200	295	ND	ND	ND
A46	April 18, 1985	ND	ND	ND	142	6,280	587	ND	ND	ND
A47	April 18, 1985	ND	ND	68	1,060	3,320	973	30	ND	ND
A48	May 9, 1985	ND	ND	1,720	24,630	18,420	6,550	ND	ND	ND
A49	April 18, 1985	ND	ND	ND	ND	ND	ND	ND	ND	ND
A50	April 18, 1985	ND	ND	ND	ND	ND	ND	ND	ND	ND
A51	April 18, 1985	ND	ND	ND	ND	ND	ND	ND	ND	ND

[a] Water contained 8.8 μg/L chloroform



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 14.--Location of hand-augered wells near well AF2.

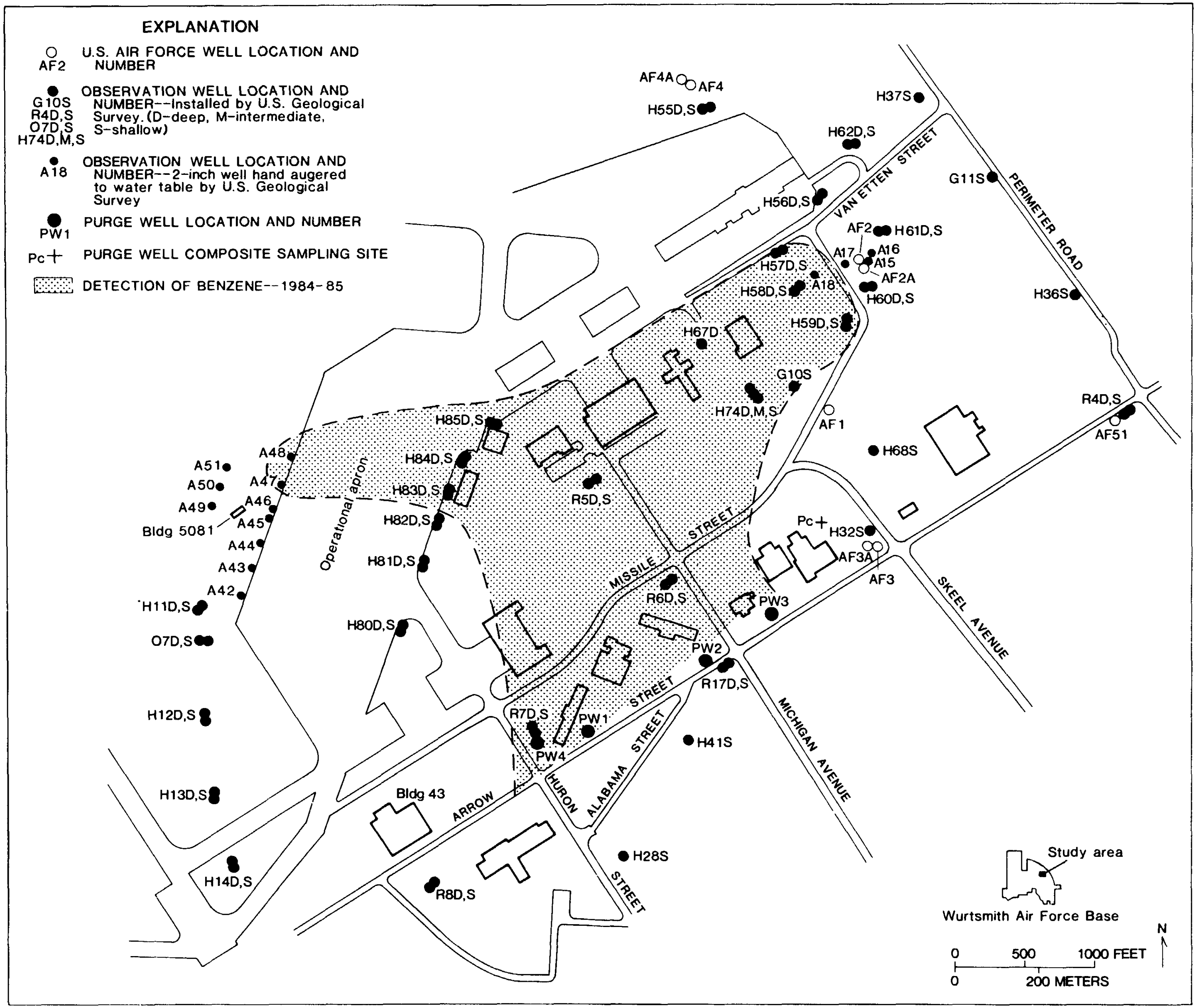
and shallow wells H55 to H62, and wells H67D, H68S, and H74S,M,D, were installed during the period January to May 1984. In April and May 1985, additional deep and shallow wells (H80 to H85) were installed upgradient; also, 10 wells (A42-A51) were hand-augered to the water table just west of the operational apron at the former sites of buried fuel tanks, and just downgradient from existing underground tanks near Building 5081. The location of these wells and other wells in the area are shown on plate 2. Analyses of water from these wells are given in tables 2 and 3. Most substances are components of fuel.

Figure 15 shows a generalized distribution of benzene in the area north of Arrow Street. The highest concentration detected (1,720 µg/L) occurred in water from well A48, whose screen intercepted the water table near the former site of an underground fuel tank. Farther downgradient, water of well H85S, whose screen was set about 10 ft below the water table, contained 917 µg/L.

Purge pumping, as well as pumping of water-supply wells, affects the distribution of benzene. Prior to installing the 1,200 gal/min Arrow Street purge system (wells PW1-PW4) in 1982, purge pumping was not great enough to draw water from the operational apron to Arrow Street. Figure 16 shows the direction of flow north of Arrow Street during three periods prior to 1985 based on measured water levels. In October 1980, when purge pumping averaged about 233 gal/min, ground water from the operational apron flowed northeastward. In January 1984, when purge pumping averaged 397 gals/min, benzene could have reached the vicinity of water-supply well AF2. In July 1984, when well AF1 was incorporated in the purge system and a withdrawal rate averaging 568 gal/min was maintained, contaminants would have been drawn to the Arrow Street purge system, but also would have still moved towards well AF2 and toward water-supply wells AF4 and AF5. This suggests that, if purge pumping is reduced, wells AF4 and AF5, and new supply wells AF30, AF31, and AF32 (plate 1) could become contaminated.

The direction of ground-water flow north of Arrow Street in April and May 1985 is shown in figure 17. At the average pumping rate during this period (759 gal/min), all water containing benzene, toluene, and dichloroethylene was being drawn to the purge system and was not being drawn toward northern water-supply wells AF4 and AF5, nor were contaminants moving off-Base under the influence of natural ground-water flow. Analyses of volatile hydrocarbons also indicate the effectiveness of maintaining purging rates at the April and May 1985 level. Benzene in water of well H67D decreased from 16 µg/L in March 1984 to "not detected" in May 1985, in well H58D from 15 µg/L in February 1984 to "not detected" in May 1985, in well H59D from 184 µg/L in January 1984 to 128 µg/L in May 1985, and in well H74M from 700 µg/L in May 1984 to "not detected" in May 1985. Contaminants that have reached the vicinity of well H59, however, may remain relatively stationary, or move slightly northeastward.

Stark and others (1983) found no benzene in water from deep and shallow wells H11-H14, R8S,D and O7D. Benzene was detected (520 µg/L and 460 µg/L) in two water samples from well H2S near Skyway Street (plate 1). It is not likely, however, that the area near well H2S is the source of benzene in water of well AF2, because the concentration in water H74M is greater than that detected in H2S, and because benzene was not otherwise detected in the previously delineated plumes orginating near Skyway Street (Stark and others, 1983, fig. 30).



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 15.--Generalized distribution of benzene in ground water north of Arrow Street.

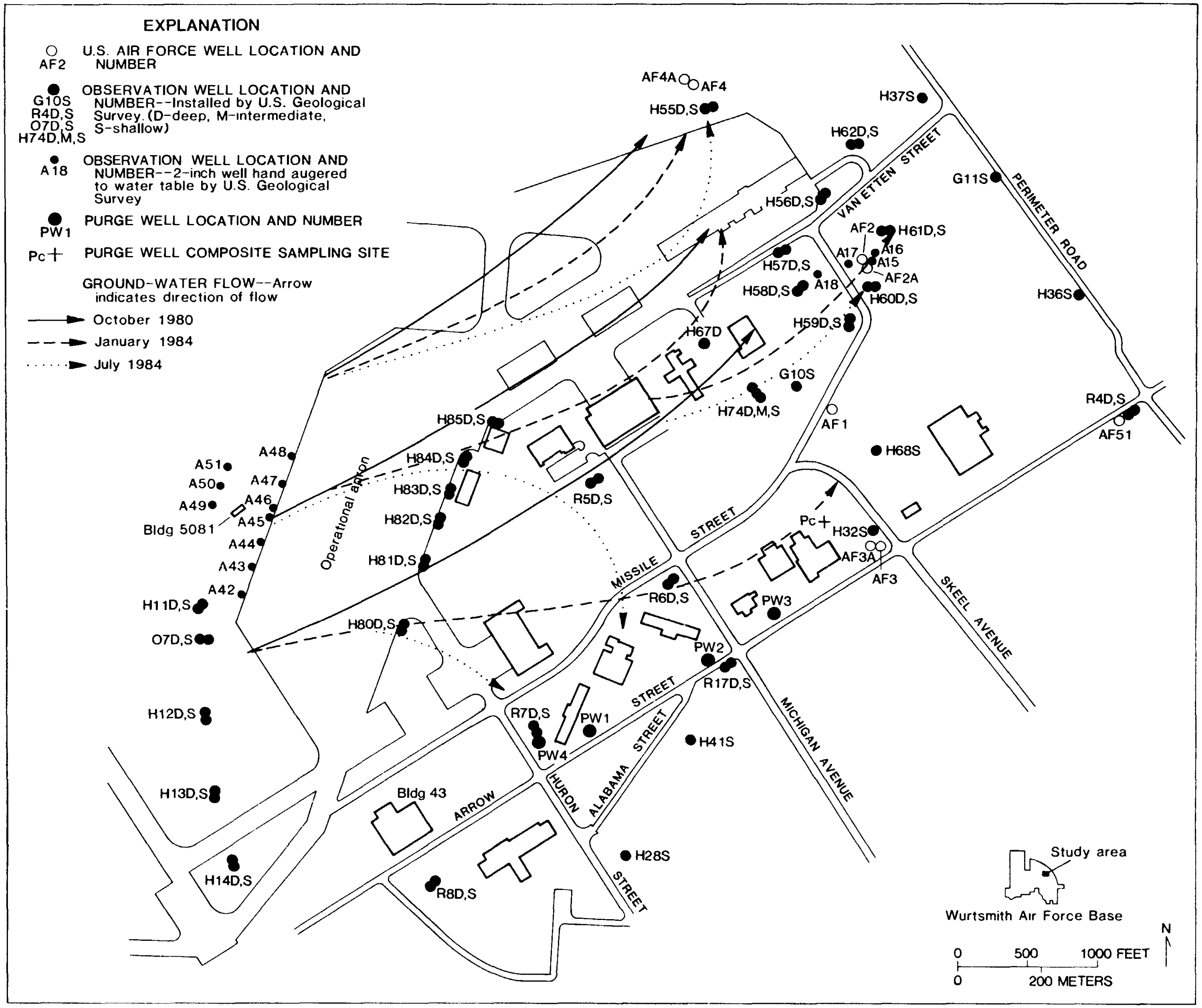


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Figure 16.--Direction of ground-water flow north of Arrow Street, 1981-84.

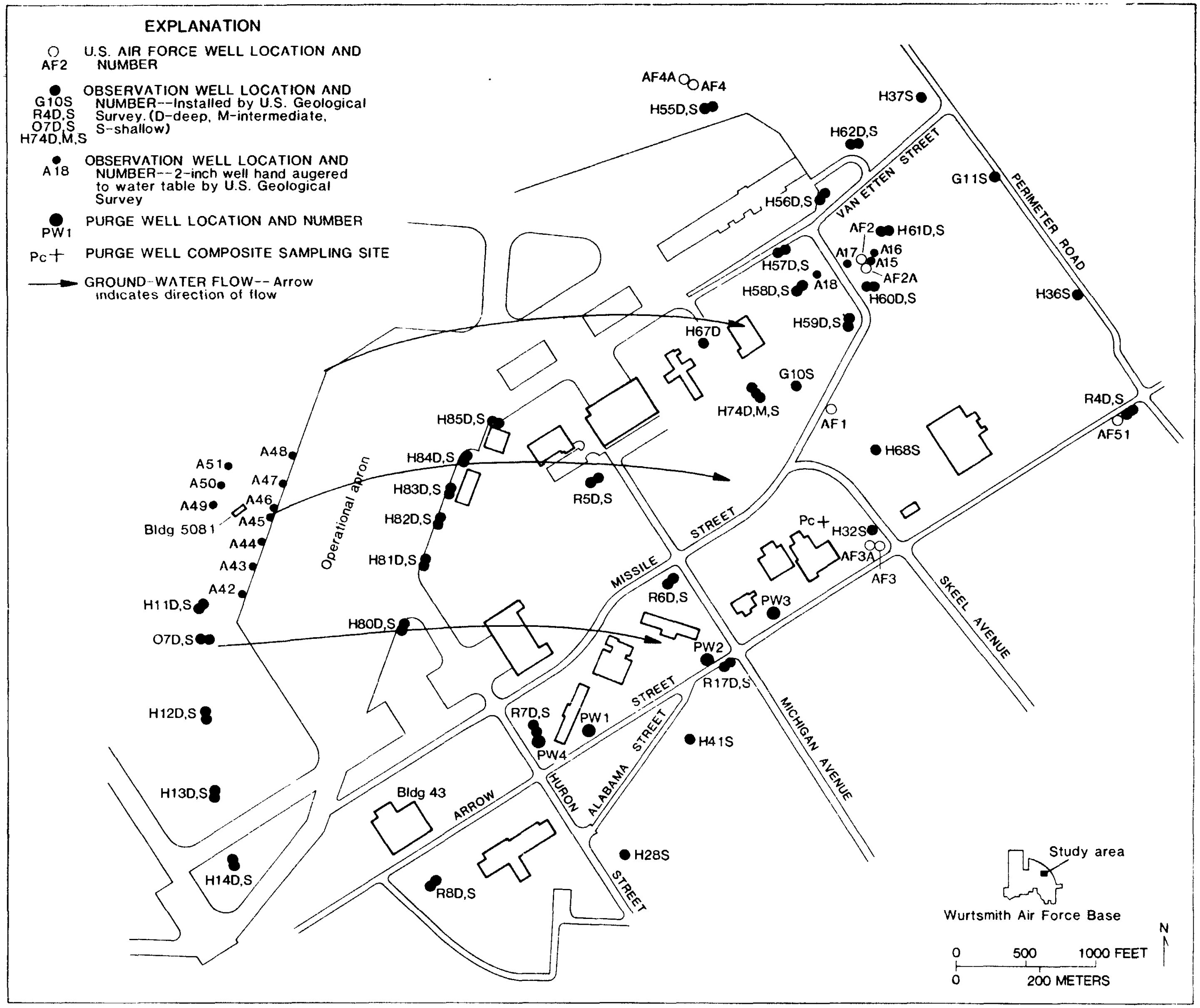

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Figure 17.--Direction of ground-water flow north of Arrow Street, April and May 1985.

Figure 18 shows that toluene occurs at the surface of the water table at the former sites of buried fuel tanks. Toluene was detected downgradient from these sites only in water from wells H81D,S, which suggests that it is either less mobile in the system or that biodegradation is efficient in removing it from the water (Wilson and others, 1983).

Figure 19 shows the generalized distribution of dichloroethylene from 1980 to 1985. The dichloroethylene plume previously delineated (Stark and others, 1983, fig. 30) is being drawn to the Arrow Street purge system, although as in the case of benzene, direct movement to well AF2 is more likely during times when the pumping rate of the purge system is reduced.

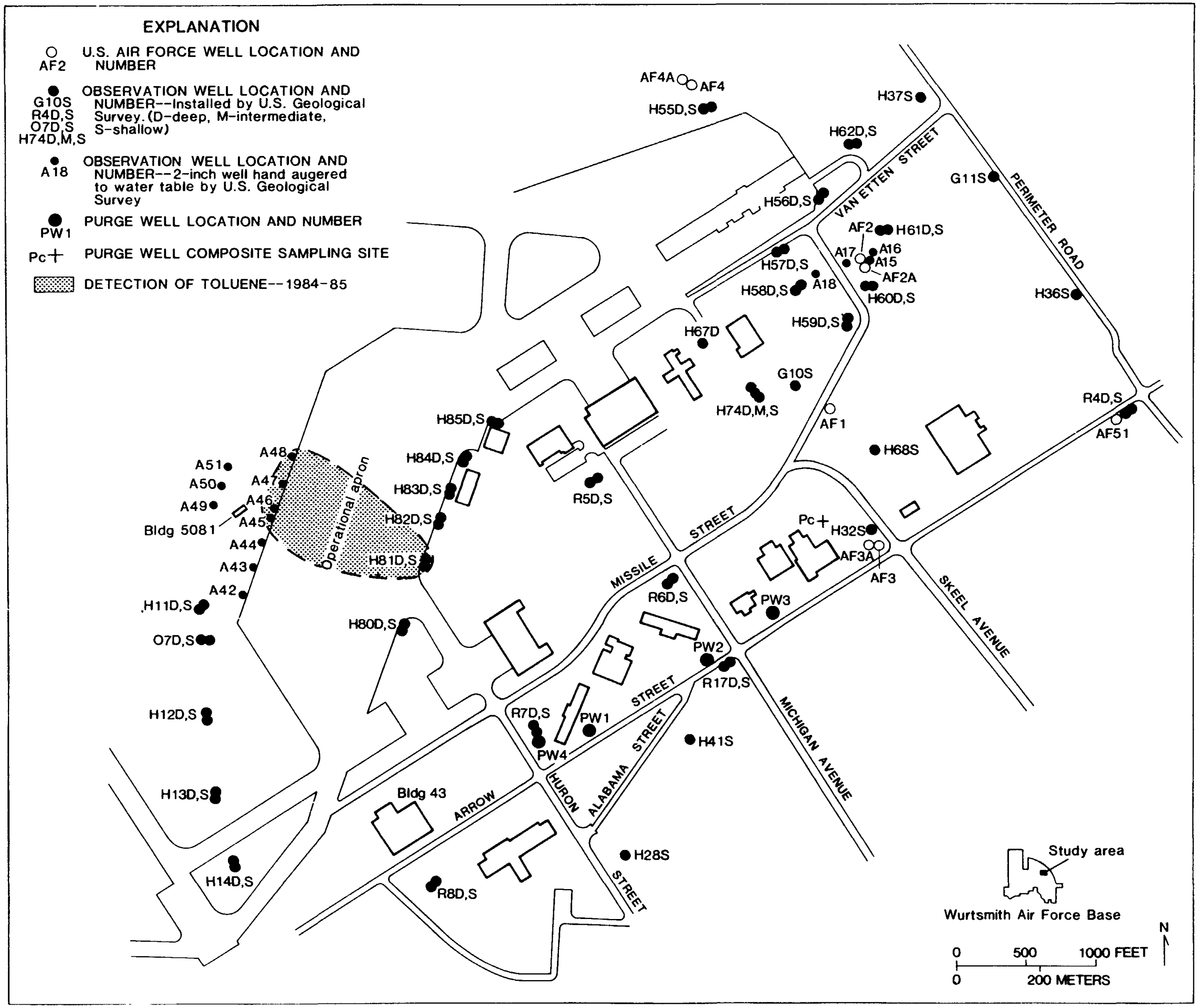
Alert Apron Area

Stark and others (1983) identified two trichloroethylene plumes in the alert apron area. One extended from a point about 400 ft west of Pride Road on the Base to just south of Pierce's Point on Van Etten Lake (fig. 20). A second, smaller plume originated in the same general area just north of the major plume. It seemed to terminate under the alert apron. The highest concentration of trichloroethylene (1,150 μg/L) was found in 1980 near the origin of the longer plume in water from well R50S. Monitoring of trichloroethylene concentrations of water in the plume and of water of Van Etten Lake by the Air Force following the initial study showed that trichloroethylene concentrations in the plumes decreased significantly after 1980. To verify this change, samples were collected from nine wells on April 10, 1984. Table 4 compares the results with maximum concentrations observed during 1980.

Table 4.--Concentrations of trichloroethylene in water of Alert Apron plumes, 1980 and 1984
[Analyses by U.S. Geological Survey]

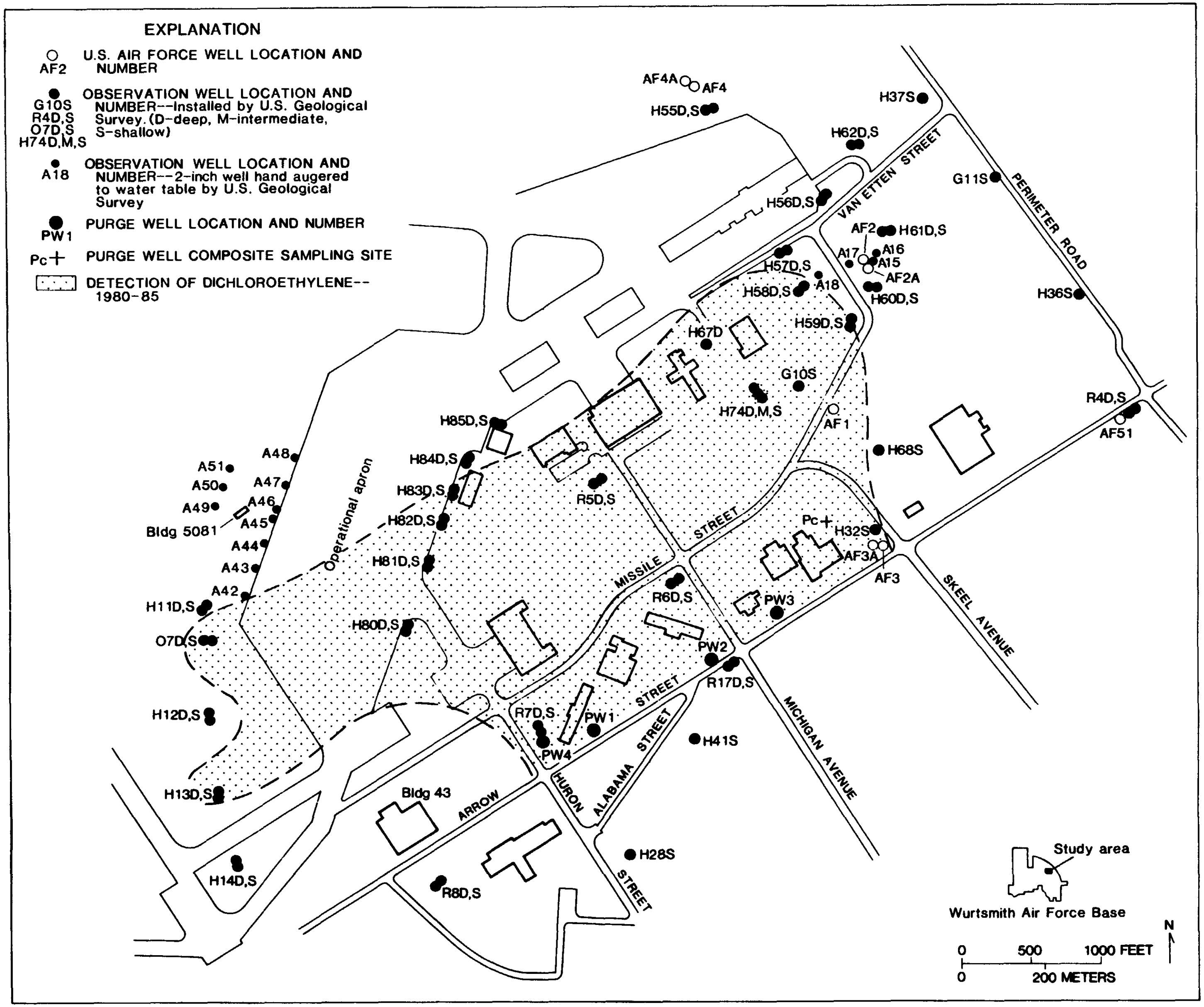
Well number	Date (1980)	Trichloroethylene (μg/L)	Date (1984)	Trichloroethylene (μg/L)
R13D	August 13	[a]ND	April 10	ND
R19D	April 30	10	do	7.6
R27D	August 13	2.0	do	ND
R29S	do	265	do	20
R34S	do	217	do	31
R36S	June 11	387	do	65
R36D	August 13	372	do	135
R49S	do	1,000	do	50
R59S	October 28	ND	do	ND

[a] ND is not detected.



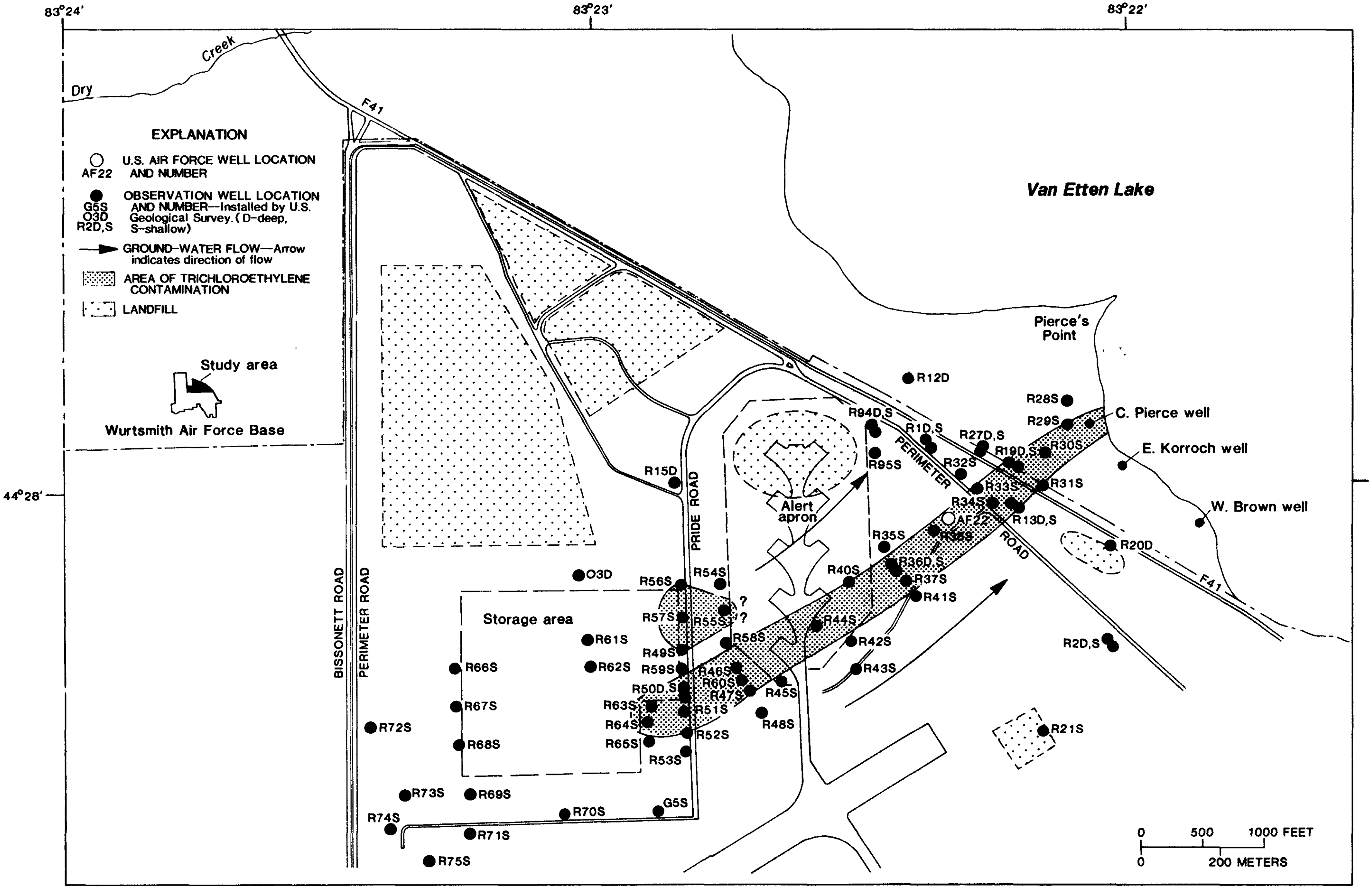
Base from Wurtsmith Air Force Base 1:7,200 map

Figure 18.--Generalized distribution of toluene in ground water north of Arrow Street.



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 19.--Generalized distribution of dichloroethylene in ground water north of Arrow Street.



Base from Wurtsmith Air Force Base 1:7,200 map

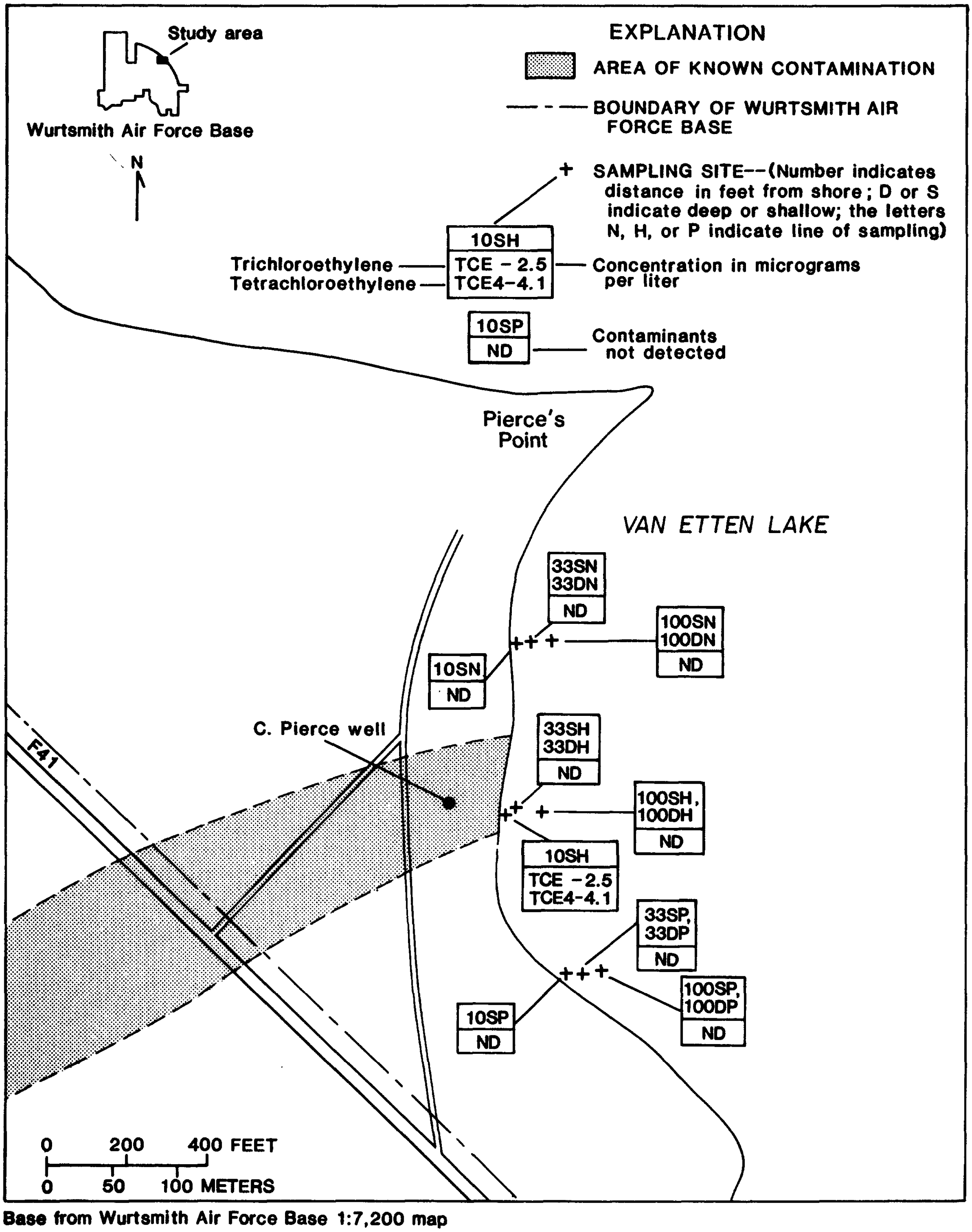
Figure 20.--Alert Apron trichloroethylene plumes.

Analyses of duplicate samples collected on April 10 by the Air Force gave results comparable to those given above. On the basis of the above data, it seems that natural flushing of trichloroethylene in the Alert Apron plumes has been more rapid and complete than anticipated.

On April 24, 1984, samples of water of Van Etten Lake were collected at sites periodically sampled by the Air Force, just offshore from the termination of the southern Alert Apron plume (fig. 21). Samples were collected at three locations 10 ft offshore at a depth of 6 in., at three locations 33 ft offshore 8 in. above the bottom and 6 in. below the water surface, and at three locations 100 ft offshore 8 in. above the bottom and 6 in. below the water surface. Volatile hydrocarbons (2.5 μg/L trichloroethylene and 4.1 μg/L tetrachloroethylene) were detected at only one site (table 5).

Table 5.--Analyses of water from Van Etten Lake, April 24, 1984
[Analyses by U.S. Geological Survey. See figure 21 for sampling sites]

Site number	Trichloroethylene (μg/L)	Tetrachloroethylene (μg/L)
10SN	ND	ND
33SN	ND	ND
33DN	ND	ND
100SN	ND	ND
100DN	ND	ND
10SH	2.5	4.1
33SH	ND	ND
33DH	ND	ND
100SH	ND	ND
100DH	ND	ND
10SP	ND	ND
33SP	ND	ND
33DP	ND	ND
100SP	ND	ND
100DP	ND	ND



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 21.--Location of Van Etten Lake sampling sites.

Northern (Perimeter Road) Landfill Area

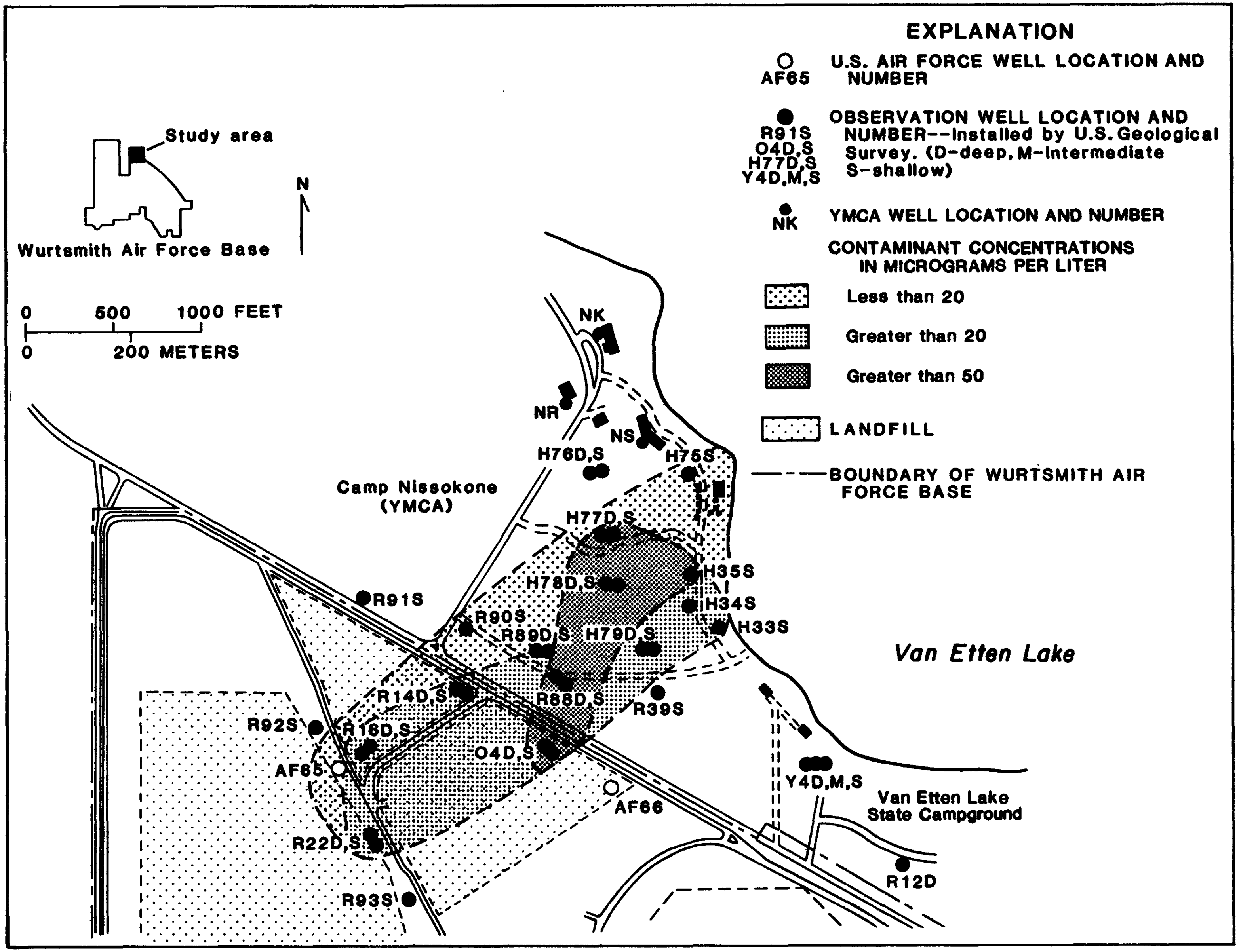
In April 1983, three new wells were drilled in the northern landfill area to verify earlier predicted movement of benzene and dichloroethylene. These wells--H33S, H34S, and H35S--were installed about 100 ft west of Van Etten Lake (fig. 22). At the same time samples of water were collected from previously installed wells R39S, R88S, and R88D. Samples of water for analysis were collected from the YMCA camp residence well (well NR), the YMCA shop well (well NS), and the YMCA kitchen well (well NK) in October 1982 and August 1984 (table 2).

Dichloroethylene concentrations in water from wells R88D and R88S increased from 155 μg/L and 145 μg/L in March 1981 (Stark and others, 1983) to 222 μg/L and 349 μg/L in April 1983. April sampling also showed 105 μg/L of dichloroethane in water from well R88S, a substance previously undetected. Volatile organic compounds were not detected in the YMCA residence, shop, or kitchen wells, nor in well R39S.

In June 1984, further investigations were conducted to determine the most hydrologically suitable sites for withdrawing contaminated water from the aquifer. In order to select sites, additional monitoring wells were required for water-level measurements and water-quality samples. Deep and shallow wells (H76D to H79D and H75S to H79S) were installed off-Base across the plume between Perimeter Road and Van Etten Lake (fig. 22).

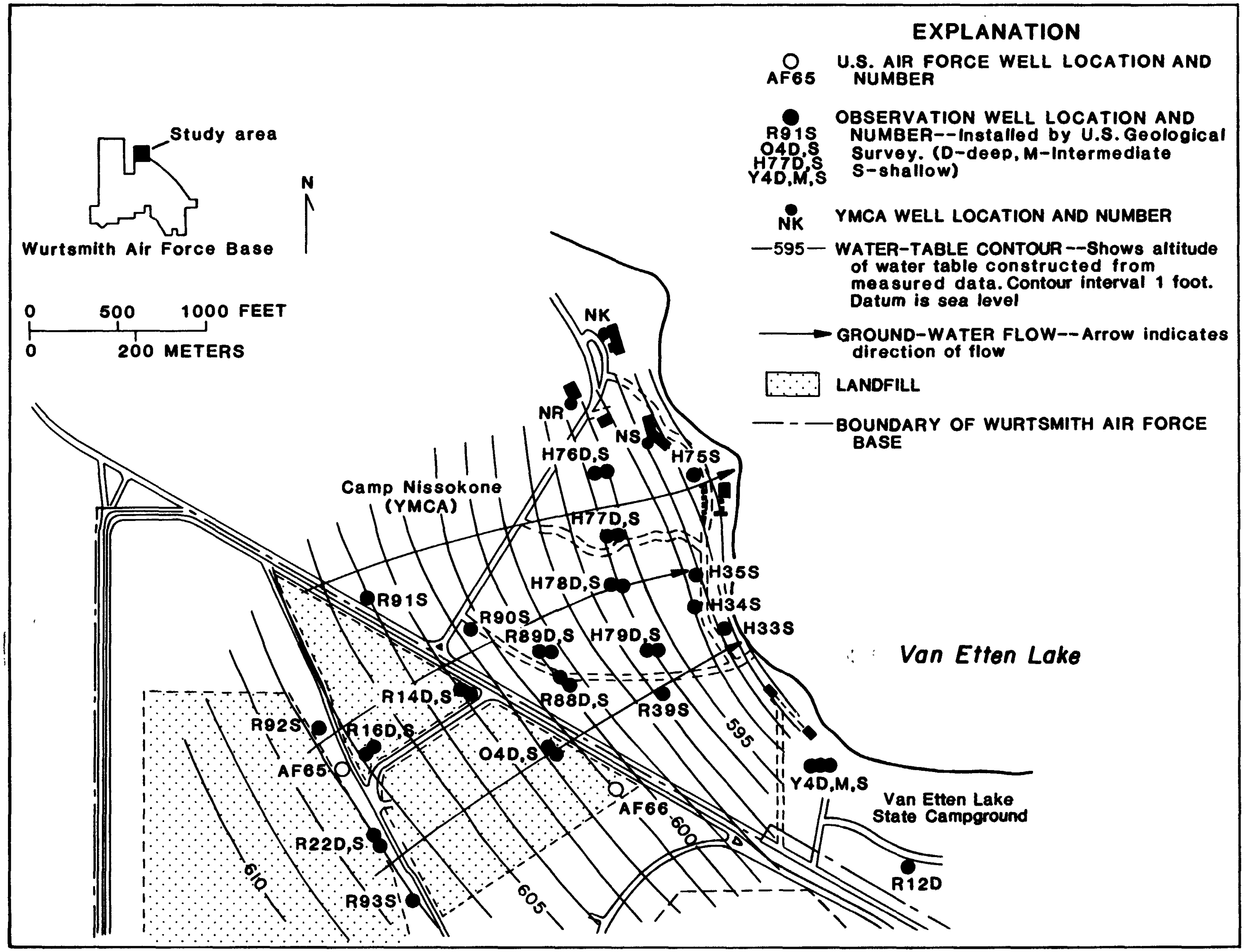
Water levels in most wells in the northern landfill area were measured in July 1984. The configuration of the water table and the direction of ground-water flow at that time are shown on figure 23. Levels were measured again in August and found to be 0.5 to 1.0 ft lower than in July. However, the configuration of the water table, and thus the direction of flow, had not changed appreciably. The estimated rate of ground-water flow was about 3 ft/d in the western part of the area and about 5 ft/d in the eastern part.

Figure 22 also shows the general outline of the Northern landfill plume based on all data collected from 1979 to 1984, and delineates those areas where concentrations of either benzene, trichloroethylene, or dichloroethylene in water exceeded either 20 or 50 μg/L at sometime during that period. Data obtained between Perimeter Road and Van Etten Lake in 1984 suggest that the boundary delineated in 1981 is accurate, and that concentrations of volatile hydrocarbons measured in 1983 and 1984 do not differ greatly, with one exception, from those found in 1979-81 work. Water from well 04S did not contain trichloroethylene in June 1984. It is possible, if the original source was small, for the trichloroethylene to have been flushed from the system naturally during the past 3 or 4 years.



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 22.--Area of trichloroethylene, dichloroethylene, and benzene contamination in the northern landfill area.



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 23.--Water-table altitude and direction of ground-water flow in the northern landfill area, July 1984.

Numerous simulations using the Base model were made to explore the most suitable sites for purge wells and most appropriate purge-pumping rates. It was assumed that installation of purge wells within the landfills should be avoided, and if wells were to be installed on Base, installation must be along Perimeter Road. An attempt was made to keep the number of purge wells and pumping rates as low as possible. Three hypothetical purge wells were initially used in model simulations. Several simulations were made with two wells on the margin of the plume pumping at one rate and a center well pumping at a slightly higher rate. Model simulations using two wells on the margin of the plume pumping 60 gal/min each, and a center well pumping 150 gal/min, indicated that nearly all the contaminated water would be captured (fig. 24). Only in a small area in the vicinity of well 04S would contaminated water fail to be drawn to the purge wells. This scheme perhaps would be satisfactory if it could be firmly established that water in the vicinity of well 04S would remain free of contaminants. Increasing the pumping rate of the two wells along the margin of the plume to 100 gal/min each, and keeping the rate of the center well at 150 gal/min, would draw contaminated water to the purge wells from the entire width of the plume (fig. 25).

To see if contaminated water could be captured by pumping less water, five hypothetical purge wells were used. Each well was pumped at 40 gal/min. The simulation indicated that most contaminated water upgradient from the wells would be captured (fig. 26), except perhaps that in the northern part of the plume. When wells were pumped at 60 gal/min each, too much uncontaminated water was drawn to the southernmost wells (fig. 27). The pumping rate of one of the northern wells and two of the southern wells was changed to minimize the amount of uncontaminated water drawn to the wells. This simulation indicated that five wells pumping, from north to south, 60, 80, 60, 40, and 40 gal/min would capture all water flowing from the area of contamination (fig. 28). This system seems to be the most hydrologically efficient for purge wells installed within the boundary of the Base.

To investigate the effectiveness of purging downgradient and off-Base, hypothetical purge wells were located perpendicular to ground-water flow lines near Van Etten Lake. Because the plume is slightly wider near the Lake, water has to be withdrawn from a larger area. Several simulations were made using different pumping rates and different numbers of wells. One that satisfactorily purged the system had four wells pumping at 60 gal/min each (fig. 29). Pumping nine wells at 25 gal/min also purged satisfactorily (fig. 30), and might be preferable because there would be less chance of drawing water from Van Etten Lake when its level is high.

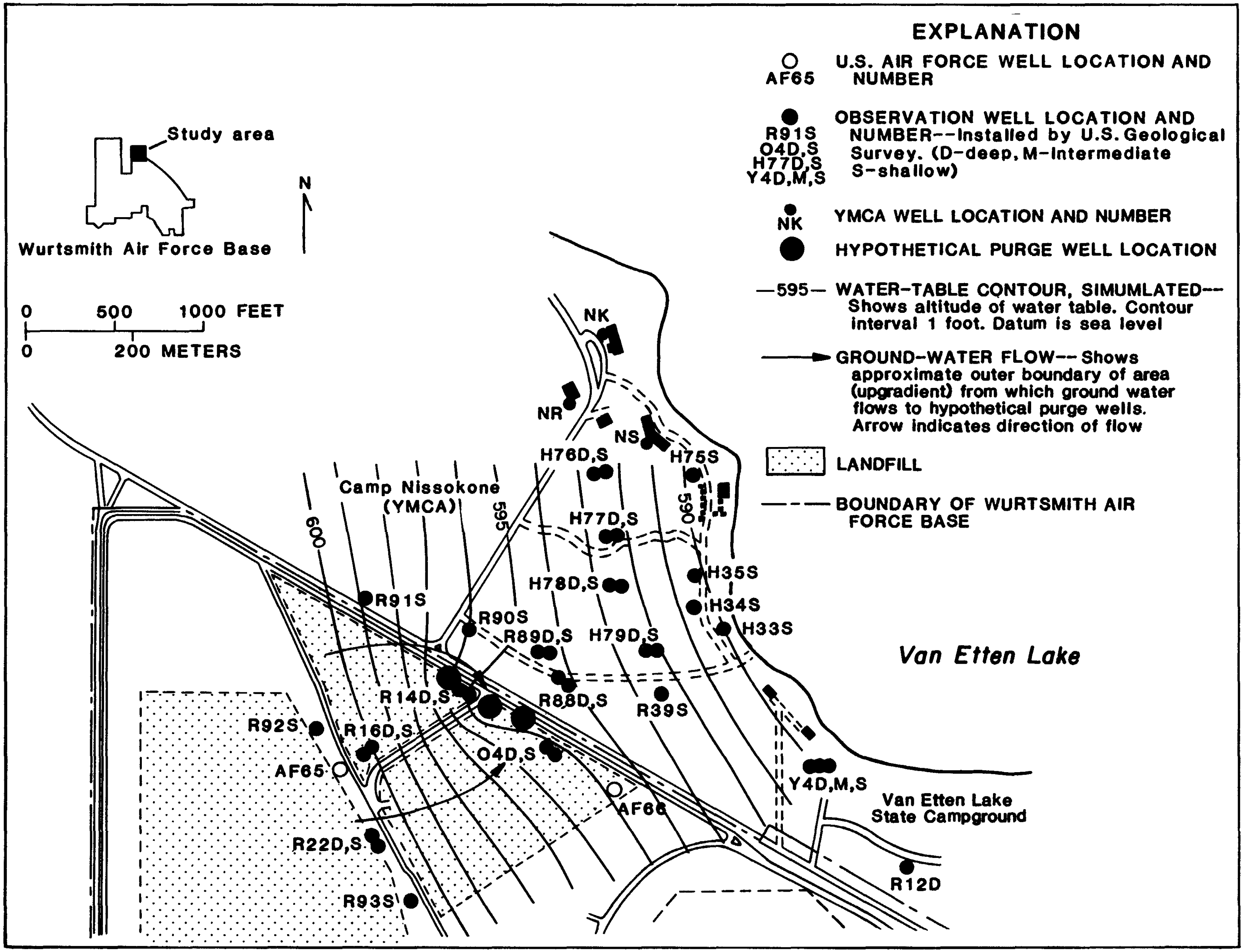


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Figure 24.--Water table resulting from pumping hypothetical purge wells in the northern landfill area (two wells pumping 60 gallons per minute each; one well pumping 150 gallons per minute).

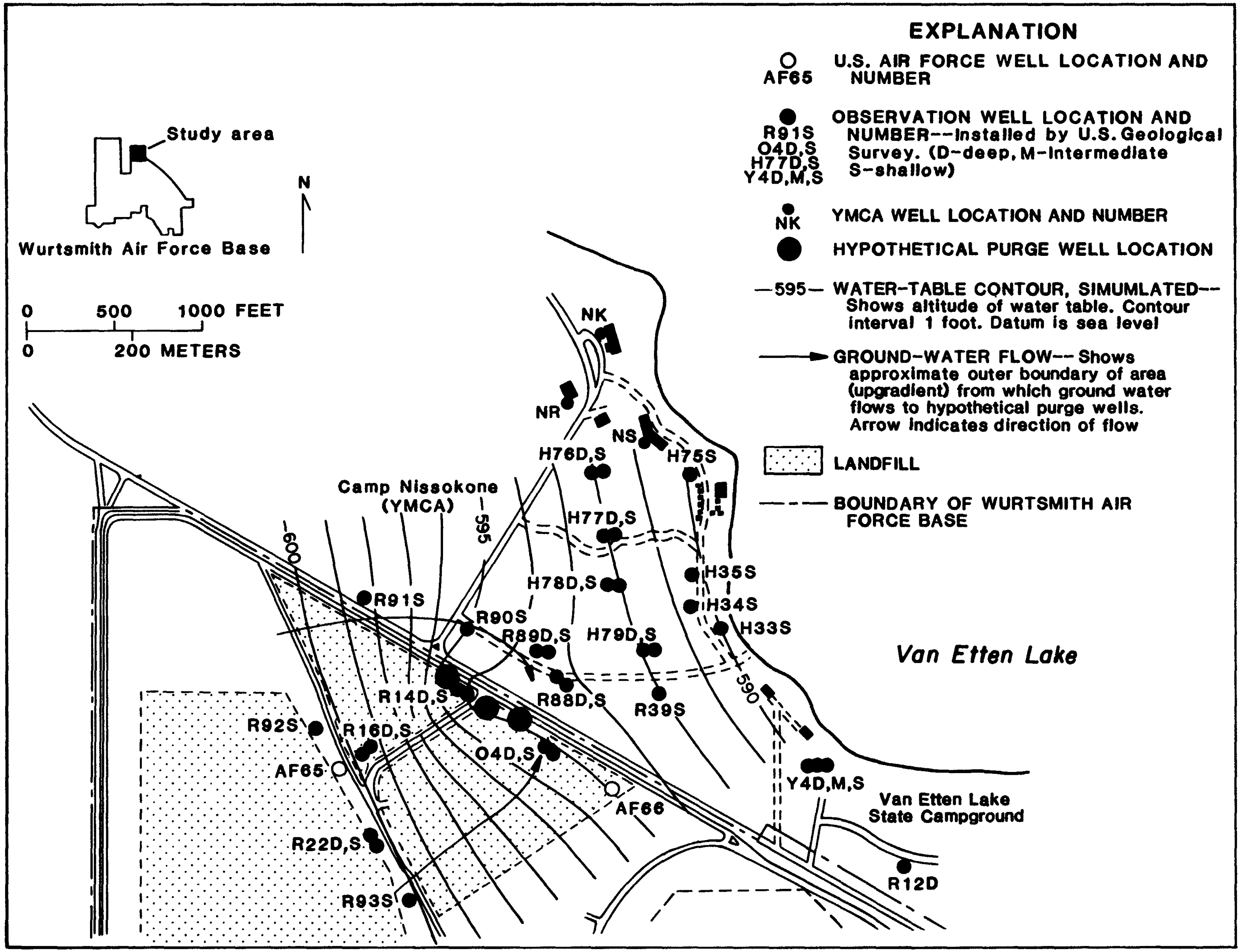

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Figure 25.--Water table resulting from pumping hypothetical purge wells in the northern landfill area (two wells pumping 100 gallons per minute each; one well pumping 150 gallons per minute).

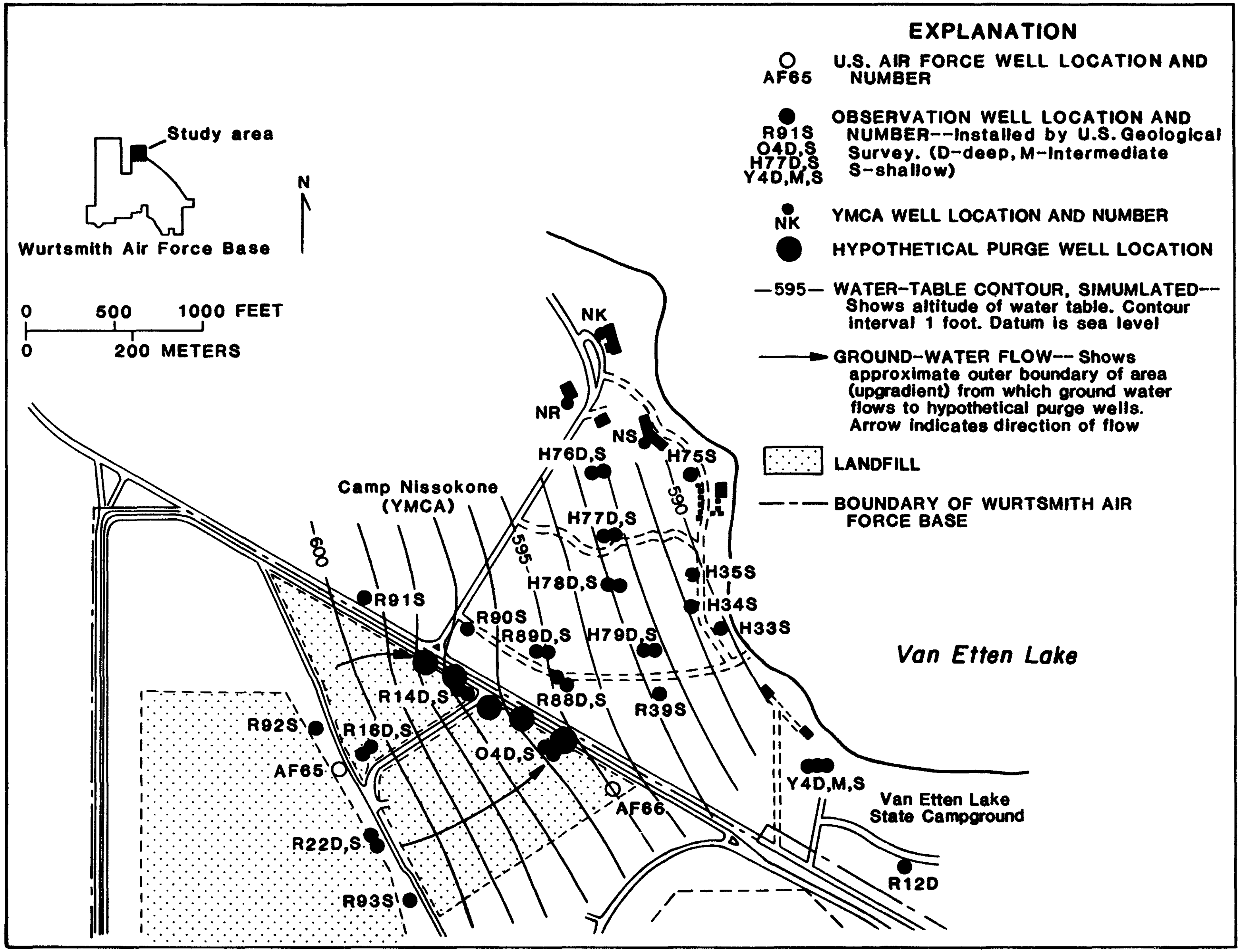

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Figure 26.--Water table resulting from pumping hypothetical purge wells in the northern landfill area (five wells pumping 40 gallons per minute each).

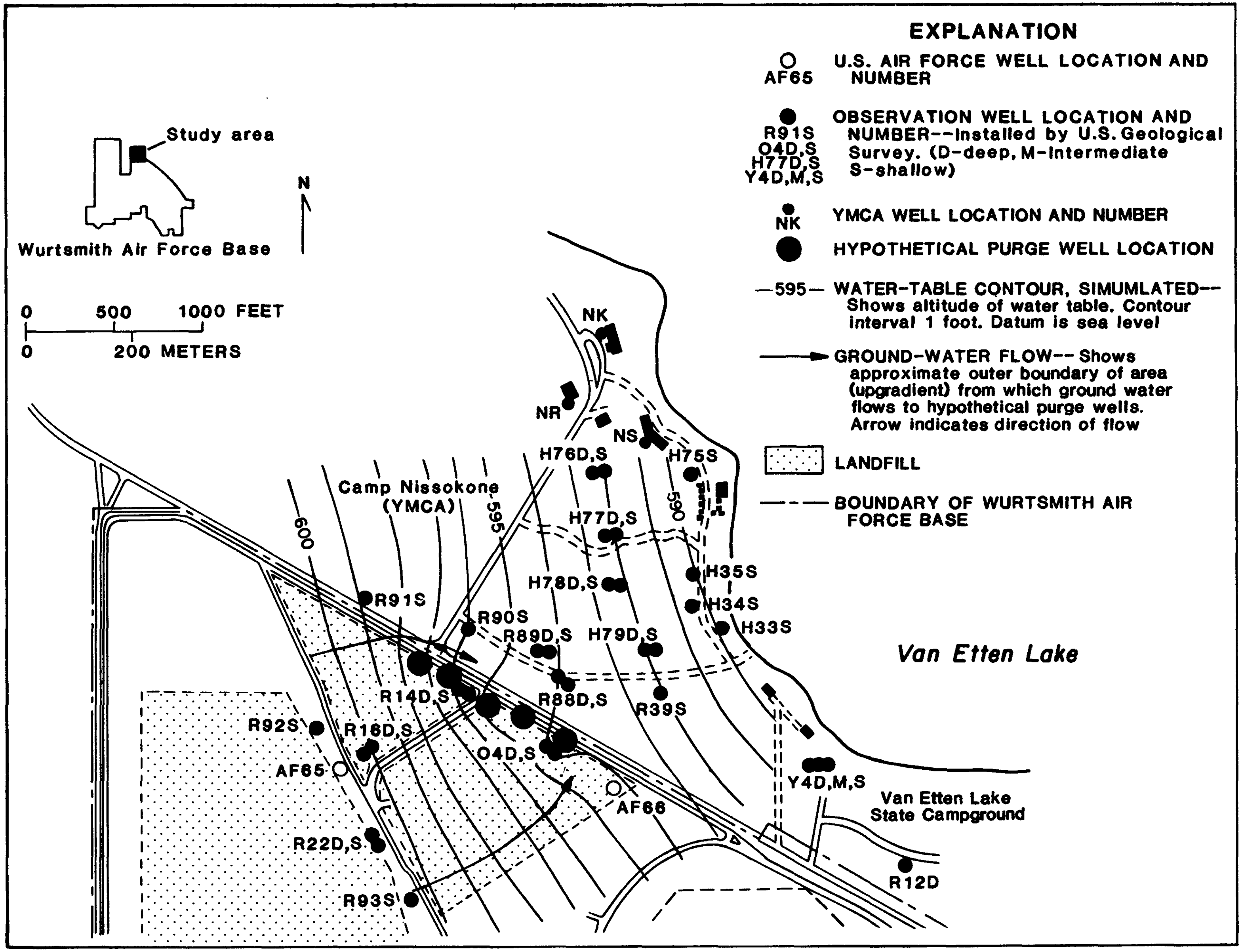

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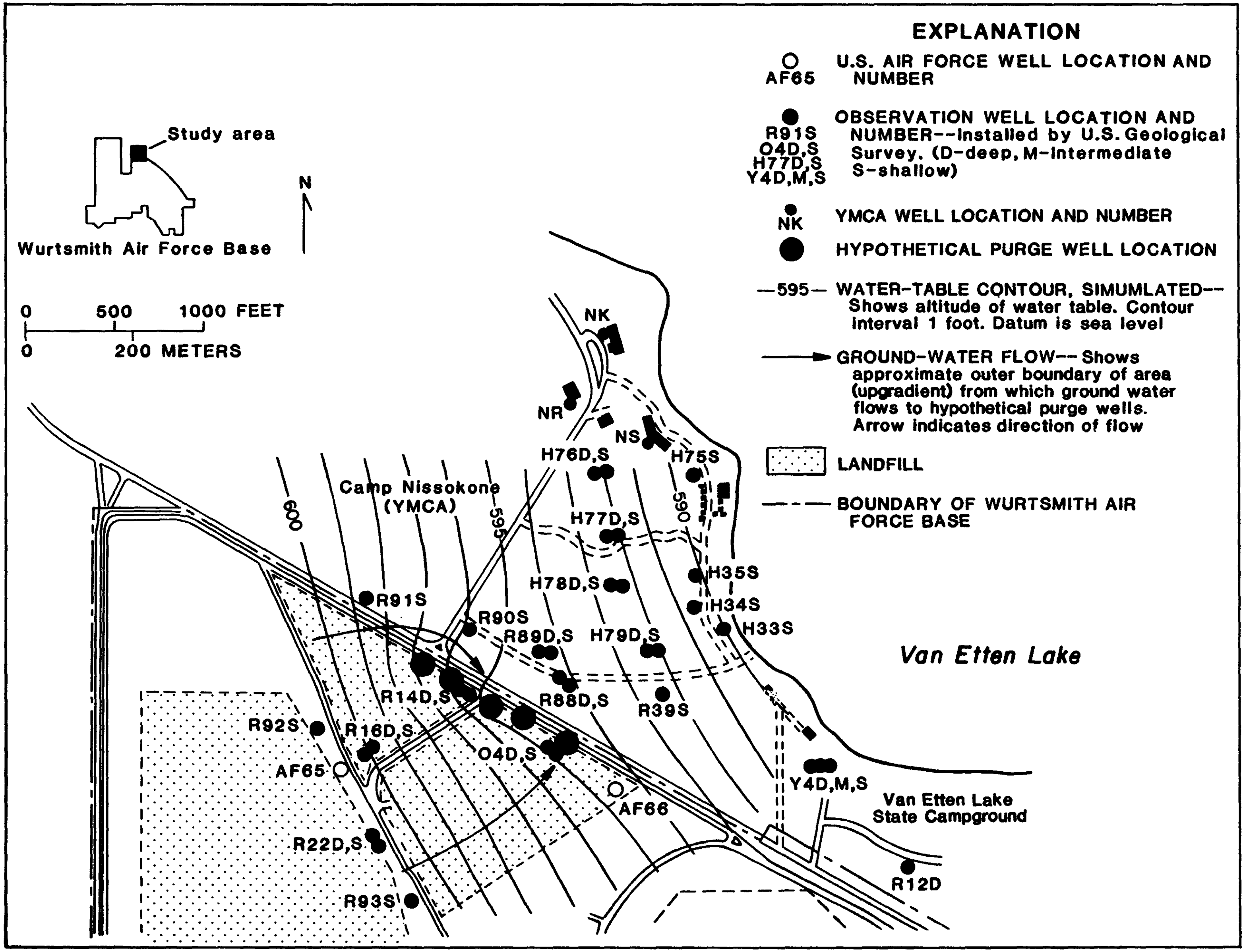
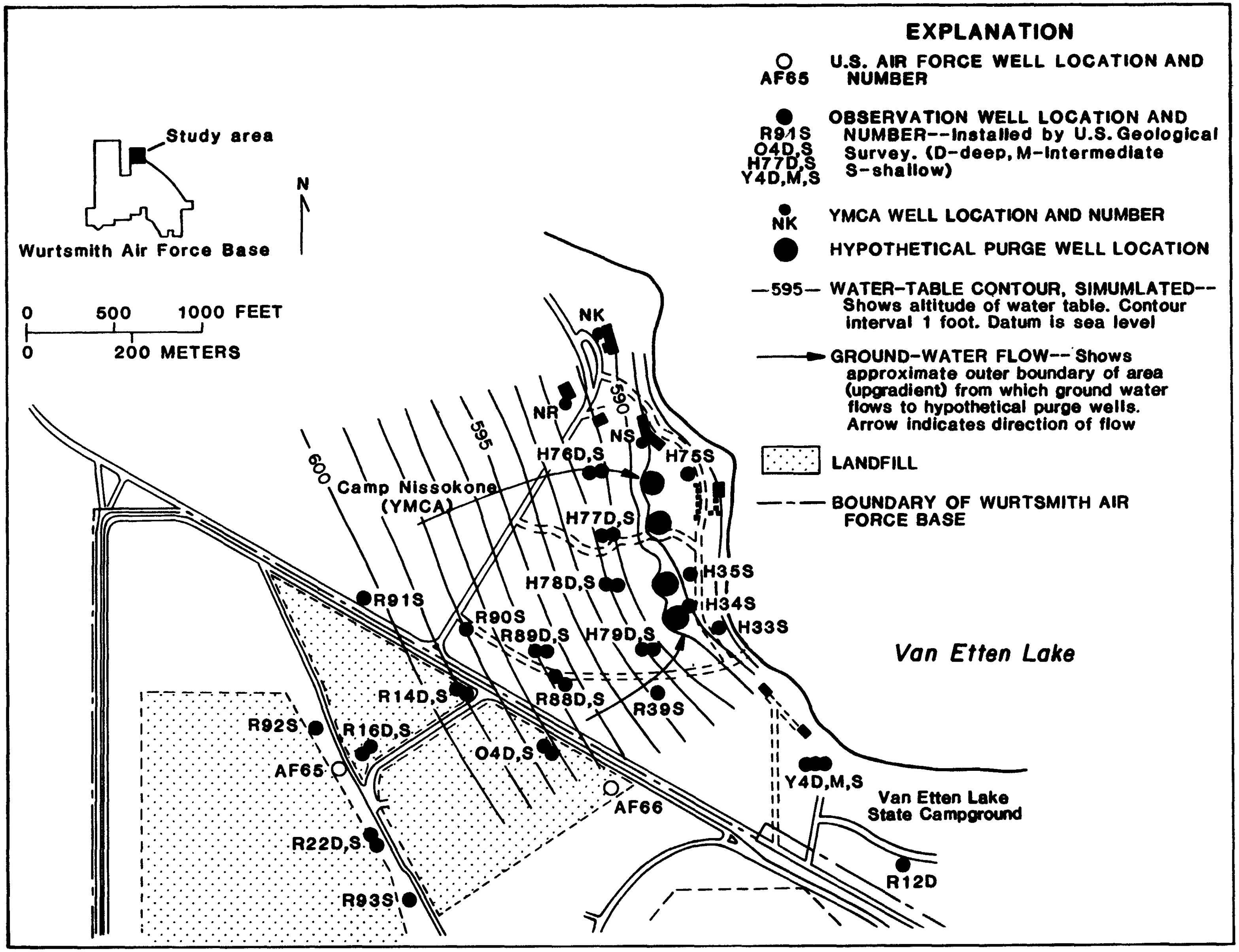
Figure 27.--Water table resulting from pumping hypothetical purge wells in the northern landfill area (five wells pumping 60 gallons per minute each).



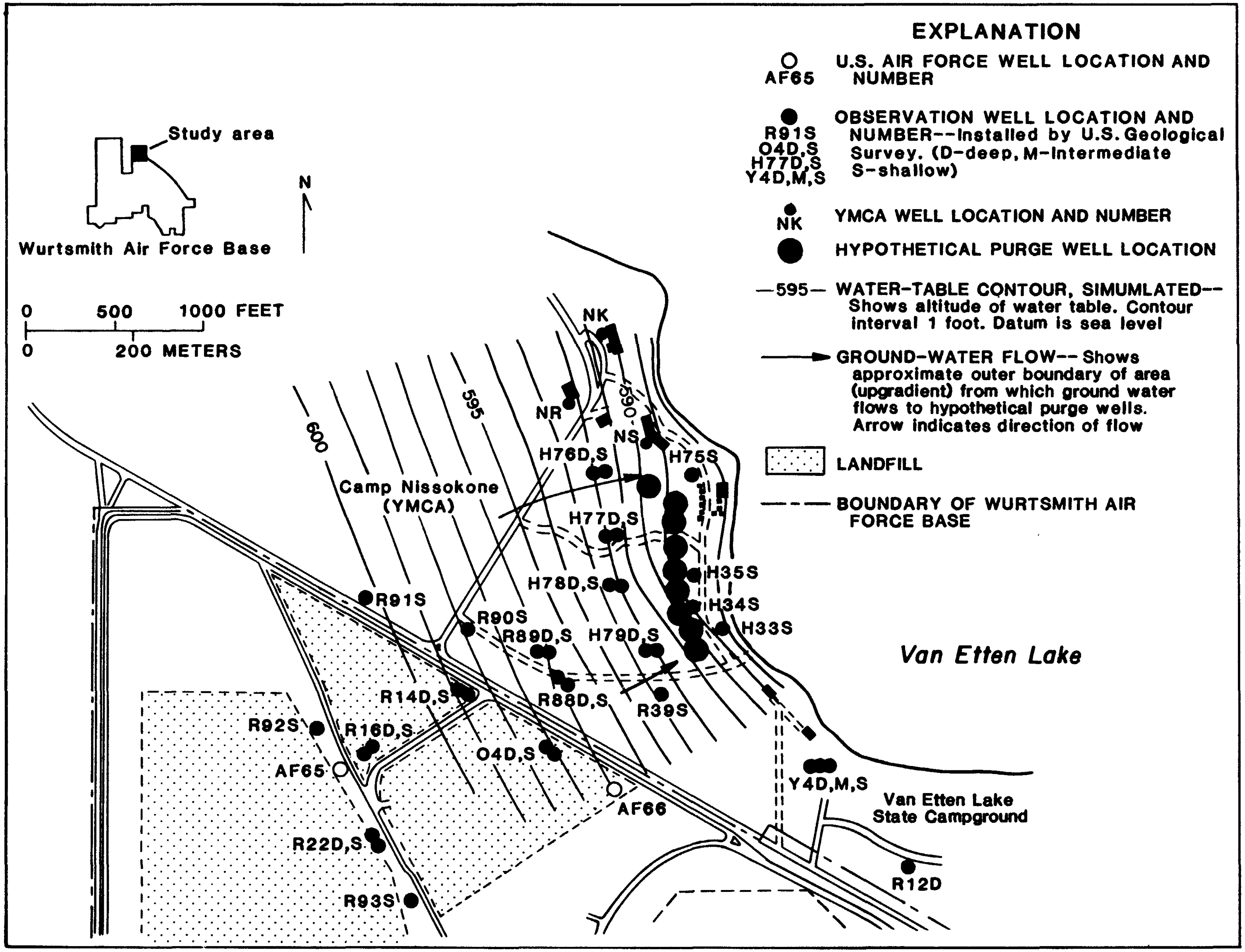
Base from Wurtsmith Air Force Base 1:7,200 map

Figure 28.--Water table resulting from pumping hypothetical purge wells in the northern landfill area (two wells pumping 40 gallons per minute each, two wells pumping 60 gallons per minute each, and one well pumping 80 gallons per minute).



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 29.--Water table resulting from pumping hypothetical purge wells in the northern landfill area (four wells pumping 60 gallons per minute each).



Base from Wurtsmith Air Force Base 1:7,200 map

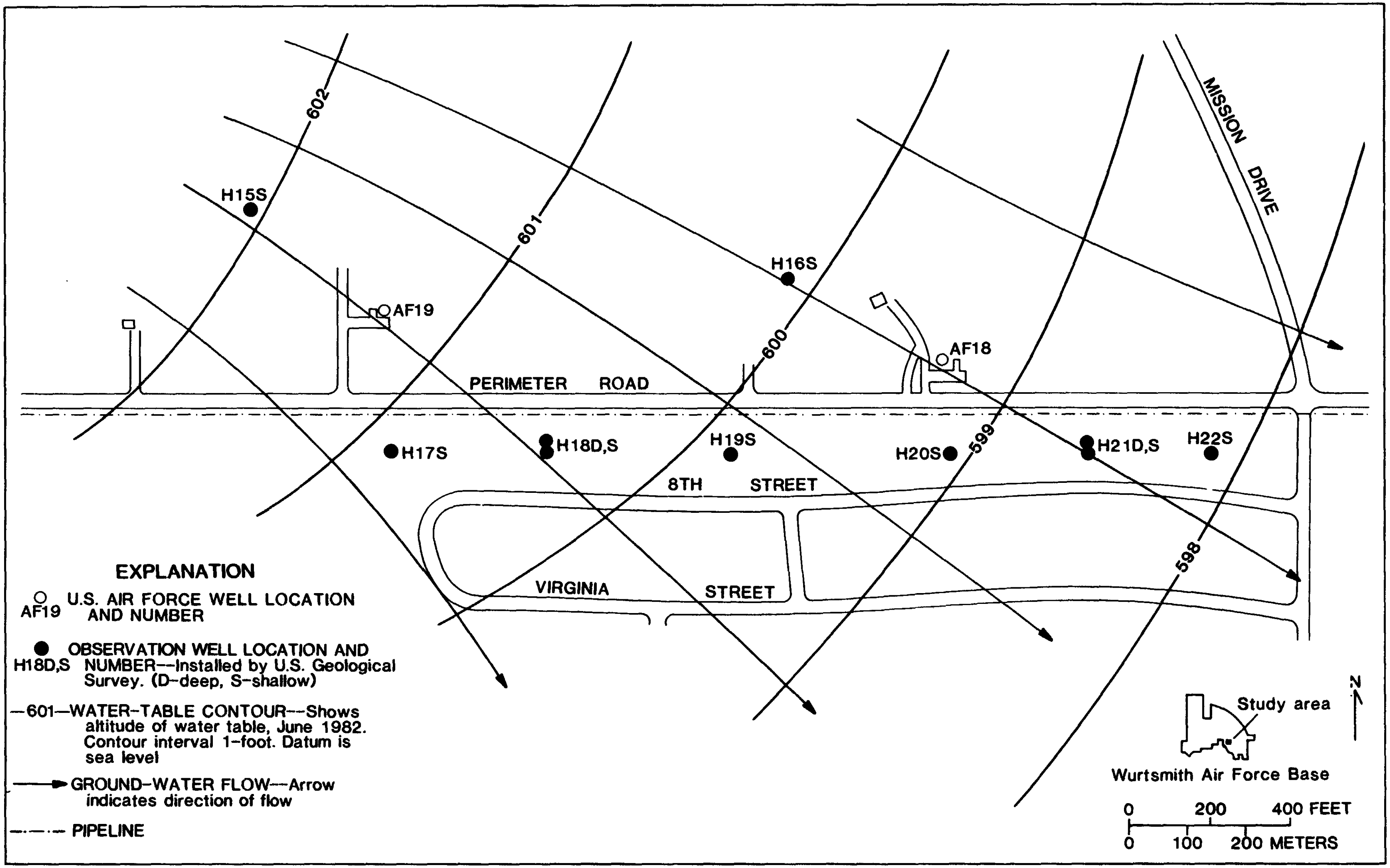
Figure 30.--Water table resulting from pumping hypothetical purge wells in the northern landfill area (nine wells pumping 25 gallons per minute each).

Mission Drive-Well AF18 Area

Trichloroethylene was detected in water-supply wells AF18 and AF19, along Perimeter Road in the southern part of the Base, in November 1977. There was initial concern that the trichloroethylene had been drawn to the area from the known spill at Building 43. Investigation indicated, however, that a ground-water divide was present between the supply wells and Building 43, and that the divide virtually precluded flow from the spill site to the wells. (Subsequent model simulations indicated that the divide existed during periods when wells AF18 and AF19 were heavily pumped.) Stark and others (1983) speculated that the pipeline from the waste-treatment plant to the seepage lagoon, which at one time carried waste water containing trichloroethylene, could have been the source if it had leaked slightly. Possible leakage was supported by unpublished chemical analyses made by the U.S. Geological Survey of water collected from wells AF18 and AF19 from 1966 to 1975. These analyses indicate that chloride and nitrate concentrations of water from these wells had, at times, been higher than at many other locations on the Base.

In April and May 1982, additional work was performed in the vicinity of wells AF18 and AF19. Ten new deep and shallow wells (H15-H22) were installed north and south of Perimeter Road (fig. 31). Well sites were selected so as to determine water quality both upgradient and downgradient of wells AF18 and AF19. In the vicinity of these wells ground-water flow is southeast. Water from each new well and from wells AF18, AF19, G20S, and effluent of the treatment plant, was analyzed for nitrogen compounds, chloride, and volatile hydrocarbons (tables 2 and 6).

Water from wells H18D and H18S contains greater amounts of nitrate than is typical of water from other wells on the Base. Two analyses showed 12 and 13 mg/L of nitrate as N in water from well H18S. Because vegetable garden plots are located a few hundred feet upgradient from these wells, fertilizers applied to these plots may be the source of the nitrate in water from wells H18D and H18S. This is supported by the fact that the chloride concentration in water from these wells is less than 4 mg/L, which would not be expected if the line were leaking in the immediate upgradient area. Two samples of water from well H21D, however, contained 60 and 73 mg/L of chloride and had specific conductance of 740 and 748 μS (microsiemens) (formerly micromhos). The organic nitrogen content was 1.1 mg/L, and the ammonia content was 0.10 mg/L, which is higher than that in water from wells other than those which may be affected by fertilizer applications. Analyses of two samples of waste water collected at the treatment plant immediately before water enters the line showed chloride concentrations of 36 and 40 mg/L and specific conductance of 782 and 787 μS. Organic nitrogen content was 1.1 mg/L, and the ammonia content was 31 mg/L. The similarity of the analysis of water from well H21D to that of water from the treatment plant suggests that the waste-water line is leaking in this area. Based on the direction of ground-water flow at the time of this investigation, leakage of the line could be occurring somewhere in a 200-ft reach eastward of well AF18.



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 31.--Well locations and direction of ground-water flow in the vicinity of wells AF18 and AF19, June 1982.

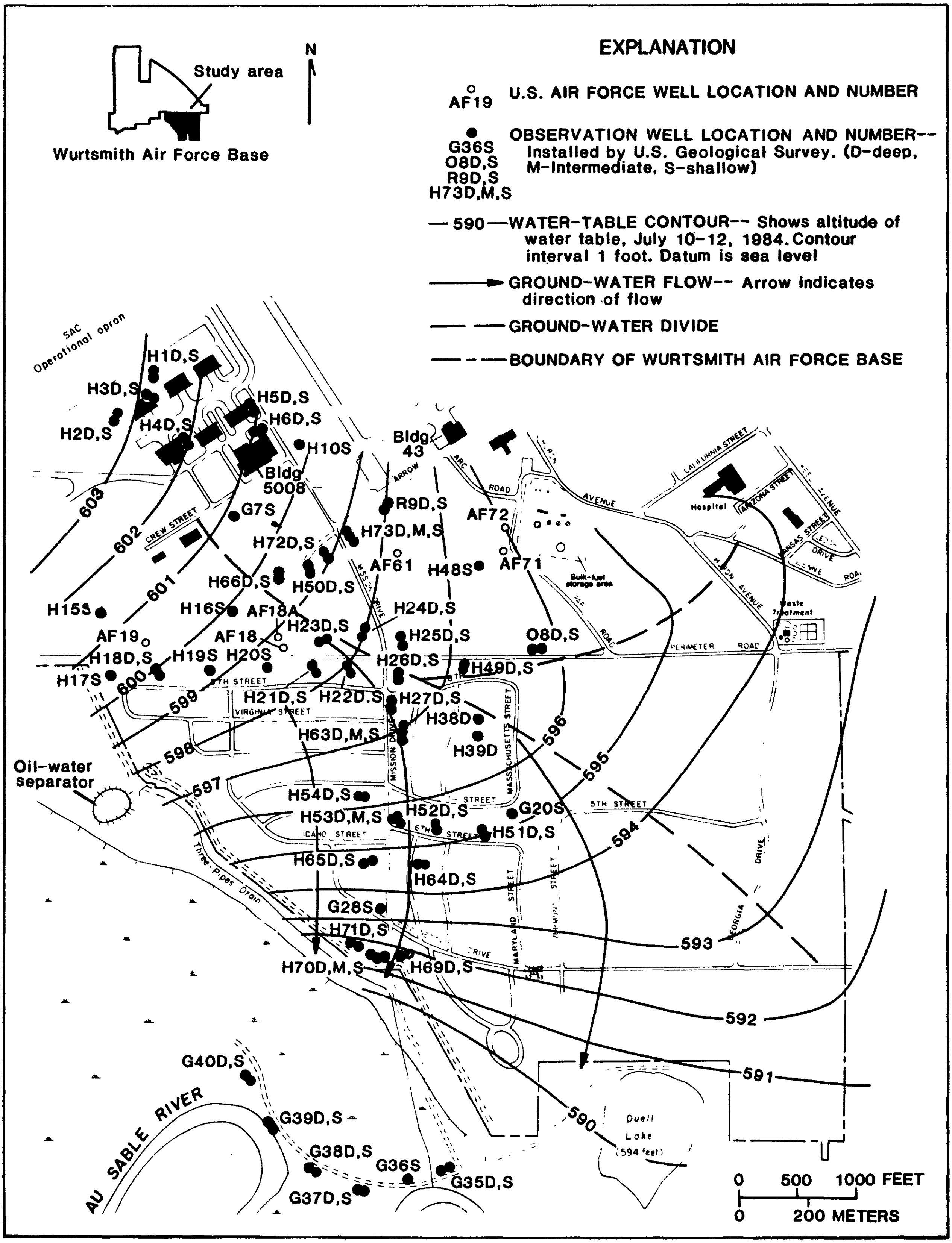
Analyses of volatile hydrocarbons in water from wells H15S to H22S in 1982 indicated trichloroethylene contamination along Perimeter Road near Mission Drive. A high concentration of trichloroethylene in water from well H22S (1,360 μg/L), the last well installed in the series, suggested the possibility of more extensive contamination.

In April 1983, a deep well (H22D) adjacent to H22S, and 10 additional deep and shallow wells (H23 to H27), were installed near the Perimeter Road-Mission Drive intersection (fig. 32). Analyses indicated that contamination was greater in the deeper part of the aquifer than in the shallow part. Maximum concentrations occurred in wells H27D and H26D. Water of well H27D had a trichloroethylene concentration of 3,290 μg/L and a dichloroethylene concentration of 1,410 μg/L; water of well H26D had a trichloroethylene concentration of 1,270 μg/L and a dichloroethylene concentration of 1,450 μg/L.

Water-level data collected in the vicinity of wells AF18-AF19 suggest that movement of contaminants was to the southeast. To determine the extent of contamination, wells H38D and H39D were installed east of Minnesota Street. Water from both wells was free of contamination. Inspection of the swampy area just south of the Base boundary indicated that Three Pipes Drain, which is about 7 ft deep, intercepts the water table and changes the direction of ground-water flow. Measurements of drain flow were made on November 8, 1983, at two sites (Sites 1 and 2, fig. 32) to determine the quantity of ground water discharging to the drain during base-flow conditions. An increase of 355 gal/min was measured. Because of this, further investigation was undertaken to define the extent of contamination, to more precisely determine the direction of ground-water flow, and to determine hydrologically suitable sites for installing purge wells. Forty-nine new wells, H48 to H73 and G27 to G40, were either drilled or hand augered. Water levels in the wells were measured periodically.

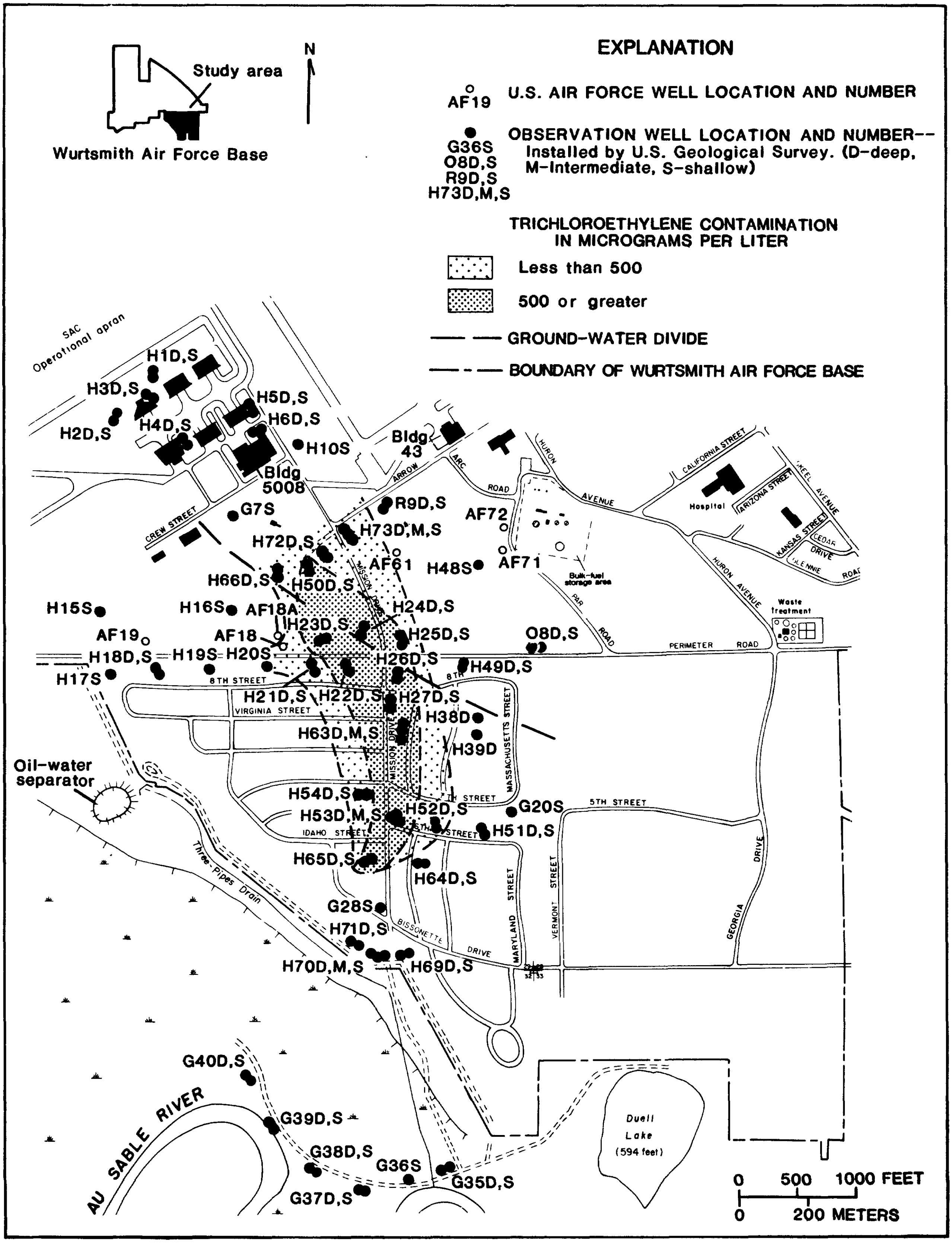
Ground-water flow in the vicinity of the Perimeter Road-Mission Drive intersection was found to shift from a generally southeastward direction to a generally southward direction because of the effects of Three-Pipes Drain. The location of the ground-water divide, which runs southeast-northwest through the area, changes from time to time as the pumping rate of the Arrow Street purge system varies. Altitude of the water table and direction of ground-water flow on July 10-12, 1984, are shown in figure 32.

Figures 33 and 34 delineate areas where trichloroethylene and dichloroethylene contamination exists in the vicinity of the Perimeter Road-Mission Drive intersection; within each area a dashed line defines a smaller area where concentrations exceed 500 μg/L. Distribution of contaminants in the plume has probably been affected by the Arrow Street purge system, and possibly by the lithologic characteristics of the deposits just south of the Base. (Along the Au Sable River the deposits affect flow in the southern part of the plume. Wells G39 and G40 (plate 1) penetrated 5 ft of clay at a depth of about 20 ft below land surface; well G26 struck clay at a depth of 25 ft and continued in clay until drilling was stopped at a depth of 60 ft.)



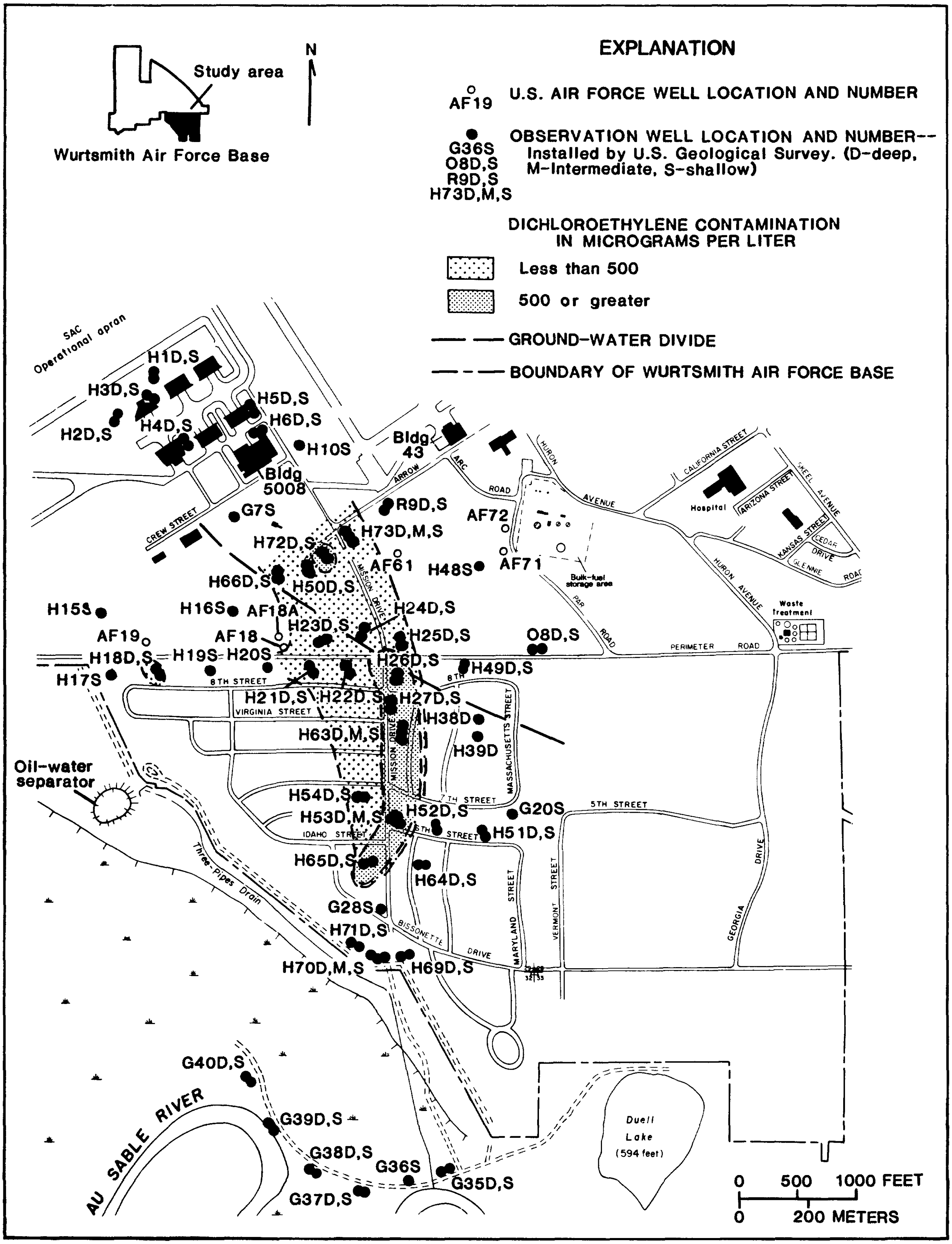
Base from Wurtsmith Air Force Base 1:7,200 map

Figure 32.--Altitude of water table and direction of ground-water flow, July 10-12, 1984.



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 33.--Area of trichloroethylene contamination in the Mission Drive-well AF18 area.



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 34.--Area of dichloroethylene contamination in the Mission Drive-well AF18 area.

Northeast of the ground-water divide, contaminants move to the Arrow Street purge system. South of the divide contaminants move toward the Au Sable River. The southern extension of contamination seems to terminate in the vicinity of wells H65D and H65S, where a trichloroethylene concentration of 279 μg/L and dichloroethylene concentration of 624 μg/L were detected in the deep well (49 ft). Upgradient in the plume, contaminants seem to be at shallow depths; downgradient they are in deeper parts of the aquifer.

Evidence of contaminant movement is indicated by comparing data collected in May and June 1982 with data obtained in April 1983. The following concentrations (table 7) were observed:

Table 7.--Trichloroethylene concentrations in the Mission Drive-well AF18 area, 1982 and 1983
[Analyses by U.S. Geological Survey]

Well number	Trichloroethylene (μg/L) May-June, 1982	Trichloroethylene (μg/L) April 1983
H21S	120, 134	69
H21D	80, 110, 123	79
H22S	1,360, 1,430, 1,720	735

This decrease in concentration suggests the plume is no longer being fed from the initial area of contamination.

Because of the location of the ground-water divide, and because it has shifted due to pumping, tracing contaminants to their origin is difficult. North of the divide, Stark and others (1983) found the highest concentrations of trichloroethylene in water of well H6S (fig. 34) near Building 5008. At the time of the study, ground-water flow in the area was eastward towards Arrow Street. During delineation of the area of contamination in 1981, concentrations shown in table 8 were found.

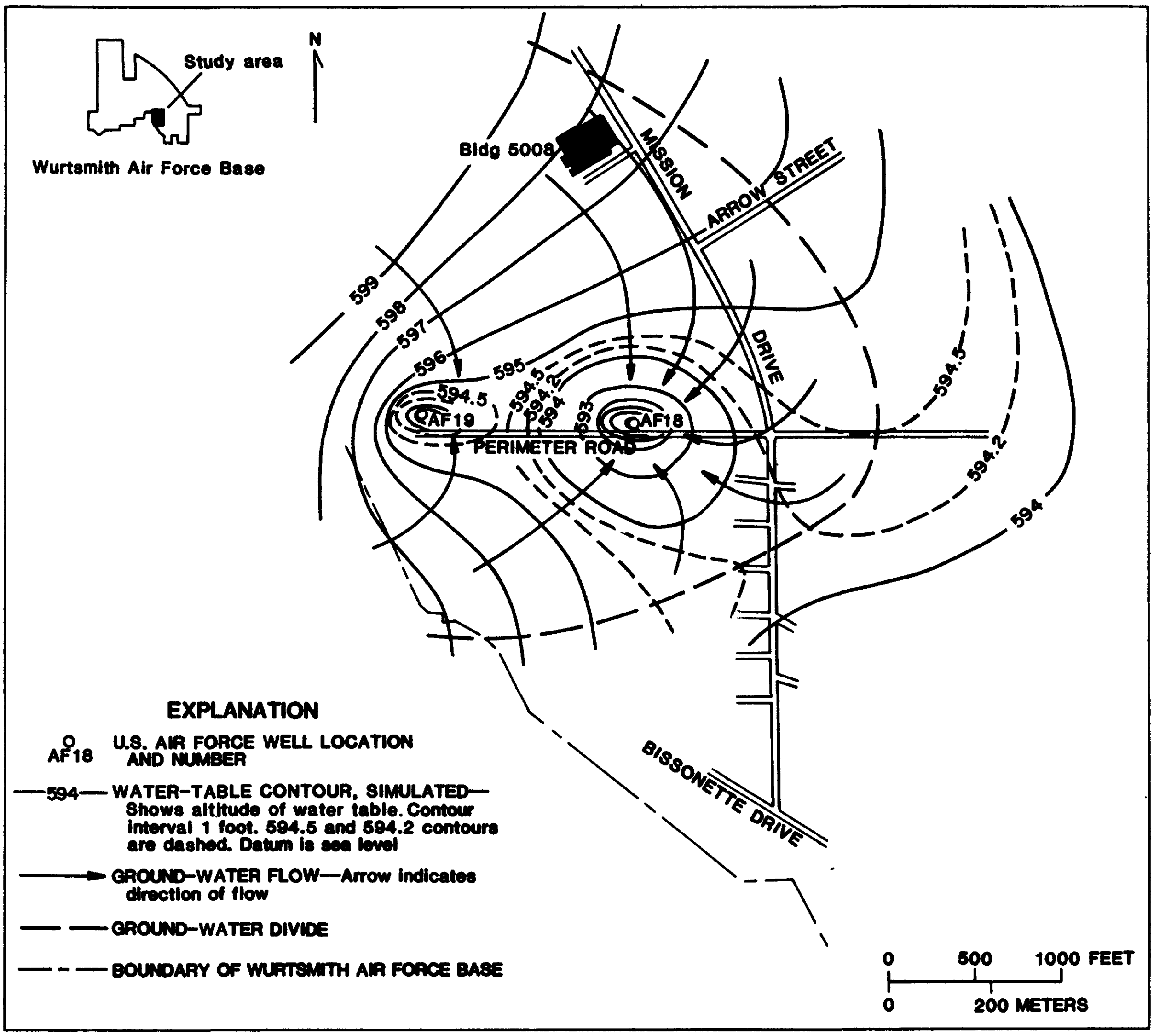
Table 8.--Trichloroethylene and dichloroethylene concentrations north of the Mission Drive-well AF18 plume (from Stark and others, 1983)
[ND is not detected]

Well number	Trichloroethylene (μg/L)	Dichloroethylene (μg/L)
G7S	32	2.0
H6S	800, 821	16, 10
H6D	3.2, ND	7.6, ND
H10S	33	64
R9S	4.9, <5, <1, 3.7, ND	ND, ND, ND, ND, ND
R9D	7.8, <5, ND, <1, ND	ND, ND, ND, ND, 6.0

At some time in the past, a source may have existed in the area of Building 5008. Air Force data indicate the concentration of trichloroethylene in water from well H6S had decreased to 8.2 µg/L on March 5, 1984. Water-supply pumping of wells AF18 and AF19, particularly when pumping of northeastern supply wells was reduced, could have drawn contaminated water southward into an area between Crew Street and Perimeter Road. This area, after discontinuance of pumping from wells AF18 and AF19, would have been southwest of the ground-water divide; contaminants then could have moved southeast in the direction of natural ground-water flow. However, occasional pumping of AF18 and AF19 would have caused contaminants to move southward to the Mission Drive-Perimeter Road intersection and could have dispersed them vertically in the aquifer, as indicated by analyses of water from wells H24S and H24D. Pumping of the water-supply wells would have drawn contaminants westward along Perimeter Road.

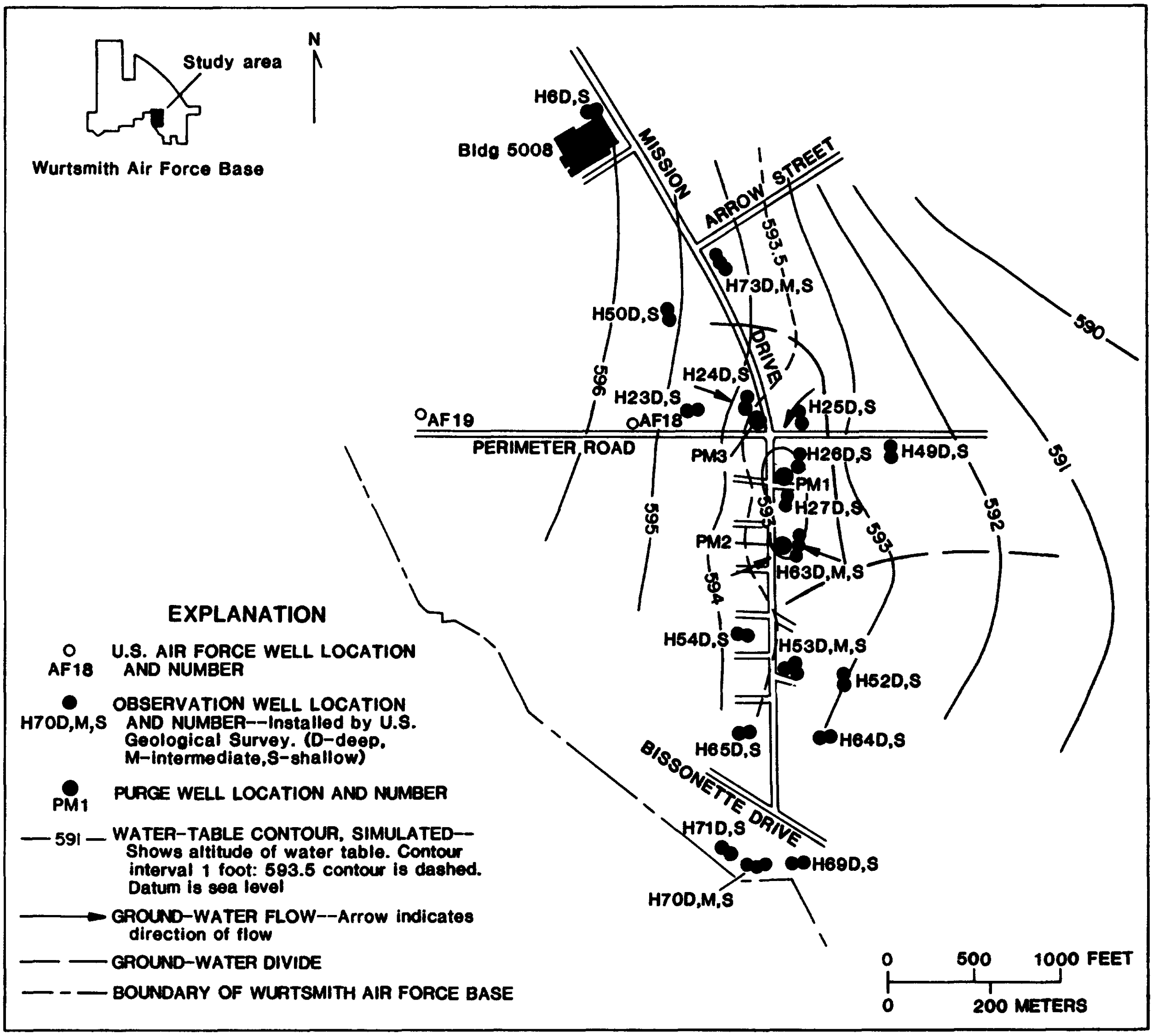
In an effort to verify the above, a simulation of possible conditions prior to purge pumping at Arrow Street was made using the Base model. An assumption was made that wells AF18 and AF19 were each pumping 300 gal/min and that other water-supply pumping on the Base had been greatly reduced; these conditions occurred in the latter part of 1977 when trichloroethylene was found in water from well AF3. The water table resulting from this simulation indicates that the direction of ground-water flow from Building 5008 would have been southeastward to Arrow Street, and then southwestward toward wells AF18 and AF19 (fig. 35). This further suggests that the source of contaminants could have been in the vicinity of Building 5008.

To determine hydrologically suitable sites for purging the aquifer, numerous model simulations were made varying the number, location, and pumping rates of hypothetical purge wells. In these simulations, AF19 was pumped at 160 gal/min; AF18 was not pumped. An initial attempt was made to keep the number of purge wells and pumping rates as low as possible. In the first simulation, hypothetical purge wells PM1, PM2, and PM3 were each pumped at 40 gal/min (fig. 36). The simulated water table indicated that much of the water in the area of highest contamination would be captured, but a necessary divide downgradient did not form. Contaminants might still continue to flow southward south of well PM2. In a following simulation, the same three wells were pumped at 100 gal/min (fig. 37). A downgradient divide developed, but depression of the water table was excessive and the cone of depression was more laterally extensive than necessary. When pumping rates were reduced (wells PM1 and PM3 pumping at 40 gal/min each and PM2 pumping at 100 gal/min) drawdown was less, yet the cone of depression was still well-defined (fig. 38). However, contaminated water in the vicinity of well H65 would not be captured by the pumping and would continue to move in a southerly direction. Another well (PM4) was then added to the system, and the water table simulated with wells PM1, PM3, and PM4 each pumping 40 gal/min and PM2 pumping 100 gal/min. Under these conditions, water from all contaminated areas south of a point midway between Arrow Street and Perimeter Road would be captured by this purge system (fig. 39). North of this point, flow would be to the Arrow Street purge system. To determine if the quantity of water pumped could be reduced, another simulation was made with all four wells pumping 40 gal/min. This simulation indicated that reduced pumping would allow contaminants to escape eastward.



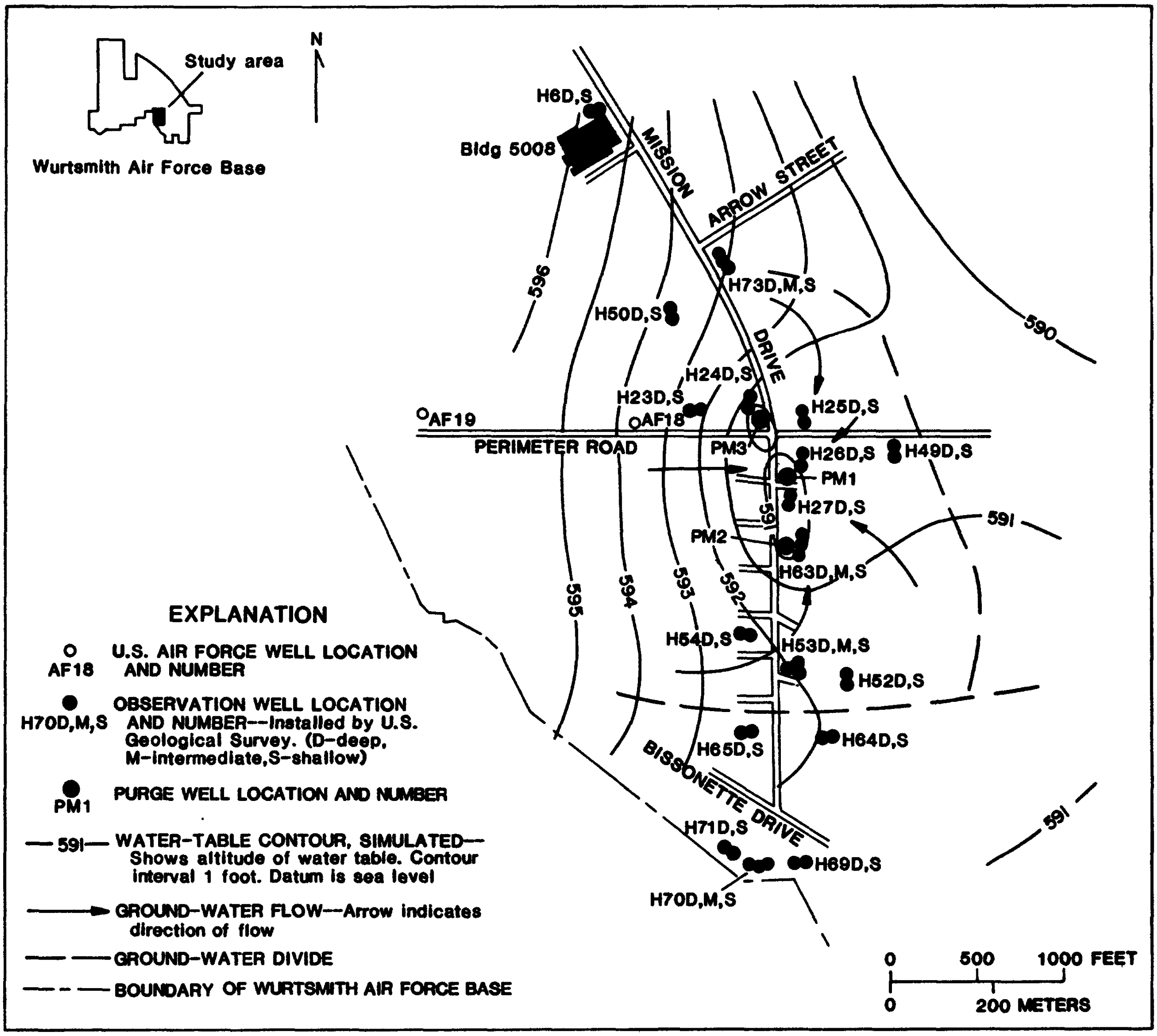
Base from Wurtsmith Air Force Base 1:7,200 map

Figure 35.--Direction of ground-water flow and altitude of water table simulated with wells AF18 and AF19 each pumping 300 gallons per minute, prior to operation of Arrow Street purge system.



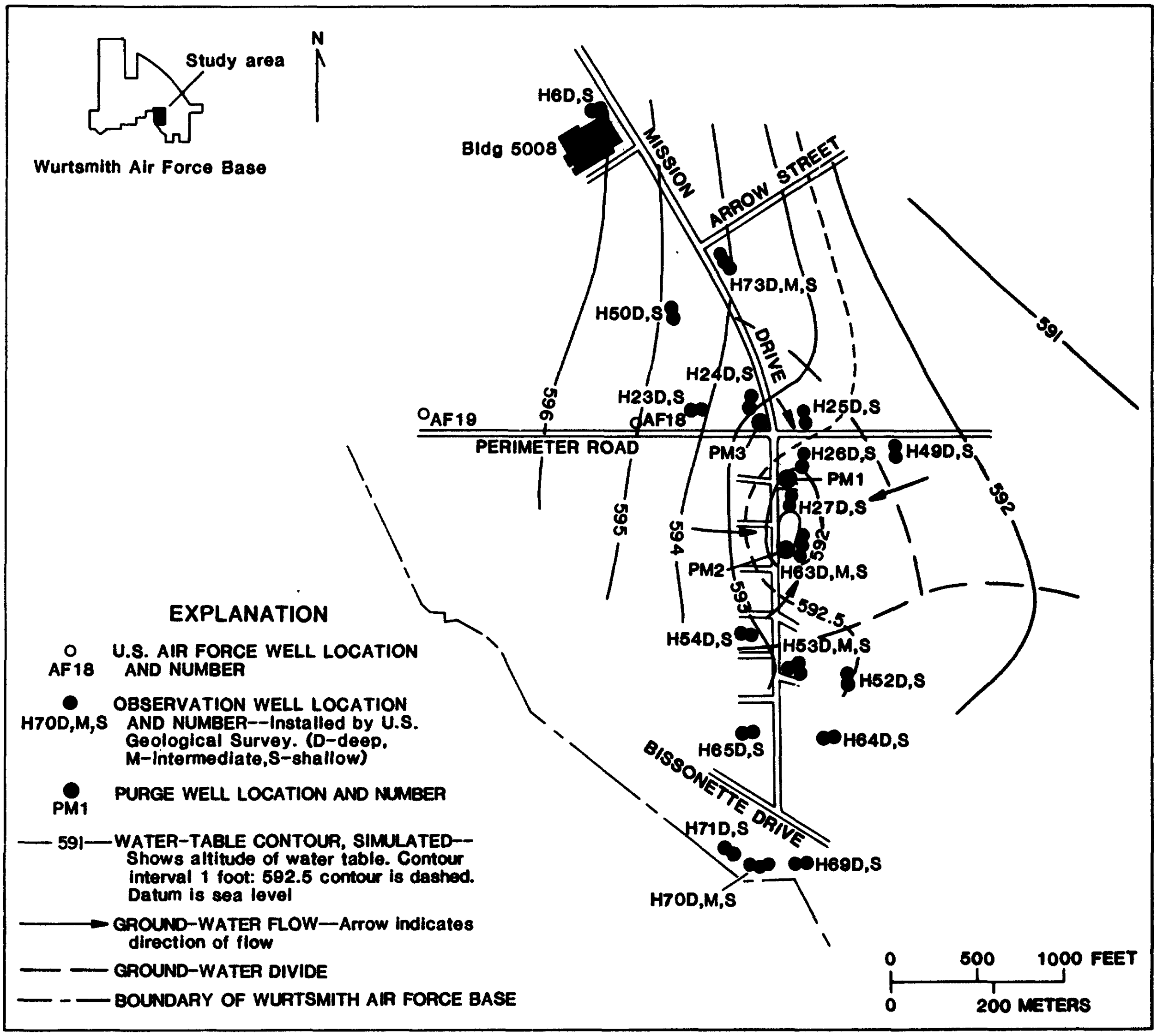
Base from Wurtsmith Air Force Base 1:7,200 map

Figure 36.--Direction of ground-water flow and altitude of water table simulated with hypothetical purge wells PM1, PM2, and PM3 each pumping 40 gallons per minute.



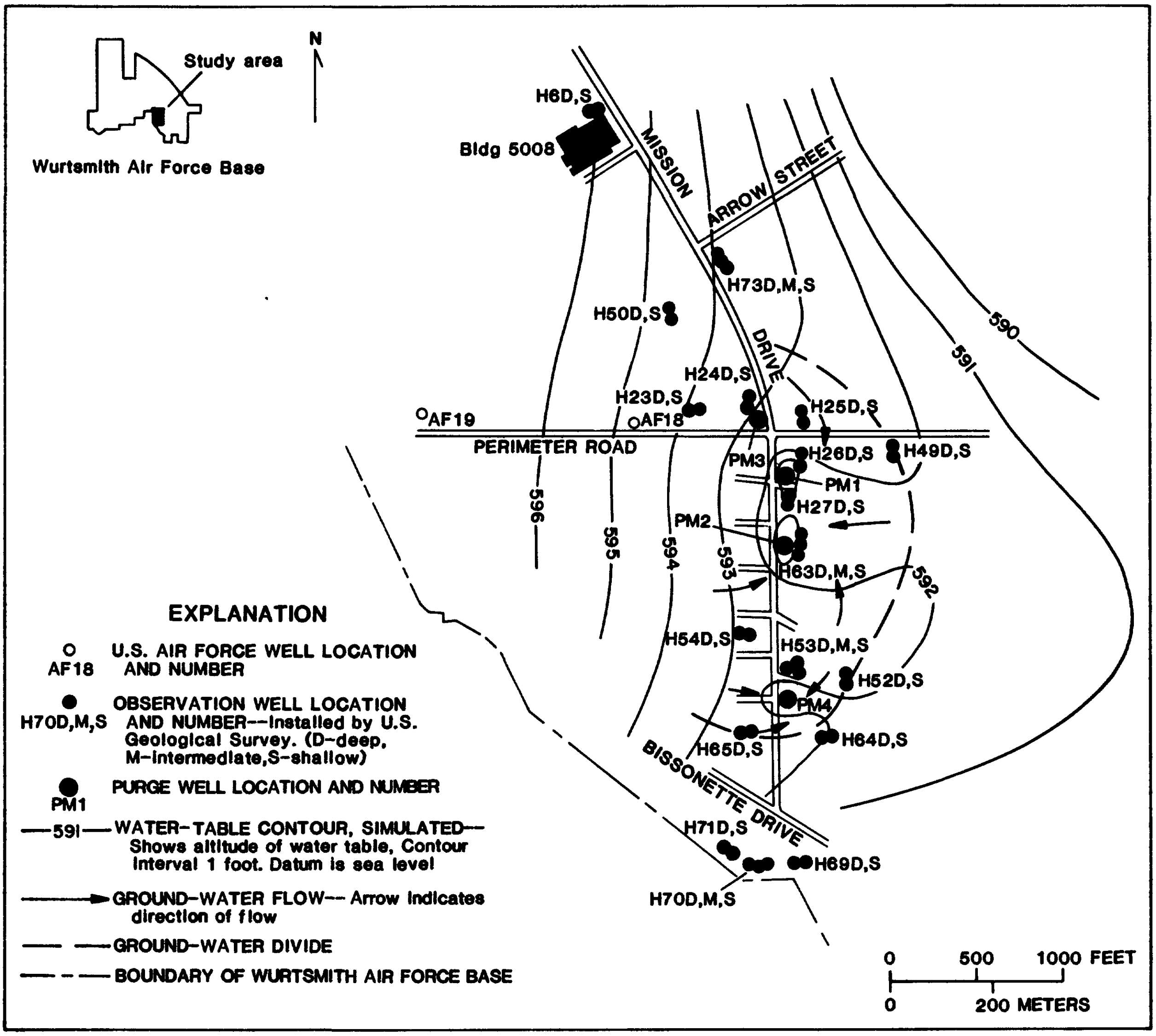
Base from Wurtsmith Air Force Base 1:7,200 map

Figure 37.--Direction of ground-water flow and altitude of water table simulated with hypothetical purge wells PM1, PM2, and PM3 each pumping 100 gallons per minute.



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 38.--Direction of ground-water flow and altitude of water table simulated with hypothetical purge wells PM1 and PM3 each pumping 40 gallons per minute, and PM2 pumping 100 gallons per minute.



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 39.--Direction of ground-water flow and altitude of water table simulated with hypothetical purge wells PM1, PM3, and PM4 each pumping 40 gallons per minute, and PM2 pumping 100 gallons per minute.

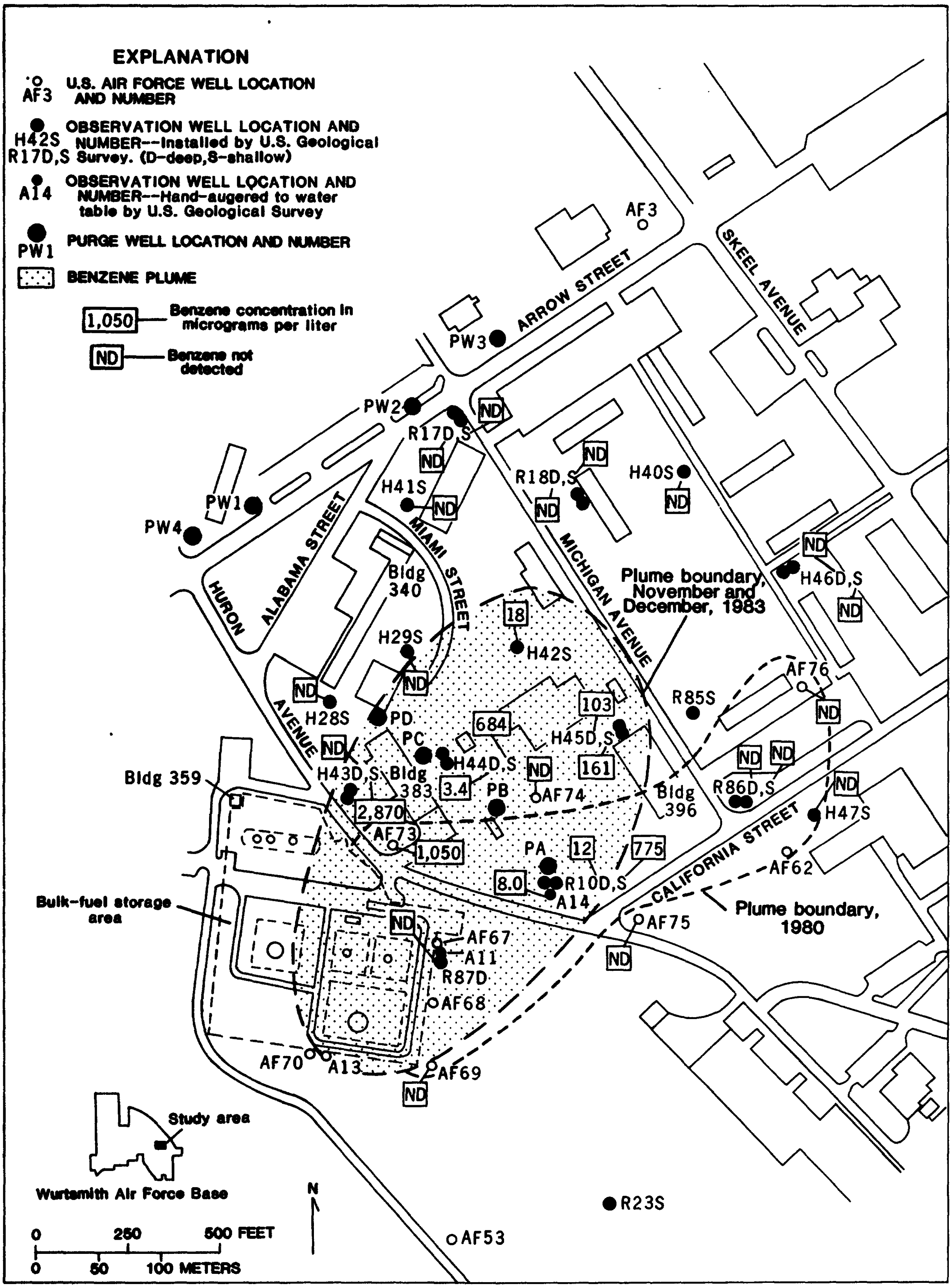
If the purge system shown on figure 39 were installed, well AF18 should not be pumped. A simulation made with wells AF18 and AF19 each pumping 300 gal/min indicates that an extensive cone of depression would occur around wells AF18 and AF19, and that contaminated water from near the Mission Drive-Perimeter Road intersection would be drawn westward. With only well AF19 pumping, however, contaminated water would not be drawn westward.

Bulk-Fuel Storage Area

Benzene Plume

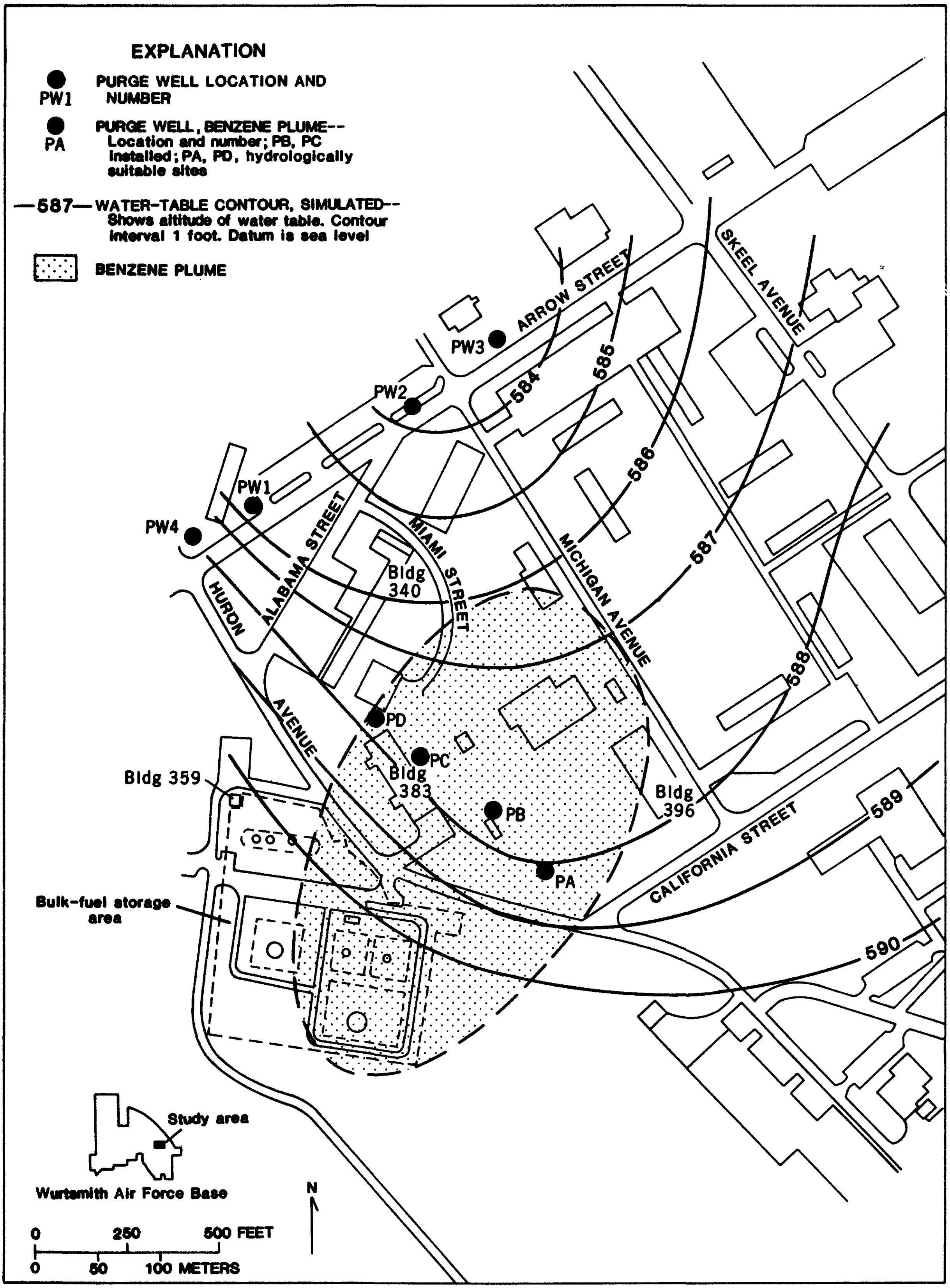
As part of previous work (Stark and others, 1983), the most hydrologically efficient sites for purging benzene and other contaminants from the aquifer near the bulk-fuel storage area were identified. Because installation of the purge system was delayed, and because purge pumping along Arrow Street has influenced the direction of benzene plume movement, additional work was undertaken in early 1984 to verify the position of the plume and to reposition, if necessary, the sites of purge wells. In the course of the investigation additional deep and shallow wells (H43D to H46D and H40S to H47S) were installed, and samples of water analyzed for volatile hydrocarbons. Figure 40 shows benzene concentrations and the boundary of the plume in November and December 1983, as well as the boundary of the plume delineated in previous work. It is apparent that, under the influence of purge pumping along Arrow Street, the benzene plume is being drawn northward. Although benzene was not detected in water from wells H28S and H29S in November 1983, benzene probably is present in the area. Analyses of water from these wells in April 1983 showed concentrations of 24 μg/L benzene and 33 μg/L ethyl benzene (H28S) and 3.3 μg/L ethyl benzene (H29S). It is possible that benzene was not detected in November 1983, because a reduction in Arrow Street purge pumping caused water levels to rise several feet in the vicinity of these wells. Samples were thus collected at a greater depth below the water table where benzene may not be present.

Based on the shift in position of the benzene plume between 1982 and 1984, the most hydrologically suitable sites for purge wells were redetermined. Several model simulations were made to choose the most appropriate locations. Sites for four possible purge wells - PA, PB, PC, and PD - are shown in figure 41. Simulations indicate that these four wells, if each is pumped at a rate of 50 gal/min, will effectively remove water from the plume and prevent farther northward movement of contaminants found near the bulk-fuel storage area. Although greater amounts of uncontaminated water would be drawn to the purge system at higher pumping rates, these new purge wells would compete for water with the Arrow Street purge system. At lesser rates, contaminated water might escape northward along the margins of the plume, if for some reason pumping in the Arrow Street system varied significantly. Also, low rates might allow contaminated water to move between the wells. The indicated benzene plume purge system is in "balance" with the Arrow Street system, provided that no major changes in the amount of water pumped by the Arrow Street system are made. Changes might alter the direction of benzene movement because the Arrow Street purge system will be the dominant one.



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 40.--Benzene concentrations and boundary of plume near bulk-fuel storage area, November and December 1983.



Base from Wurtsmith Air Force Base 1:7,200 map

Figure 41.--Hydrologically suitable locations for purge wells in benzene plume and simulated water table (four wells pumping 50 gallons per minute).

Much of the water north of the proposed purge wells, however, would continue to flow to the Arrow Street purge system. The highest concentration of benzene detected north of the proposed purge wells was 161 μg/L in water from well H45S. Judging by the fact that benzene was undetectable in water from wells H17D,S, R18D,S, H28S, H29S, and that the concentration of benzene in water from well H42S was only 18 μg/L, only low concentrations of benzene from the area north of the purge wells are likely to reach the Arrow Street purge system. Benzene detected in water from well H45S (161 μg/L) could result from incidental spillage around the despensing units just upgradient and, thus, be unrelated to the bulk-fuel storage area.

Analyses of base/neutral compounds in water from wells R10S, H43S, H44S, H45S, R86S, and R87D (fig. 40) indicate that concentrations of most were less than the detection limit of 1 μg/L (table 9). Only benzo (A) anthracene was found in water from all six wells sampled; concentrations did not exceed 4 μg/L, however. Low levels of bis (2-ethyl hexyl) phthalate were found in water from wells H43S (3 μg/L) and R86S (4 μg/L). Napthalene was found in water from wells H43S (3 μg/L) and R10S (23 μg/L). Although not part of the base/neutral priority pollutant analytical scheme, laboratory work also detected dimethyl phenol, phosporic acid-triphenyl ester (all samples), dimethyl benzene, and ethyl benzene. Highest concentrations were those of 1,4-dimethyl benzene in water from well R10S (100 μg/L) and well H45S (210 μg/L).

Table 9.--Analyses of base/neutral compounds in ground water
[Analyses by U.S. Geological Survey. Results in micrograms per liter (μg/L). ND indicates not detected.]

Well number	Date	Benzo (A) anthracene	Bis (2-ethyl hexyl) phthalate	1,4-Dimethyl benzene	2,4-Dimethyl phenol	Naphthalene	Phosphoric acid - tri-phenyl ester
R10S	November 7, 1983	2	ND	100	17	23	7.8
H43S	November 7, 1983	2	3	ND	ND	3	8.6
H44S	November 8, 1983	4	ND	ND	ND	ND	13
H45S	November 8, 1983	2	ND	210	9.2	ND	6.7
R86S	November 7, 1983	1	4	ND	ND	ND	4.9
R87D	November 8, 1983	2	ND	ND	ND	ND	5.8

Analyses of water from 15 wells (H28S to H87D) in the area show that lead and oil and grease are present in low concentrations (table 6, at end of report). Iron and manganese concentrations were unusually high in water from some of the wells. Wide variations of concentration from well to well suggest that localized bacterial action, related to the presence of the fuel substance, may be responsible. Dissolved-solids concentration, as suggested by measurements of specific conductance, also is quite variable. In such a small area this is indicative of contaminants entering the system.

Accumulation of Fuel on Ground-Water Surface

During routine sampling of wells in the bulk-fuel storage area in November 1983, fuel was found floating on the water surface in wells AF67 and AF68 (plate 2). Although water samples from these wells had contained high concentrations of volatile hydrocarbons, accumulations of fuel had not been found in prior work either by the Geological Survey or the Air Force. Because of the proximity to the fuel storage tanks, leakage of the tanks or leakage of issue and fill lines to the tanks seemed possible. Leakage of the Harrisville line, which brings JP-4 fuel to the Base, also was a possibility, although the generally downgradient position of the line seemed to indicate leakage was a less likely source. A spill of fuel several years ago, which probably drained to the ditch east of the storage tanks, also was thought a possible source.

In late November 1983, to determine areal distribution of the fuel, 2-in.-diameter wells A1-A13 were hand augered to the water table adjacent to the concrete retaining walls around the JP-4, Mogas, heating fuel, and deicer tanks (plate 3). One 2-in. well (A14) was augered to the water table between wells R10S and R10D because water from well R10S had contained the highest benzene concentration (1,309 μg/L) in the area during the 1979-81 study. Measurements of water levels confirmed that ground-water flow was northeastward from the tanks (fig. 42).

At all well locations, with the exception of that of A13, the presence of a fuel substance was obvious, either by odor or visually. Wells A1 and A11 had the most fuel; about half the samples had traces of fuel floating on the water surface in the sample bottle, although only a film existed in some. Well AF67, however, did not show the quantity observed about a month previously. Because water levels had risen during the month, it was possible that the fuel floating on the water surface was above the well screen. Well A11, augered adjacent to AF67, had its screen set so as to intercept the water table.

Water, water/fuel mixtures, or fuel from augered wells A1-A13, and wells AF67 and AF68, were sent to the laboratory for a qualitative confirmation that the substance in samples was a fuel substance (table 10). Fuel was confirmed at all sites except well A13. Subsequently samples of JP-4, Mogas, deicer, heating fuel no. 2, heating fuel no. 6, and diesel fuel no. 2, were collected from storage tanks in the bulk-fuel area and sent to the laboratory to determine a chromatographic profile of each. Along with these samples, samples of water from wells AF67 and AF73, and a sample of the fuel floating on the surface of water in well A1, also were sent. Various instrument settings and repetitive analyses of each samples indicated that the fuel found in the area was JP-4. Figure 43 shows some of the results.

In late January 1984, the investigation was expanded by augering wells A19-A22 adjacent to the JP-4 tank 7000 (plate 3). On February 9, these wells, and also wells A1 and A11, were sampled. No fuel was found on the surface of the water table near the JP-4 tank although the odor of the water and soils suggested that the concentrations in water might be high.

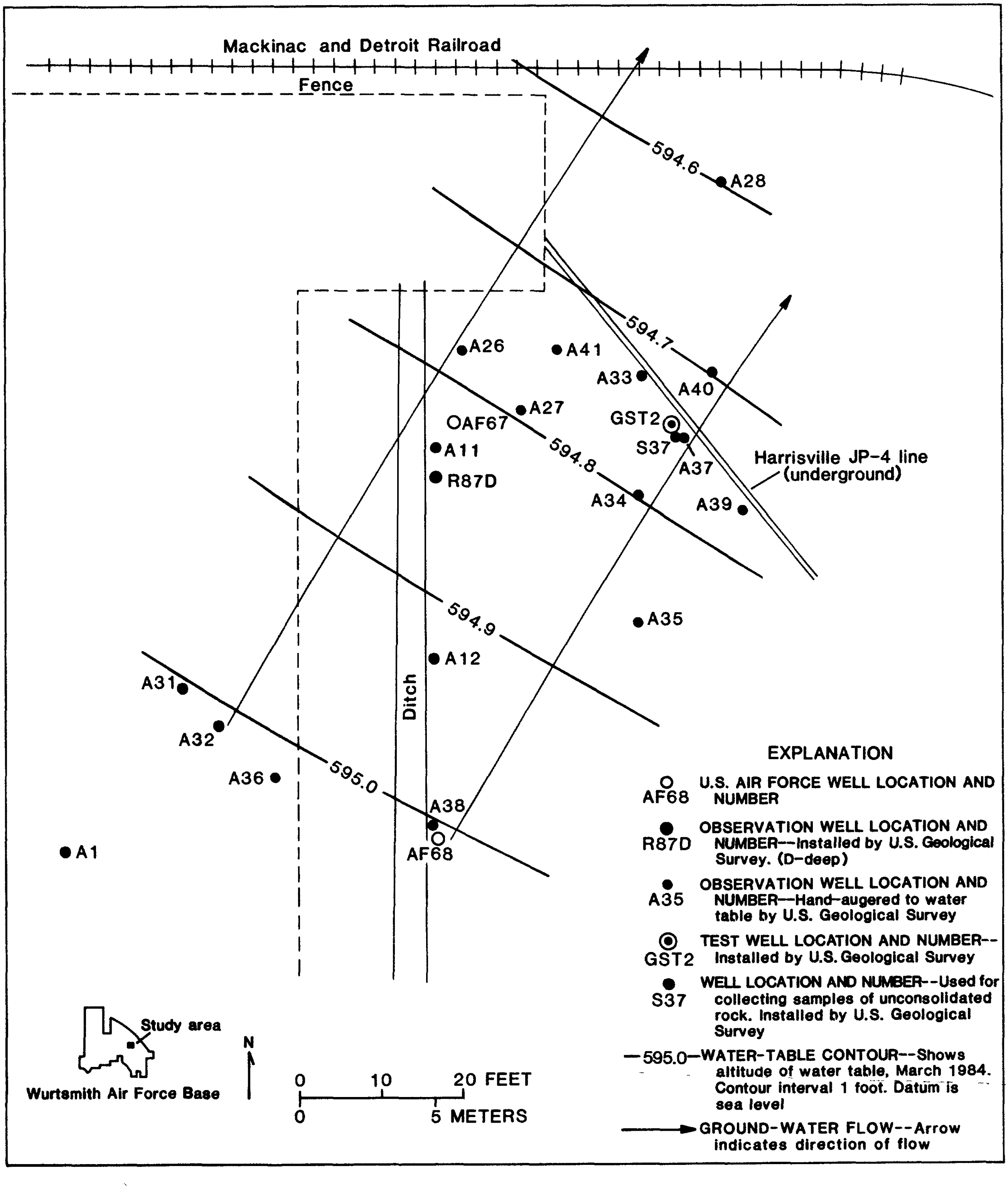


Figure 42.--Altitude of water surface and direction of ground-water flow, March 1984.

Table 10.--Chemical analyses and physical observations of volatile hydrocarbons and fuel in bulk-fuel storage area

[Analyses by U.S. Geological Survey. Results in micrograms per liter (μg/L). NA means not applicable; ND means not detected.]

Well number	Date	Tri-chloro-ethylene	1,2 Di-chloro-ethylene	Benzene	Toluene	Xylene	Ethyl benzene	Tetra-chloro-ethylene	Methylene chloride	Other
A1	November 30, 1983	NA	NA	NA	NA	NA	NA	NA	NA	(a,b)
A2	November 29, 1983	NA	NA	NA	NA	NA	NA	NA	NA	(a)
A3	November 30, 1983	NA	NA	NA	NA	NA	NA	NA	NA	(a)
A4	November 30, 1983	NA	NA	NA	NA	NA	NA	NA	NA	(a)
A5	November 30, 1983	NA	NA	NA	NA	NA	NA	NA	NA	(a)
A6	November 30, 1983	NA	NA	NA	NA	NA	NA	NA	NA	(a)
A7	November 30, 1983	NA	NA	NA	NA	NA	NA	NA	NA	(a)
A8	November 30, 1983	NA	NA	NA	NA	NA	NA	NA	NA	(a)
A9	November 30, 1983	NA	NA	NA	NA	NA	NA	NA	NA	(a)
A10	December 1, 1983	NA	NA	NA	NA	NA	NA	NA	NA	(a)
A11	November 30, 1983	NA	NA	NA	NA	NA	NA	NA	NA	(a)
A12	November 30, 1983	NA	NA	NA	NA	NA	NA	NA	NA	(a)
A13	December 1, 1983	NA	NA	NA	NA	NA	NA	NA	NA	(c)
A14	December 1, 1983	ND	ND	40	168	ND	32	ND	ND	(d)
A19	January 26, 1984	NA	NA	NA	NA	NA	NA	NA	NA	(e)
A20	January 26, 1984	NA	NA	NA	NA	NA	NA	NA	NA	(e)
A21	January 26, 1984	NA	NA	NA	NA	NA	NA	NA	NA	(e)
A22	January 26, 1984	NA	NA	NA	NA	NA	NA	NA	NA	(e)
A23	January 27, 1984	NA	NA	NA	NA	NA	NA	NA	NA	(e)
A24	January 27, 1984	NA	NA	NA	NA	NA	NA	NA	NA	(e)
A25	January 27, 1984	NA	NA	NA	NA	NA	NA	NA	NA	(e)
AF67	November 30, 1983	NA	NA	NA	NA	NA	NA	NA	NA	(a)
AF68	November 30, 1983	NA	NA	NA	NA	NA	NA	NA	NA	(a)

[a] Qualitative analysis confirmed presence of JP-4 fuel in water. Thin film accumulated on surface of water in standing sample.

[b] Approximately 0.5 ft of fuel on water surface in well casing.

[c] No odor or visual evidence of fuel.

[d] Water contained 51 μg/L chloroform.

[e] Strong odor of fuel in water and soil.

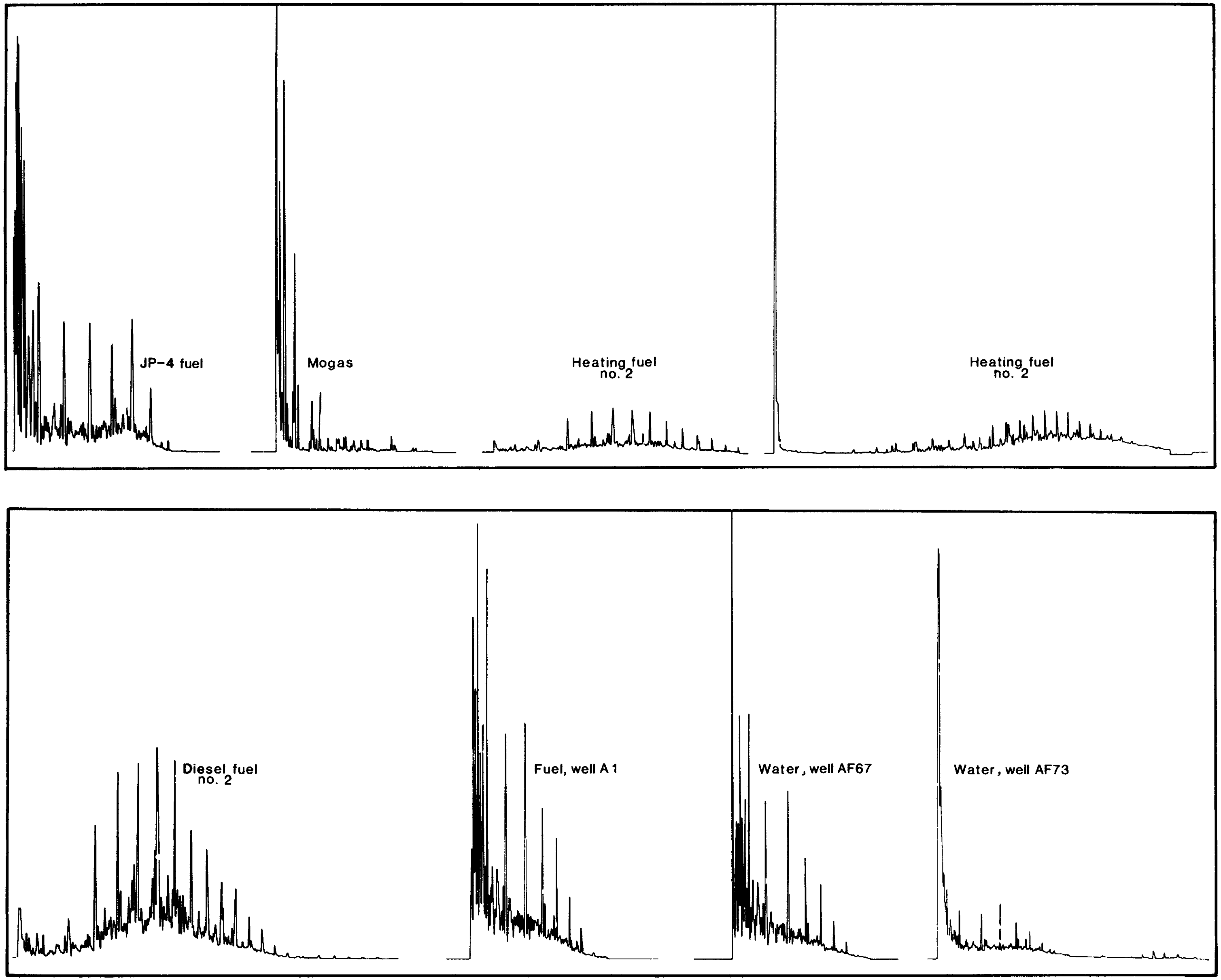


Figure 43.--Chromatograms of fuel and water, bulk-fuel storage area.

In March 1984, 2-in.-diameter wells A23-A41 were augered to the water table, and a 6-in.-diameter well, GST2, was installed with a screen intercepting the water table. At six locations soil samples were collected adjacent to the Harrisville JP-4 line in an effort to determine if the line was leaking. No evidence of this was found.[6]

Figure 44 shows the amounts of fuel found on March 20, 1984, and the screen setting relative to the water table and sea level. Tables 11 and 12 show the altitude of the water table and the amount of fuel that accumulated after well installation. Wells A1, A11, A26, A27, A33, and A37 contained the greatest amount of fuel. If the southern JP-4 tank (7000) were leaking, water in wells augered adjacent to the tank (A19-A22) should have contained fuel; they did not after a period of two weeks. Also, wells A31, A32, and A36, located between wells A1 and A11, would be expected to show fuel, because they are downgradient from the tank (Fig. 42 and plate 3). Although water levels were measured on several occasions, no fuel was found in wells A31, A32, or A36.

Because no leaks were detected in the JP-4 tank or lines, it seems probable the JP-4 on the water surface is a result of the spill that occurred several years ago, and that the JP-4 enters wells from the capillary zone. Movement of oil, fuel, and other liquid hydrocarbons less dense than water to (and subsequent dispersion in) the capillary zone has been studied by a number of investigators. In general, conclusions of most are in agreement, and differences seem to be terminological rather than substantive. Schwille (1967) concluded that oil reaching the water table depresses it slightly, and in spreading laterally, tends to rise into the capillary fringe and continue to spread at that level. Spreading ceases and the oil becomes laterally immobile when oil in the pore structure reaches a minimum that depends on the nature of the subsurface material. When oil saturation is reduced further, flow through the pores ceases, and the oil forms isolated "islands". Schwille also concluded that dispersion of the oil occurs near the top of the capillary fringe where water saturation was 75 to 85 percent, which is in agreement with the American Petroleum Institute's (1980) suggestion that no movement of oil and water occurs where the water saturation of the capillary fringe is 70 percent or greater. Shepherd (1983) concludes that the movement of liquid hydrocarbons is maximized at a level about two-thirds the height of the capillary zone above the water table. Shepherd, however, considers the top of the capillary fringe to be the level where water saturation was 100 percent. He also concludes that liquid hydrocarbons accumulate on the water surface in wells by entering the well screen in a mobile layer that ranges in thickness from about 4 mm (0.16 in.) in coarse gravel to about 40 mm (1.6 in.) in fine sand or silt. As liquid hydrocarbons accumulate, water in the screen is displaced, and accumulation continues until no additional water can be forced through the screen to the surrounding aquifer. Shepherd also states that movement of liquid hydrocarbons ceases when the hydrostatic potential for spreading is balanced by the resistence of capillary water to immiscible

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[6] Subsequent uncovering of the line by the Air Force confirmed that the line was not leaking.

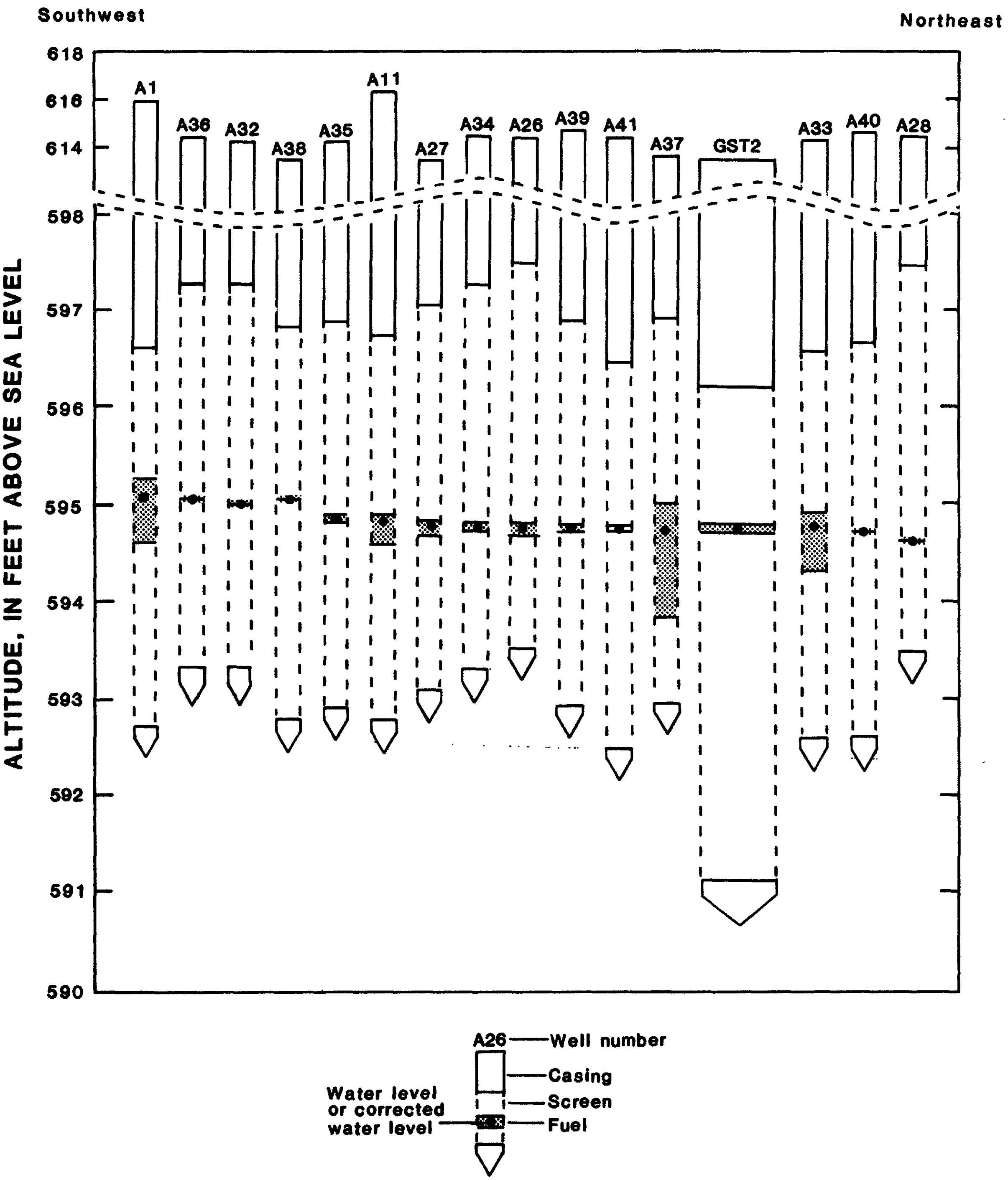

Figure 44.--Accumulation of JP-4 on water surface of wells in bulk-fuel storage area, March 20, 1984. (Well locations are shown on plate 3.)

Table 11.--Altitude of water table in bulk-fuel storage area
[NM means not measured. -- means well not installed.]

Well		Altitude of water table, in feet [Water levels are corrected for density of JP-4]															
Number	Altitude of measuring point (ft above sl)	Nov. 7, 1983	Jan. 26, 1984	Feb. 9, 1984	Mar. 7, 1984	Mar. 8, 1984	Mar. 20, 1984	Mar. 28, 1984	Mar. 29, 1984	Apr. 9, 1984	Apr. 10, 1984	Apr. 11, 1984	Apr. 24, 1984	June 8, 1984	July 10, 1984	Aug. 30, 1984	Sept. 18, 1984
A1	616.18	--	NM	NM	NM	NM	595.12	NM	595.51	NM	595.26	NM	NM	595.54	NM	594.83	594.80
A11	616.46	--	NM	NM	594.84	NM	594.84	595.23	NM	594.92	NM	NM	NM	595.29	NM	594.93	594.58
A14	615.59	--	NM	NM	NM	NM	NM	594.53	NM	NM	NM	NM	NM	NM	NM	NM	NM
A26	614.54	--	--	--	594.77	NM	594.77	NM	NM	NM	NM	NM	NM	NM	NM	594.68	594.52
A27	613.69	--	--	--	594.82	NM	594.81	NM	NM	594.88	NM	NM	NM	595.25	NM	594.63	594.50
A28	614.56	--	--	--	NM	NM	594.61	594.89	NM	NM	NM	NM	NM	NM	NM	594.34	594.29
A32	614.49	--	--	--	NM	NM	595.02	NM	NM	NM	595.17	NM	NM	595.43	NM	594.72	594.69
A33	614.25	--	--	--	594.76	NM	594.75	595.06	NM	594.83	NM	NM	NM	595.19	594.85	594.52	594.44
A34	614.72	--	--	--	594.80	NM	594.80	NM	NM	NM	NM	NM	NM	NM	NM	594.59	594.51
A35	614.41	--	--	--	NM	NM	594.88	NM	NM	NM	NM	NM	NM	NM	NM	594.66	594.58
A36	614.64	--	--	--	NM	NM	595.06	NM	NM	NM	595.22	NM	NM	NM	NM	594.77	594.74
A37	613.96	--	--	--	594.73	NM	594.74	595.07	NM	594.82	NM	594.83	595.04	595.21	594.85	594.49	594.45
A38	613.47	--	--	--	NM	NM	595.05	NM	NM	NM	NM	NM	NM	NM	NM	594.77	594.72
A39	614.90	--	--	--	NM	594.78	594.77	NM	NM	NM	NM	NM	NM	595.22	NM	NM	594.48
A40	614.75	--	--	--	--	594.73	594.72	595.02	NM	594.81	NM	NM	NM	NM	NM	594.49	594.43
A41	614.69	--	--	--	--	594.77	594.77	595.11	NM	NM	NM	NM	NM	NM	NM	594.56	594.46
GST2	613.56	--	--	--	--	NM	594.76	595.07	NM	594.84	594.95	594.95	595.09	595.22	594.88	NM	594.48
AF67	614.03	594.25	--	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
AF68	615.34	NM	--	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM

displacement. Figure 45 is a generalized description of the dispersion of a liquid hydrocarbon from a surface spill drawn from the work of investigators cited above. For purposes of illustration, the top of the capillary fringe has been considered to be that point where the mean water saturation is about 75 percent (Bear, 1979).

Accumulation of fuel in wells by means discussed above is supported by the fact that a correction for JP-4 density results in water levels that match the level of the surrounding water table. This is shown by wells GST2 and A37 on figure 44, which are 4 ft apart. Further support for the presence of JP-4 in the capillary fringe is also indicated by comparing the amount of JP-4 in wells A33, GST2, and A37 on March 20, 1984, and noting that the screen setting of well GST2 is about 0.4 ft lower than in the other two wells.

Table 12.--Accumulation of fuel in wells in bulk-fuel storage area
[Results are in feet. D means detected but not measured,
ND means not detected, NM means not measured, and
-- means well not installed.]

Well number	Nov. 7, 1983	Jan. 26, 1984	Feb. 9, 1984	Mar. 7, 1984	Mar. 8, 1984	Mar. 20, 1984	Mar. 28, 1984	Mar. 29, 1984	Apr. 9, 1984	Apr. 10, 1984	Apr. 11, 1984	Apr. 24, 1984	June 8, 1984	July 10, 1984	Aug. 30, 1984	Sept. 18, 1984
A1	--	0.42	0.63	NM	NM	0.63	NM	0.01	NM	0.21	NM	NM	0.00	NM	0.75	1.00
A11	--	.46	.72	0.16	NM	.28	0.12	NM	0.10	NM	NM	NM	.08	NM	.43	.22
A14	--	NM	ND	NM	NM	NM	ND	NM	NM	NM	NM	NM	NM	NM	NM	NM
A26	--	--	--	D	D	.11	NM	NM	NM	NM	NM	NM	NM	NM	1.10	1.13
A27	--	--	--	.10	NM	.14	NM	NM	.02	NM	NM	NM	.00	NM	.50	.64
A28	--	--	--	NM	NM	.01	.00	NM	NM	NM	NM	NM	NM	NM	.00	.00
A32	--	--	--	ND	ND	ND	NM	NM	NM	.00	NM	NM	.00	NM	.00	.00
A33	--	--	--	.44	NM	.59	ND	NM	.07	NM	NM	NM	.01	0.18	.38	.53
A34	--	--	--	.02	ND	.05	ND	NM	NM	NM	NM	NM	NM	NM	.13	.14
A35	--	--	--	ND	ND	.08	ND	NM	NM	NM	NM	NM	NM	NM	.09	.08
A36	--	--	--	ND	ND	ND	ND	NM	NM	.00	NM	NM	NM	NM	.00	.01
A37	--	--	--	.95	0.95	1.17	.11	NM	.40	NM	0.37	0.13	.05	.60	1.29	1.27
A38	--	--	--	ND	ND	ND	ND	NM	NM	NM	NM	NM	NM	NM	.00	.03
A39	--	--	--	ND	ND	.02	ND	NM	NM	NM	NM	NM	.00	NM	.05	.06
A40	--	--	--	--	ND	.01	ND	NM	.01	NM	NM	NM	NM	NM	.00	.28
A41	--	--	--	--	ND	.02	ND	NM	NM	NM	NM	NM	NM	NM	.00	.04
GST2	--	--	--	--	.02	.03	ND	NM	.00	.00	.00	.02	.13	.00	.00	.01
AF67	1.25	ND	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
AF68	D	ND	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM

Data collected on March 28 and March 29, 1984, indicated that the fuel had moved out of the screens. Fuel in well A1 decreased from about 0.6 ft on March 20 to about 0.01 ft on March 29; fuel in well A37 decreased from 1.17 ft to 0.11 ft. During the week of March 19 substantial rain, as well as snow, fell. From March 20 to March 28 the water level in the area rose 0.4 ft. It is probable that, as the zone containing JP-4 became water saturated, the fuel was immobilized, and thus no longer drained to the wells. If immobilization did occur, it suggests that the occasional increase in the moisture content of the capillary zone is one process tending to retain JP-4 in the area. Undoubtedly, the ditch running south from the oil-water separator has an effect on the fuel and its migration in the system, particularly just adjacent to the ditch. Water discharged to the ditch from the oil-water separator over an extended period, and water from surface drainage to the ditch, probably spreads laterally before recharging the water table, and increases the moisture content of the capillary zone. This could also be a factor in immobilizing fuel in the area. The fact that wells A28, A29, and A14 have shown no fuel at the surface of the water table further suggests that movement of JP-4 downgradient has been restricted. Water of well A14, however, does contain dissolved hydrocarbons characteristic of a fuel substance.

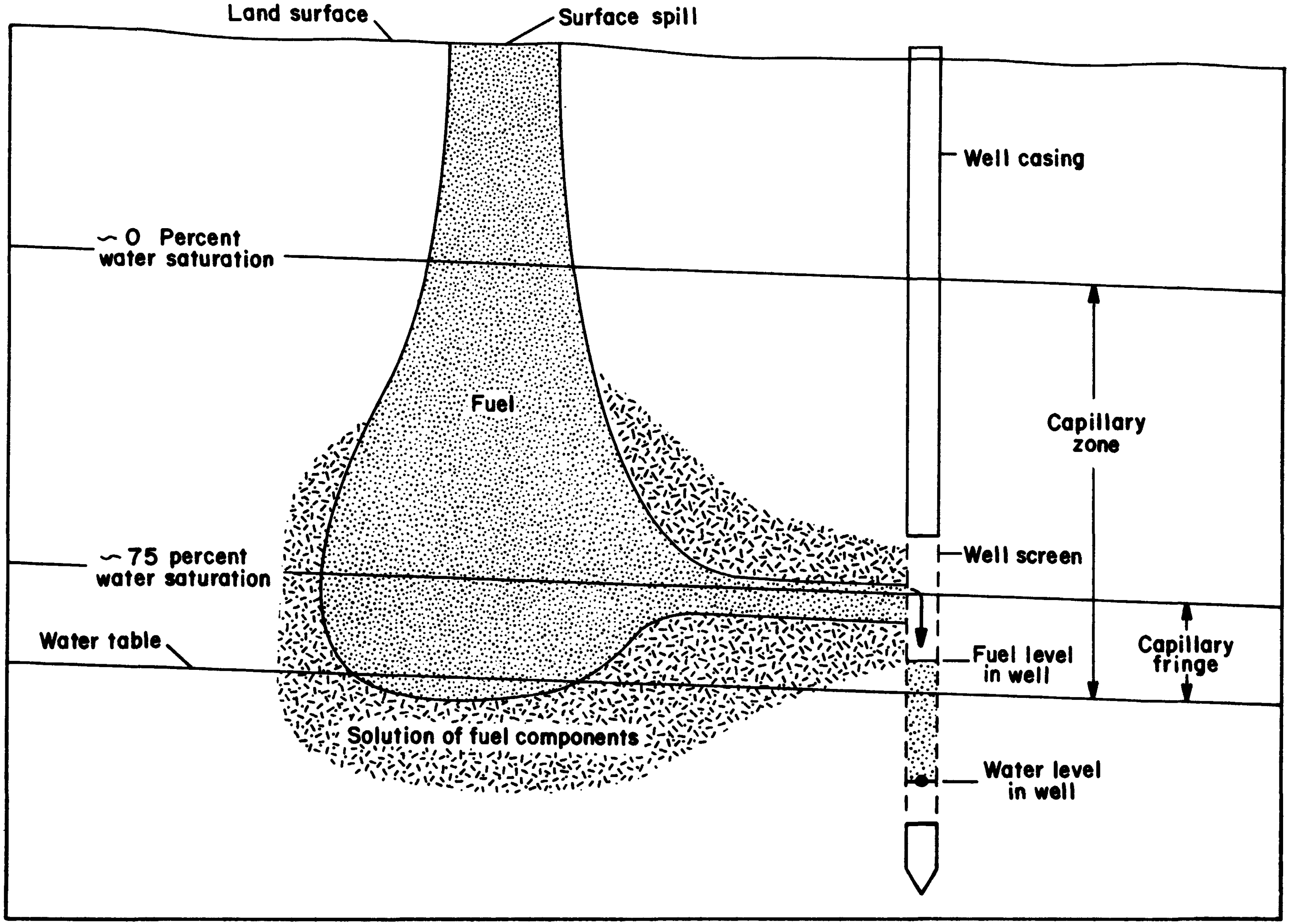

Figure 45.--Generalized distribution of a fuel substance near the water table resulting from a surface spill.

Data seem to indicate that only the more soluble components are entering the ground-water system. Base/neutral analyses (table 9) support this view. Many of the higher molecular weight hydrocarbons are less mobile in a ground-water system, and also may be more easily attacked by bacteria. Bacterial action is quite evident. On March 20, 1984, precipitation of iron from water pumped from the surface of the water table and collected in 150 gal containers began shortly after collection started. After 24 hours, the water had the characteristic rust color of iron suspended in water. Although analyses were not made, the amount in the water could easily have exceeded the 29,000 μg/L found in water from well R10S located about 250 ft downgradient (table 6). It is probable that biodegradation of JP-4 causes the depletion of dissolved oxygen, which permits iron and manganese, common in these deposits, to be dissolved. Precipitation occurs where the water comes in contact with the atmosphere.

Figure 46 shows the result of pumping well GST2 on March 20-22. Initially, 120 gal of water were pumped from the well to see if the fuel level in well A37 (4 ft away) would change. Only a small change in the amount of fuel occurred. All fuel was then pumped from the surface of well A37, after which 87 gal of water-fuel mixture was withdrawn during the next 6 hours to see if fuel would drain to well A37 when a small cone was created. At the end of the period more than 0.7 ft of fuel had collected on the water table. The fuel on the surface was again pumped off and the water and fuel levels left to recover naturally. The fuel level went up slowly. Later, water only was pumped from the well; for a short period following pumping, fuel seemed to drain to the well faster. The above data support the view that movement of fuel in the capillary fringe is, in general, quite slow.

In late April 1984, well GST2 was deepened 10 ft and a 20-ft well screen installed so as to extend above and below the previous screen setting. This permitted withdrawal of more water from the well and assured the interception of any thin zone of JP-4 that might be present. The amount of fuel in the wells was monitored as water levels seasonally rose and declined.

Table 12 gives the amount of fuel measured in wells November 1983 to September 1984. Water levels have been corrected for the density of JP-4 if it was present. Figure 47 shows the area where accumulations of JP-4 on the water surface were greatest during the period. Most of the fuel is found between the ditch and the Harrisville JP-4 line. The only exception is at the site of well A1, which is upgradient and west of the ditch, nearer JP-4 storage tank 7000.

Figure 48 shows the amount of fuel found on the water surface in wells on September 18, 1984; figure 49 shows the direction of ground-water flow on the same date. The maximum amount of fuel, 1.27 ft, was found in well A37. Well GST2, about 4 ft from well A37, contained only 0.01 ft of fuel. Increasing the screened interval in GST2 in April did not result in the accumulation of fuel in well GST2. This suggests that the fuel does not form a continuous layer throughout the area, but is present in small isolated pockets.

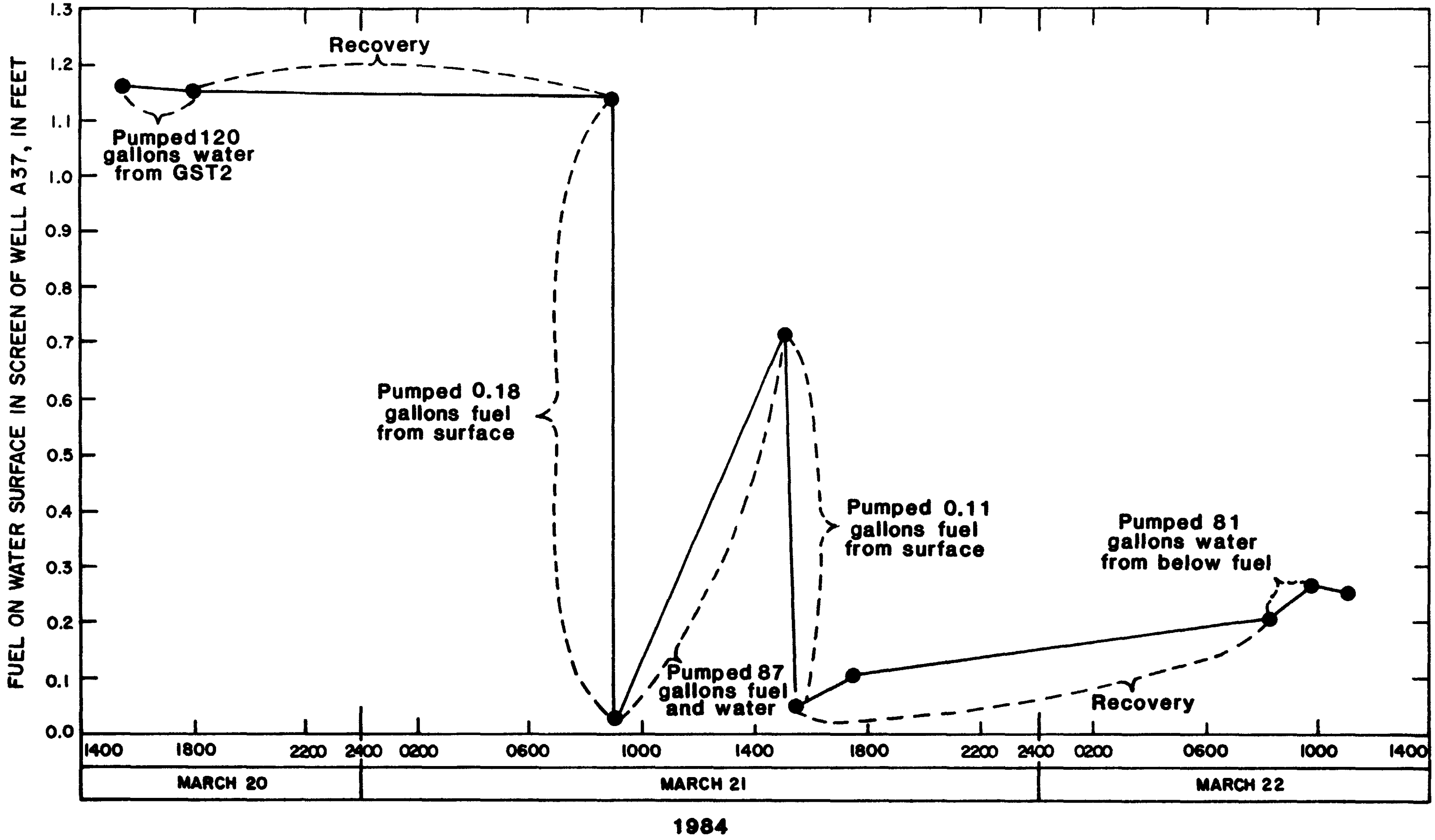

Figure 46.--Fuel-water withdrawal relations, well A37.

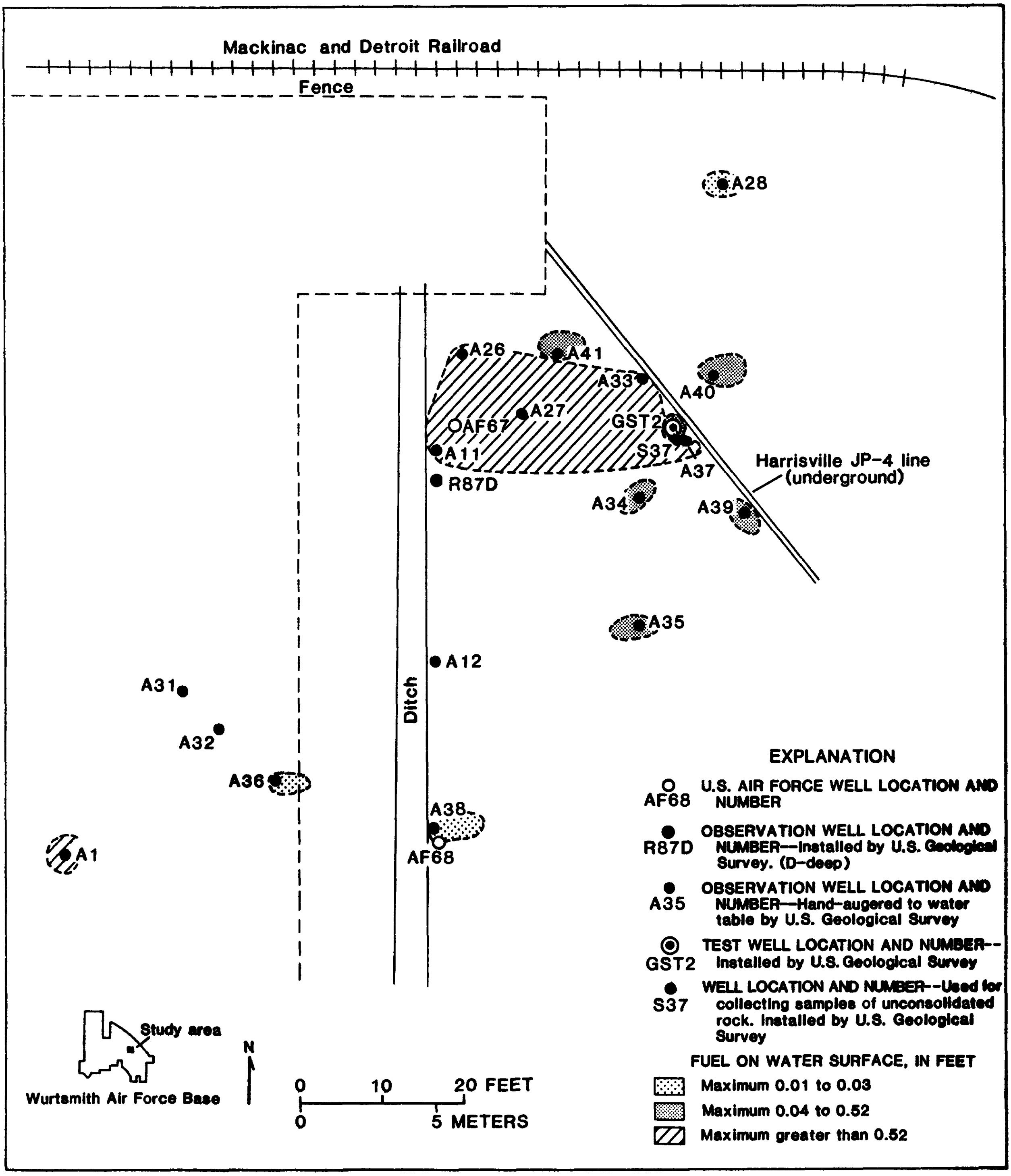

Figure 47.--Areas of accumulation of fuel on water surface.

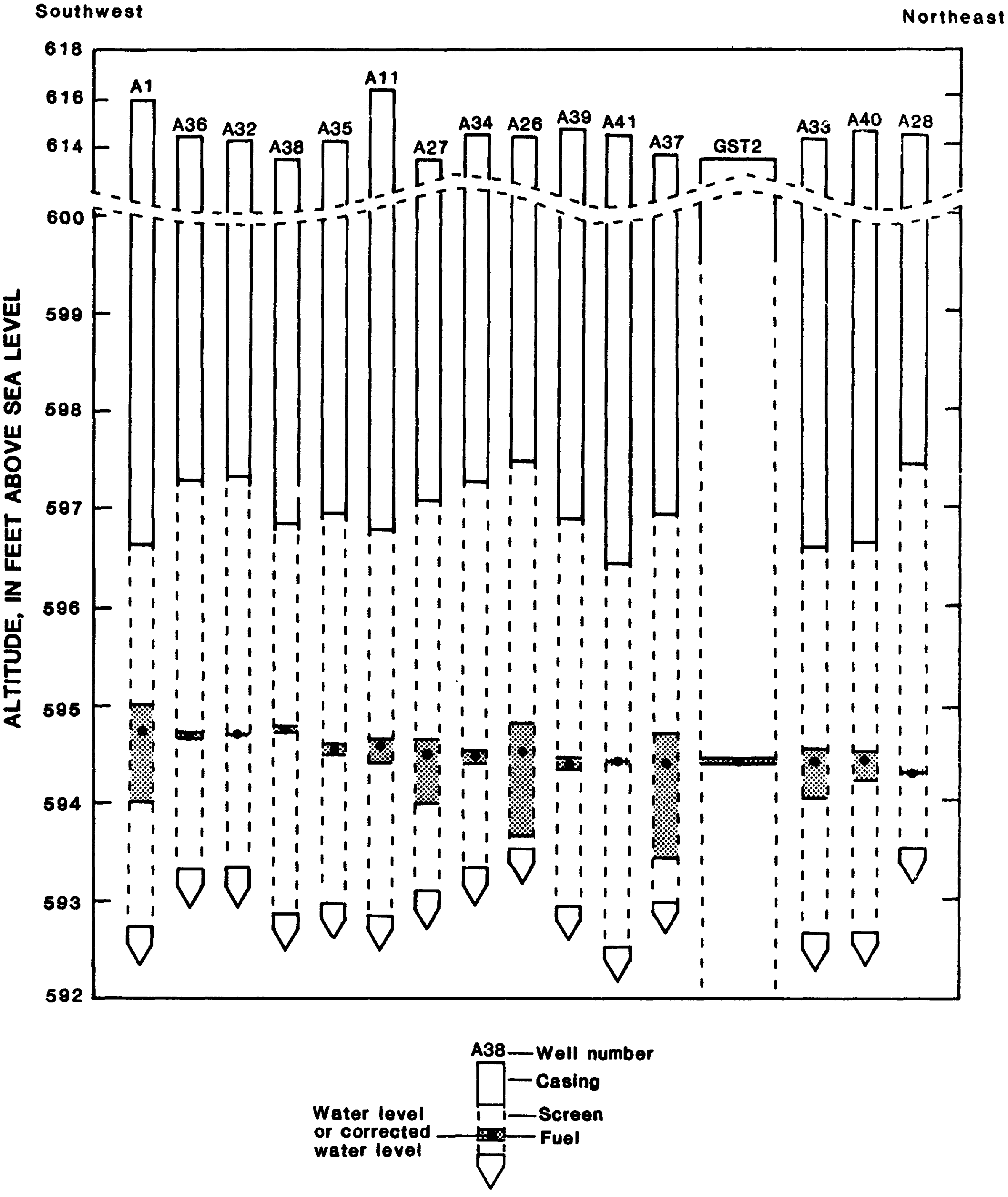

Figure 48.--Accumulation of JP-4 on water surface in wells, September 18, 1984. (Well locations are shown on plate 3.)

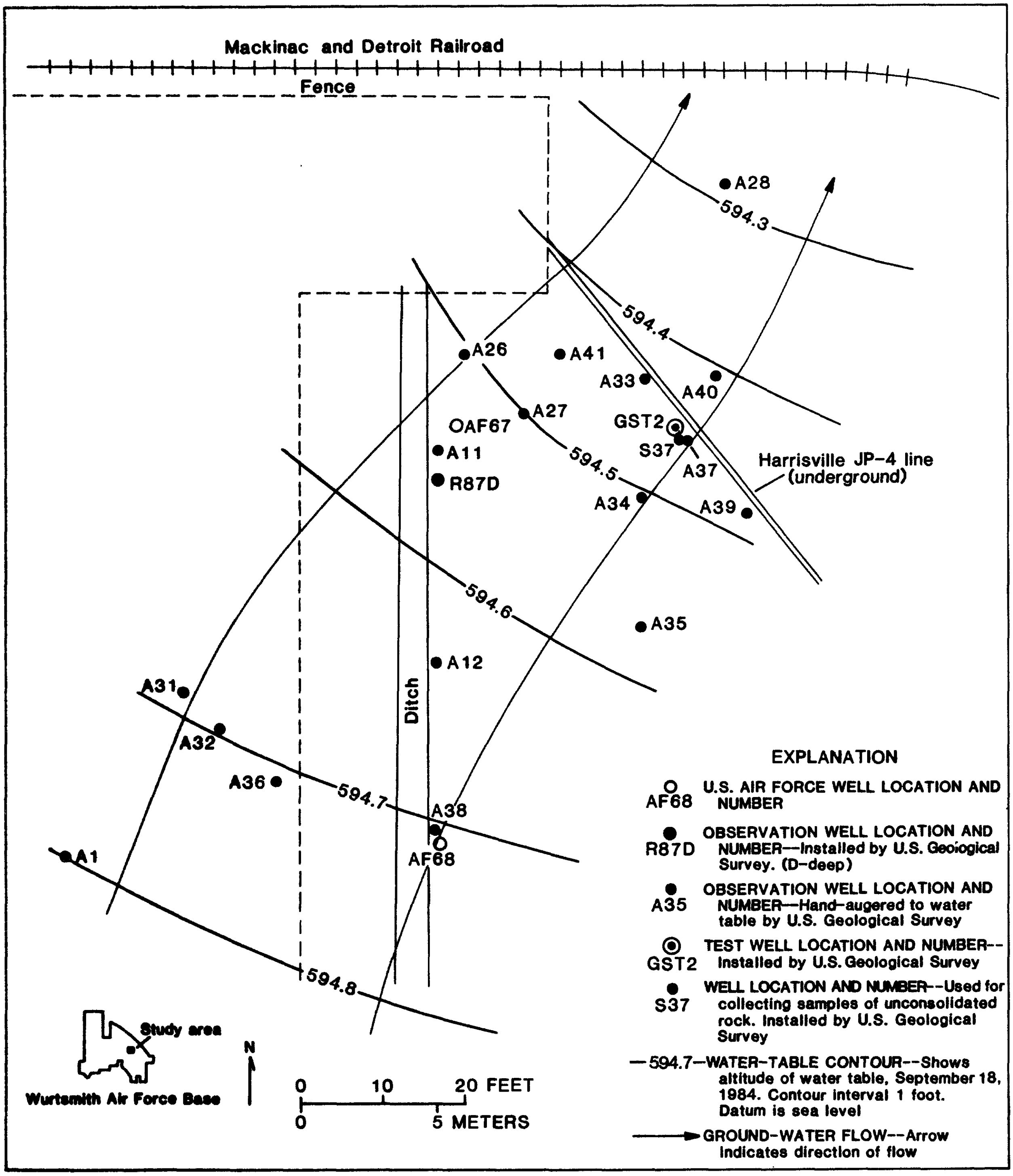

Figure 49.--Altitude of water surface and direction of ground-water flow, September 18, 1984.

Figure 50 shows the relation between the amount of fuel on the water surface and the altitude of the water table in wells A1, A11, A33, and A37 between March and September 1984. The plotted water levels have been corrected for the density of JP-4. It seems clear that fuel drained to the wells when water levels in the area just east of the ditch fell below an altitude of about 595.2 to 595.3 above sea level.

Samples of soil were collected from an auger hole, S37, about 1 ft from well A37. Cores were obtained at 0.25-ft intervals beginning 1.75 ft above, and continuing to, the water table. A single core representing the first 0.25 ft below the water table was also collected. At the time core samples were collected, well A37 had accumulated more than 1 ft of fuel on the surface of the water in the well screen. Cores were analyzed for fuel content using a gas chromatograph-mass spectrometer system equipped with a flame ionization detector and results were compared to a JP-4 standard. Separate portions of each core were also weighed, dried, and weighed again to determine the moisture plus fuel content. Figure 51 shows the results. The JP-4 content is highest just above the water table. The zone of fuel moving to wells is probably between the top of the capillary fringe (0.4 to 0.5 ft above the water table, altitude about 594.9), and the altitudes of 595.2 to 595.3 previously cited as those above which no fuel accumulated in wells. According to Shepherd (1983), coarse to medium sand, such as that at Wurtsmith Air Force Base, will allow fuel to flow in a mobile layer about 12 mm (0.47 in.) thick.

In an attempt to find out the effect that purging of the aquifer would have on fuel levels in wells, particularly the level in well A37, well GST2 was pumped about 22½ hours, from 0934 on September 19 to 0817 on September 20. For the first 4 hours, the pumping rate was 36 gal/min; thereafter, the rate was 28.5 gal/min. Figure 52 shows the effect of pumping well GST2 on the fuel level in well A37. Although the water level in A37 had been drawn down about 0.7 ft by 0740 on September 20 just prior to turning pumps off at 0817, the fuel level had decreased only 0.18 ft during the first 22 hours of pumping. Once pumps were off and water levels began to rise, a more rapid loss in fuel took place. Within the next 2 hours, 0.30 ft was lost from the water surface. No adequate explanation for this is evident. As the water table recovered, fuel moved out of the screen into the aquifer. It is possible that, if lowering the water table by 0.7 ft in well A37 also caused a sufficient decrease in the moisture content of the soil near the initial water table, fuel could have moved into the aquifer as the water level returned to its initial position.

At intervals during pumping of well GST2, samples of water were collected for analysis of volatile hydrocarbons, and specific conductance and iron were measured. These data are given in table 13. They indicate that major changes

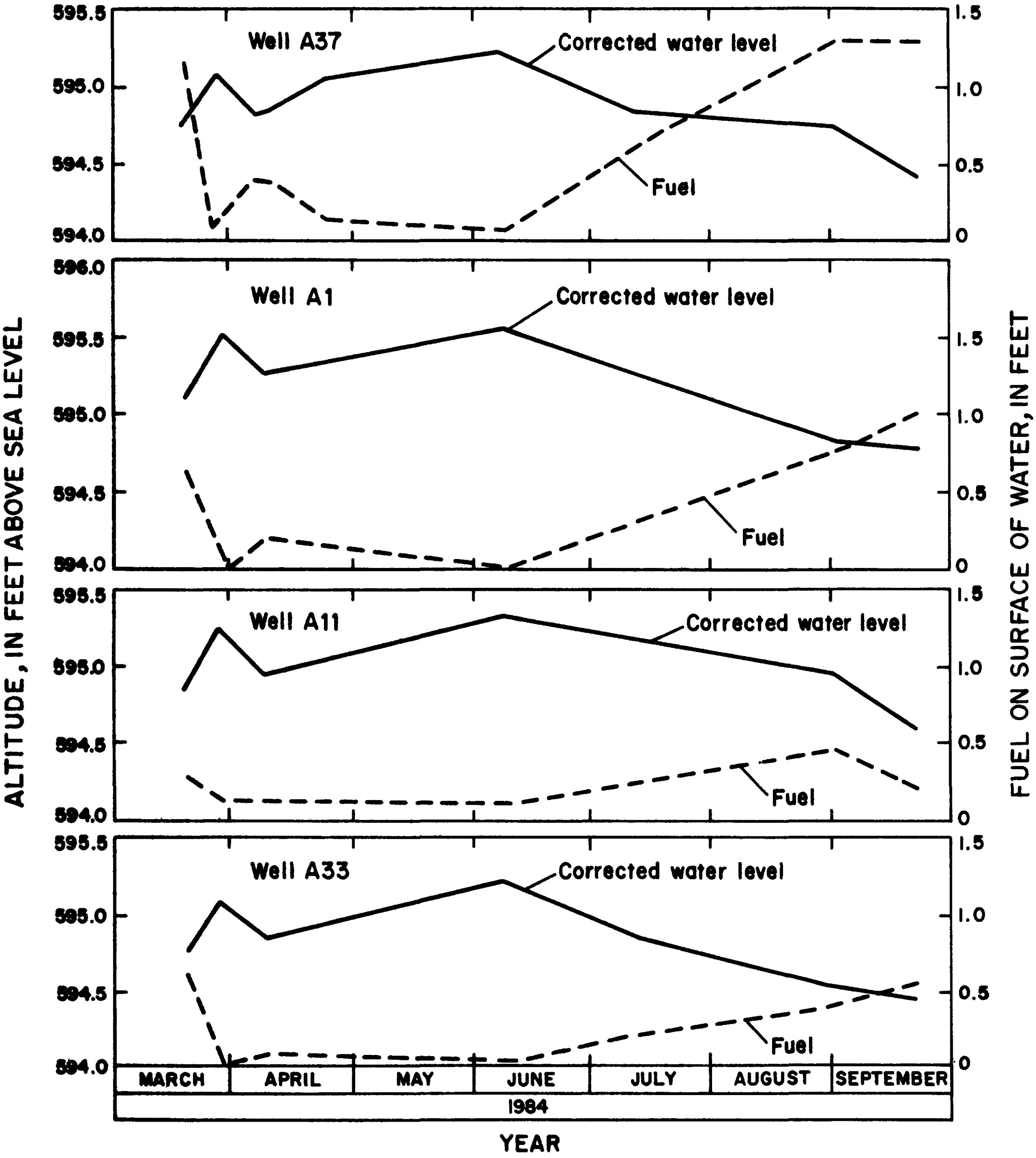

Figure 50.--Relation of the amount of JP-4 on water surface to the altitude of the water table.

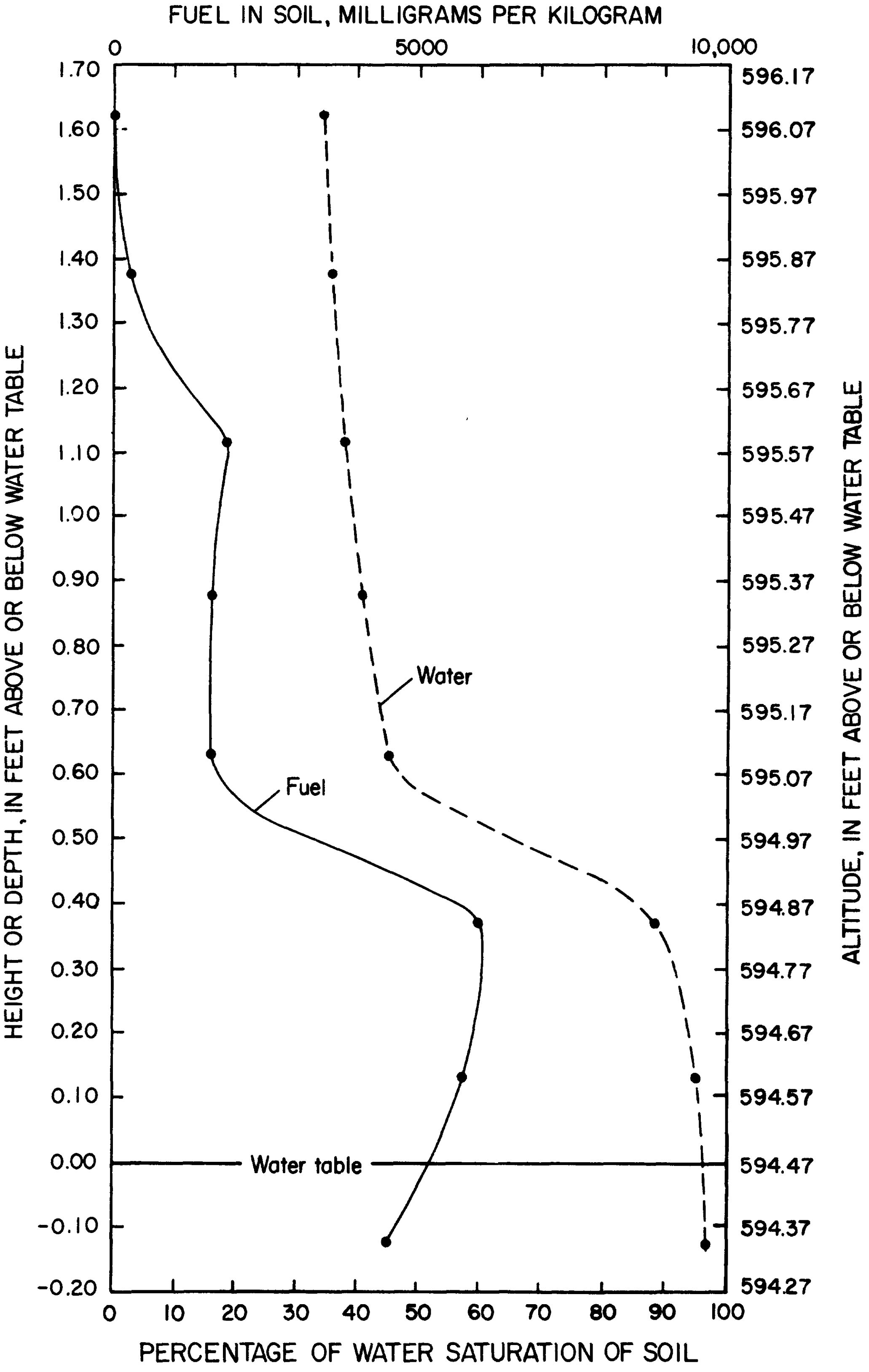

Figure 51.--Water and fuel in auger hole S37, September 18, 1984.

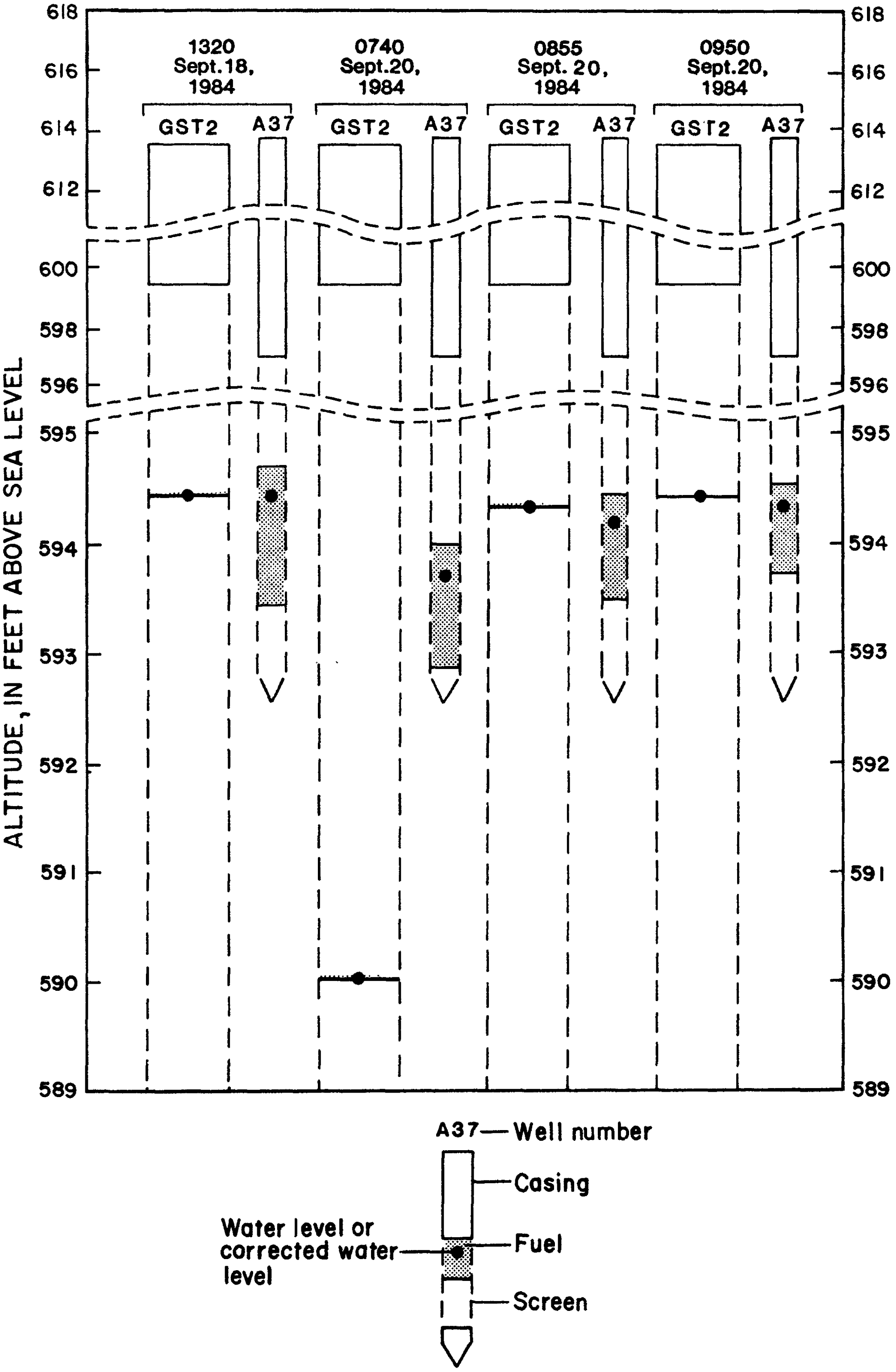

Figure 52.--Relation of water and fuel levels in wells GST2 and A37 before, during, and after purging. (Well locations are shown on plate 3.)

Table 13.--Chemical analyses of water from well GST2
[Analyses by U.S. Geological Survey. ND means not detected.]

Date	Time	Specific conductance (μmhos)	Iron,[a] total (mg/L)	Benzene (μg/L)	Toluene (μg/L)	Ethyl benzene (μg/L)	Xylene (μg/L)	Trichloroethylene (μg/L)	Dichloroethylene (μg/L)	Tetrachloroethylene (μg/L)
September 19, 1984	0941	703	13.5	360	ND	507	2,940	ND	ND	ND
Do	1043	725	15.0	227	ND	578	3,220	ND	ND	ND
Do	1508	806	19.0	319	ND	634	3,670	ND	ND	ND
Do	2352	719	16.5	241	ND	540	3,380	ND	ND	123
September 20, 1984	0810	706	14.5	223	ND	436	3,400	ND	ND	ND

[a] Field determination

in the chemical characteristics of the water did not occur during pumping, although slightly higher concentrations of volatile hydrocarbons did occur about 5½ hours after pumping started. This suggests that the removal of the fuel trapped in the capillary fringe by purging is likely to be difficult. Analyses of purged water suggest that there probably has been a decrease in the release of some of the more hazardous components of the fuel to the aquifer, if the analyses are compared to those of Stark and others (1983). Also, the proportions of benzene, toluene, and xylene in the ground water are different from the proportions in pure JP-4. Toluene is not detected in the water, which might suggest selective biodegradation just at the water table (Wilson and others, 1983). Bacterial action is obvious and its occurrence is supported by iron analyses (table 13).

Based on the above investigations, it is believed that fuel accumulating on the surface of water near the bulk-fuel storage area originated from a spill that occurred several years ago. The fuel has spread to its maximum extent, and is now in small isolated pockets in the area. Ground water is being contaminated by the solution of the more soluble components such as benzene, but bacterial action is vigorous and may be the reason toluene is low in the benzene plume. Because the water table has risen and fallen over a several year period, JP-4 is now distributed throughout the capillary fringe as described by Schwille (1971). Fluctuations in the water table also have facilitated a very slow downgradient movement of the JP-4. Figure 53 illustrated what was believed to the situation in 1984.

No estimate can be made of the amount of JP-4 on the surface of the water table in the bulk-fuel storage area, but data suggest that the amount is not great. Test results suggest that removal by purging may not be possible, and that, if the quantity of JP-4 in the system is small, drainage to an interception ditch also may not be feasible.

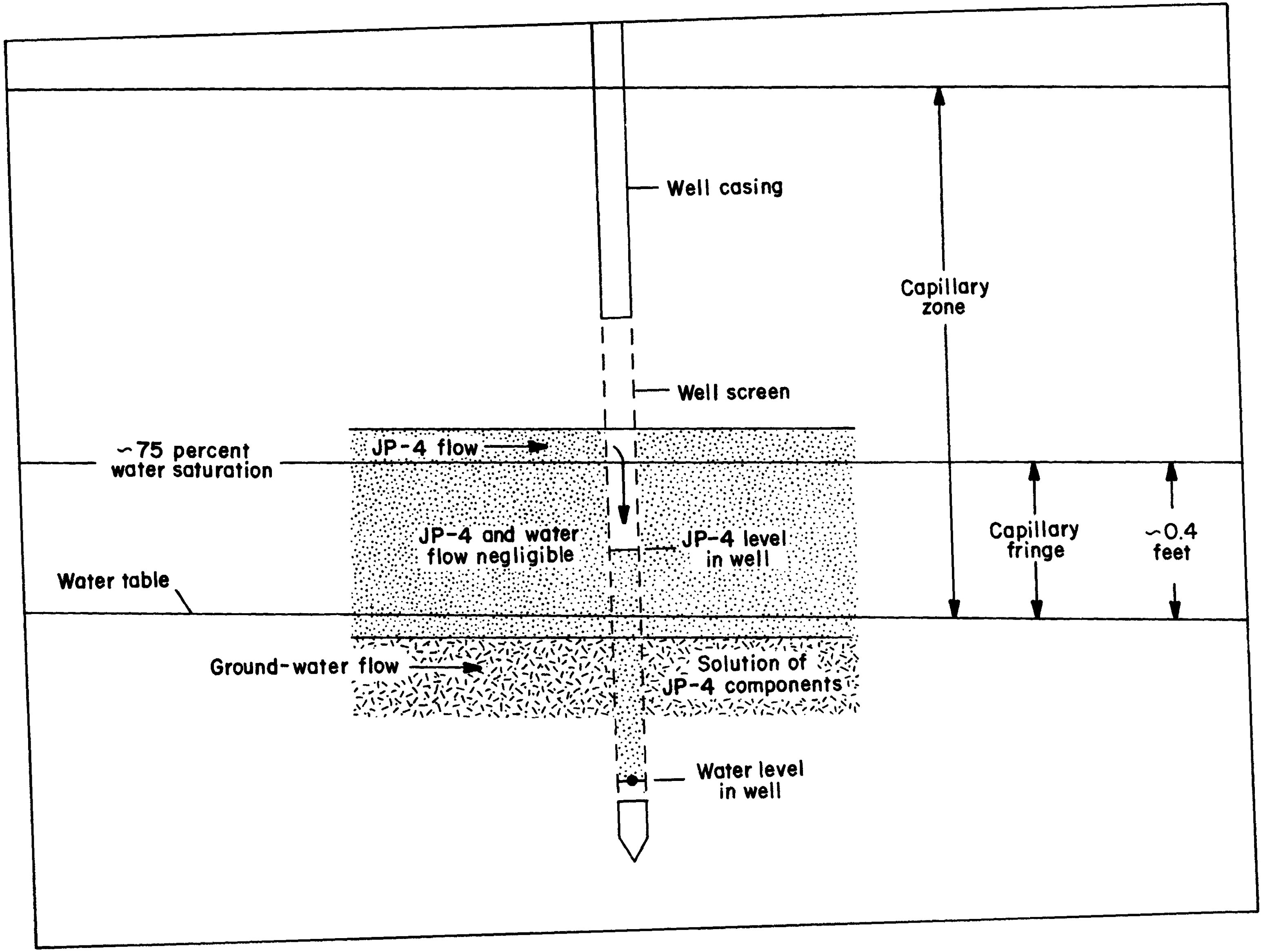

Figure 53.--Generalized description of the accumulation of JP-4 in wells in bulk-fuel storage area.

Supplemental Water Supply for Base

During periods of heavy demand, wells AF4 and AF5 cannot supply sufficient water to meet Base needs. Because of this, investigations to identify a location near wells AF4 and AF5 where ground water of suitable quality could be withdrawn were begun. In January and February 1984, an 8-in.-diameter test well, GST1, and five water-level monitoring wells (G30-G34), were installed (plate 1). Well GST1, about 1,000 ft northwest of well AF5, was completed with 20 ft of nominal 8-in.-diameter screen set between 39 and 59 ft below land surface. Lithology of materials penetrated by the well is given in table 14.

Table 14.--Lithology of materials in well GST1

Lithology	Depth (feet)
Sand, fine to very coarse, mostly clear quartz, some gravel	0-50
Sand, medium to very coarse, and gravel; pebbles 1/2 to 2 inches in diameter	50-56
Sand, fine, some clay	56-62

On February 15-16, 1984, a pumping test was conducted at well GST1. The static water level was 17.7 ft below land surface and the saturated thickness of the aquifer was 41 feet. Drawdown, at a pumping rate of about 150 gal/min for 20 hours, was 20.3 feet. Distance-drawdrown and time-drawdown analyses of the pumping data indicate a hydraulic conductivity for the aquifer of about 105 ft/d. Results of the test indicated that two or three water-supply wells, each yielding about 300 gal/min, could be installed in the area to provide a supplemental supply. To determine if water quality was suitable, samples were collected from well GST1, and from well R21S, about 1,300 ft upgradient (table 15). Only iron (420 µg/L) exceeded the drinking-water regulations of the U.S. Environmental Protection Agency (1977b). Analyses were also made of water from both wells for 99 volatile organic, base/neutral, and pesticide compounds. None were detected. Radiochemical analyses of gross alpha, gross beta, radium-226, and gross gamma indicated that normal background levels in water were not exceeded.

In March and April 1985, the Air Force installed three new supply wells (AF30, AF31, and AF32) in the vicinity of GST1 to supplement the Base water supply (plate 1). Each of the wells are 67 ft deep and have 12-in.-diameters and 10-ft-long screens. The new wells are 400 to 600 ft northwest of supply well AF5. Because of this, and because heavy pumping in the well field might draw contaminants to the wells from other areas, each well was designed to pump no more than 200 gal/min, using a staggered pumping schedule. Although capable of supplementing the present Base supply, these wells are not expected to meet future, anticipated peak demands.

Table 15.--Chemical and physical properties of water from wells GST1 and R21S, February 16, 1984
[Analyses by U.S. Geological Survey]

Constituent or property	Well GST1	Well R21S
Alkalinity (mg/L as $CaCO_3$)	120	89
Arsenic, total (μg/L as As)	1	1
Barium, total recoverable (μg/L as Ba)	100	<100
Boron, dissovled (μg/L as B)	<20	<20
Cadmium, total recoverable (μg/L as Cd)	<1	<1
Calcium, dissolved (mg/L as Ca)	41	38
Chloride, dissolved (mg/L as Cl)	1.6	1.2
Chromium, total recoverable (μg/L as Cr)	<1	<1
Copper, total recoverable (μg/L as Cu)	3	<1
Fluoride, dissolved (mg/L as F)	<.1	<.1
Hardness (mg/L as $CaCO_3$)	140	120
Hardness, noncarbonate (mg/L as $CaCO_3$)	22	30
Iron, dissolved (μg/L as Fe)	12	<3
Iron, total recoverable (μg/L as Fe)	420	420
Lead, total recoverable (μg/L as Pb)	4	2
Manganese, dissolved (μg/L as Mn)	8	<1
Manganese, total recoverable (μg/L as Mn)	10	<10
Magnesium, dissolved (mg/L as Mg)	9.7	5.9
Mercury, total recoverable (μg/L as Hg)	.2	.4
Nitrogen, nitrate, total (mg/L as N)	5.0	4.0
Nitrogen, nitrite, total (mg/L as N)	.01	.01
Oil and grease, total (mg/L)	1	<1
pH, field (units)	8.0	8.0
Phenols, total (μg/L)	<1	<1
Potassium, dissolved (mg/L as K)	.4	3.6
Selenium, total (μg/L as Se)	<1	<1
Silica, dissolved (mg/L as SiO_2)	7.1	4.8
Silver, total recoverable (μg/L as Ag)	<1	<1
Sodium, dissolved (mg/L as Na)	2.2	.9
Solids, residue at 180°C, dissolved (mg/L)	180	216
Solids, sum of constituents, dissolved (mg/L)	148	120
Specific conductance, field (μmhos)	289	331
Sulfate, dissolved (mg/L as SO_4)	14	12
Temperature (°C)	10.0	10.5
Zinc, total recoverable (μg/L as Zn)	10	10

In December 1985, a deep well, GST3, was installed to determine the water-bearing characteristics of materials underlying the shallow sand and gravel aquifer in the vicinity of the present well field, and to determine if these underlying materials could be used as a source for additional Base water supplies. Lithology of materials penetrated by the well is given in table 16.

Table 16.--Lithology of materials in well GST3

Lithology	Depth (feet)
Glacial sand and gravel	
Sand, very fine to coarse, subrounded to rounded, mostly clear quartz; some gravel, pebbles ¼ to 2 inches in diameter	0-67
Gravel, pebbles 1 to 2 inches in diameter; some medium to coarse sand	67-70
Lacustrine deposits (clay unit)	
Clay, soft, gray; contains some sand near base	70-103
Glacial till	
Clay; sandy, gravelly	103-165
Sand and silt	165-172
Bedrock (Marshall Formation)	
Sandstone, some shaly zones; some 2- to 3-inch deep cavities (fractures) between 179 and 185 feet	172-190

The well was completed as an open hole with the casing set at 172 ft. A gamma-ray log of the well (fig. 54) verified the stratigraphic breaks shown above.

After completion, the well was pumped for 20 minutes at 10 gal/min. During pumping, the water level rose from 7.8 ft to 5.2 ft below land surface. Water level in well GST1, a 59-foot-deep well in the shallow sand and gravel aquifer 200 ft to the south, was 18 ft below land surface.

Water from GST3 had a specific conductance of 7,290 µS and a salty taste. Based on the specific conductance, which suggests a dissolved-solids concentration in excess of that suitable for drinking, the aquifer underlying the clay unit is not a potential source of water for the Base.

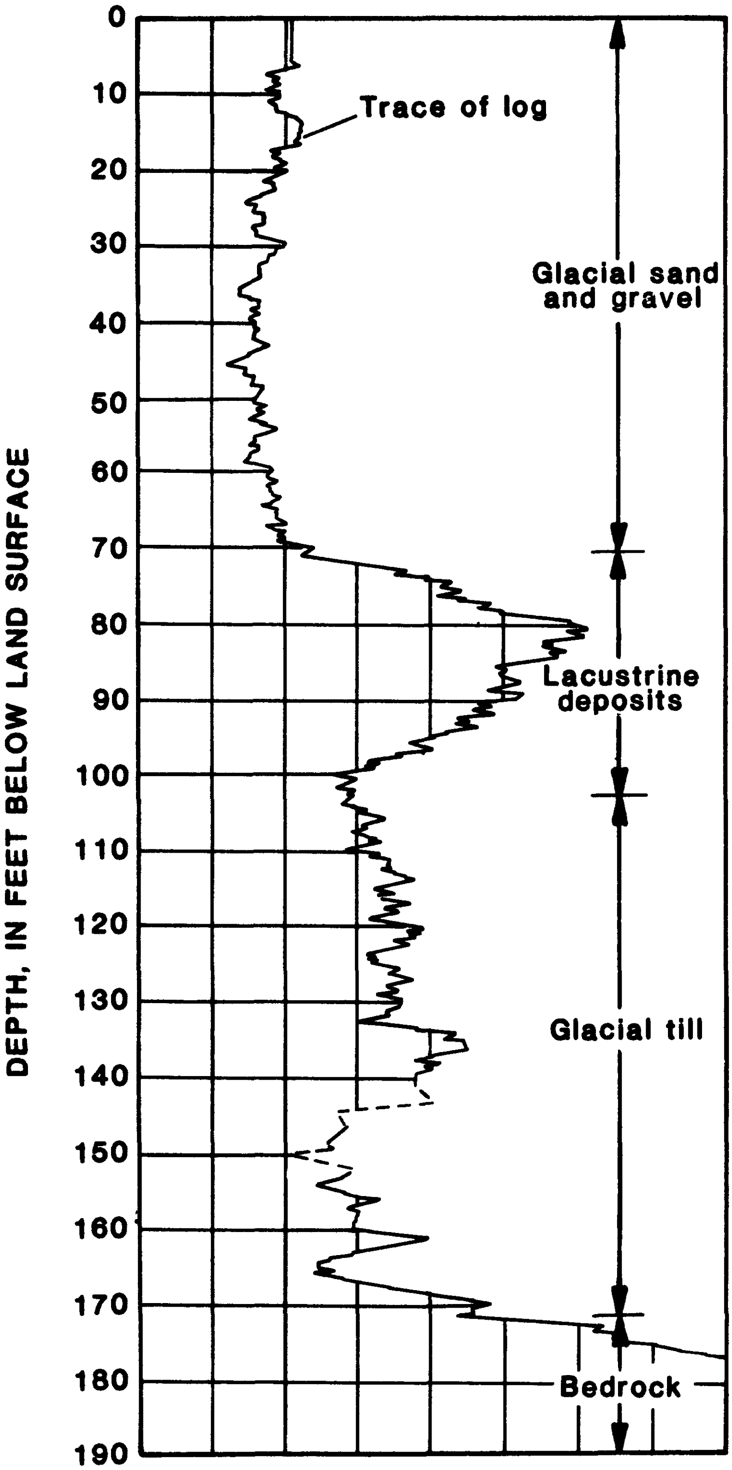

Figure 54.--Gamma-ray log of well GST3 showing stratigraphic breaks between rock units.

SUMMARY AND CONCLUSIONS

The principal aquifer in the Wurtsmith Air Force Base area is a sand and gravel unit that extends from land surface to a depth that averages 65 ft. The unit is mostly a medium to coarse sand containing some gravel. Thin beds of clay are present at depths ranging from 5 to 15 ft in the northern part of the Base. Beds of relatively impermeable lacustrine clay and glacial till at least 100 ft thick underlie the sand and gravel unit.

The sand and gravel aquifer is mostly under water-table conditions. The depth to water ranges from about 25 ft along the northeastern part of the Base to less than 10 ft at places along the western part. Under natural conditions, most ground-water flow is toward Van Etten Lake, Van Etten Creek, and the Au Sable River. Natural water levels fluctuate from 1 to 3 ft annually. The general configuration of the water table, however, does not change significantly. In areas influenced by pumping, the depth to water and direction of flow changes significantly as water moves toward the pumped wells.

A two-dimensional, finite-difference, ground-water-flow model, based on modeling work in 1979-1981, was used to simulate water levels and describe ground-water movement. Average flow ranges from 0.8 ft/d in the eastern part of the Base to 0.3 ft/d in the western part. At some locations, however, rates as high as 5 ft/d occur. Hydraulic conductivity is about 100 ft/d in the eastern part of the Base and about 150 ft/d in the western part; a value of 120 ft/d, however, was found to be most appropriate in model simulations.

The trichloroethylene purge system along Arrow Street, which went into operation in April 1982, was sampled in April and September 1983, to verify that the system was operating effectively. Water-level measurements throughout the area were also made to verify that ground-water containing trichloroethylene was not flowing off-Base. In April 1983, a year after the system went into operation, concentrations of trichloroethylene in the central part of the most highly contaminated area had decreased from a range of 1,000 to 2,000 μg/L to about 500 μg/L; the length and width of the plume also decreased. By September 1983, the plume's length and width had decreased further; the maximum concentration of trichloroethylene in the central part of the plume was 206 μg/L. Data indicate that ground water is being drawn to the purge wells from all directions; no contaminated water from the area is moving off-Base. From November 1977 to June 1985, about 900 gallons of trichloroethylene were removed from the aquifer. During the first 6 months of 1985, about 9.6 millon gallons of water were being withdrawn for each gallon of trichloroethylene removed.

Movement of trichloroethylene to a Knights of Columbus well east of Perimeter Road is thought to be from a small area east of Skeel Avenue. Trichloroethylene could have reached the general area before the Arrow Street purge system went into operation; a ground-water divide, however, now separates the purge system from the area east of Skeel Avenue and the Knights of Columbus well.

Investigation of benzene detected in water-supply well AF2 indicates that the source is probably the area near Building 5081 on the western edge of the operational apron where six underground fuel tanks are located. Near the site of one former tank, water at the surface of the water table contained 1,720 µg/L benzene and 24,630 µg/L toluene. Downgradient, the highest concentration of benzene (700 µg/L) was found in water from well H74M, about 600 ft west of well AF2. During periods of normal purge pumping along Arrow Street, benzene is drawn to the purge system. During periods when purge pumping is low, benzene is drawn towards wells AF2, AF4, and AF5.

A decrease in the concentration of trichloroethylene in the Alert Apron plume was verified by data collected in April 1984. Near the origin of the plume, the concentration of water from well R49S decreased from 1,000 µg/L in August 1980, to 50 µg/L in April 1984. In the downgradient part, water from well R29S decreased from 265 µg/L in 1980, to 20 µg/L in 1984. Analyses of water samples collected at nine locations near the surface and near the bottom of Van Etten Lake, just offshore from the termination of the plume, indicated that the contaminants (2.5 µg/L trichloroethylene and 4.1 µg/L tetrachloroethylene) were present at only one location.

A more extensive investigation of the movement of benzene and dichloroethylene in the Northern landfill area was conducted from April 1983 to July 1984. Highest concentrations of contaminants seem to be along the southern margin of the plume. In general, concentrations found in water do not differ greatly from those observed in 1981. The most hydrologically suitable scheme for purging on-Base is a system of five wells--two pumping 40 gal/min, two pumping 60 gal/min, and one pumping 80 gal/min. An off-Base purge system of nine wells, each pumping 25 gal/min, also would be hydrologically suitable.

An area of contamination, extending in a generally north-south direction along Mission Drive in the southern part of the Base, has been delineated. Maximum concentrations detected in water were 3,290 µg/L trichloroethylene (well H27D), and 1,480 µg/L dichloroethylene (well H63M). A ground-water divide trends northwest-southeast through the area of contamination. South of the divide, flow is to the Au Sable River; north of the divide flow is to the Arrow Street purge system. At some time in the past, a source may have existed in the area of Building 5008. Hydrologically suitable sites for purging were identified along Mission Drive. Three wells withdrawing 40 gal/min and one well withdrawing 100 gal/min should remove contaminants from the aquifer and prevent further southward movement of contaminants.

An investigation of the position of a known benzene plume near the bulk-fuel storage area indicates that the position of the plume and direction of its movement had changed since operation of the Arrow Street purge system began. The benzene plume is moving northward, but it has not reached Arrow Street. Model simulations indicate that the previously proposed purge well locations should be changed. The most hydrologically efficient sites are northeast of Huron Avenue. Four wells, each pumping 50 gal/min, should effectively remove water from the plume and prevent further northward movement.

During investigation of the benzene plume near the bulk-fuel storage area, JP-4 fuel was found to be accumulating on the water surface in wells immediately east of the storage tanks. No leakage of tanks or lines was detected; it seems probable that the JP-4 results from a spill that occurred several years ago. Most of the JP-4 is trapped in the capillary fringe above the water table, and drains to wells when water levels are seasonally low. Tests suggest that removal of the JP-4 by purging the aquifer will be difficult.

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DEFINITION OF TERMS

Altitude. Vertical distance of a point or line above or below sea level. In this report, all altitudes are above sea level.

Altitude Contour. An imaginary line connecting points of equal altitude, whether the points are on the land surface, on the clay surface, or on a potentiometric or water-table surface.

Aquifer. A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. It is also called a ground-water reservoir.

Bedrock. Designates consolidated rocks.

Concentration. The weight of dissolved substance or sediment per unit volume of water expressed in milligrams per liter (mg/L) or micrograms per liter (µg/L). When reported per unit weight of solid material, it is expressed in milligrams per kilogram (mg/kg) or micrograms per kilogram (µg/kg).

Divide. A line of separation between drainage systems. A topographic divide delineates the land from which a stream gathers its water; a ground-water divide is an imaginary line on a potentiometric or water-table surface on each side of which the potentiometric surface slopes downward away from the line.

Equipotential line. An imaginary line in an aquifer on which every point has the same potentiometric head. As used in this report, equipotential lines define the water table. The value identifying a given line is the altitude of all points on that line.

Ground water. Water that is in the saturated zone from which wells, springs, and ground-water runoff are supplied.

Hydraulic conductivity. The volume of water at the prevailing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. In general terms hydraulic conductivity is the ability of a porus medium to transmit water.

Hydrograph. A graph showing the variations of stage, flow, velocity, discharge, or other aspect of water with respect to time.

Permeability, intrinsic. A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. It is a property of the medium alone, and is independent of the nature of the fluid and of the force field.

Picocurie (pCi). One trillionth (1×10^{-12}) of the amount of radioactivity represented by a curie (Ci). A curie is the amount of radioactivity that yields 3.7×10^{10} radioactive disintegrations per second. A picocurie yields 2.22 disintegrations per minute.

Potentiometric surface. In aquifers, the levels to which water will rise in tightly cased wells. More than one potentiometric surface is required to describe the distribution of head. The water table is a particular potentiometric surface.

Recharge. The process by which water is infiltrated and is added to the zone of saturation. It is also the quantity of water added to the zone of saturation.

Runoff. That part of precipitation that appears in streams; the water draining from an area. When expressed in inches, it is the depth to which an area would be covered if all the water draining from it in a given period were uniformly distributed on its surface.

Specific capacity. The rate of discharge of water from a well divided by the drawdown of water level within the well.

Specific conductance. A measure of the ability of water to conduct an electric current, expressed in microsiemens (μS) per centimeter at 25°C [formerly termed micromhos (μmhos)]. Because the specific conductance is related to amount and type of dissolved material, it is used for approximating the dissolved-solids concentration of water. For most natural waters the ratio of dissolved-solids concentration (in milligrams per liter) to specific conductance (in microsiemens) is in the range 0.5 to 0.8.

Specific yield. The ratio of the volume of water that the rock, after being saturated, will yield by gravity, to the volume of rock. It is used for water-table aquifers.

Transmissivity. The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

Water table. That surface of a body of unconfined ground water at which the pressure is atmospheric. It is defined by levels at which water stands in wells.

APPENDIXES

APPENDIX A: DATA TABLES

Table 1.--Selected data for wells at Wurtsmith Air Force Base

Well number	Altitude of measuring point (feet)	Depth of well below land surface (feet)	Casing diameter (inches)	Height of measuring point above land surface (feet)	Water level below measuring point (feet)	Date water level measured
G27S	608.32	17.8	2.00	3.2	19.12	10-25-83
G28S	615.11	22.2	2.00	1.8	22.21	10-26-83
G29S	607.41	30.8	2.00	1.7	19.28	1-25-84
G30S	612.44	30.8	2.00	1.7	20.48	1-25-84
G31S	614.96	41.4	2.00	1.6	20.95	1-25-84
G32S	615.83	41.0	2.00	2.0	21.35	1-25-84
G33S	616.03	36.1	2.00	2.4	20.61	1-25-84
G34S	615.43	36.6	2.00	1.9	18.71	1-25-84
G35D	595.50	26.0	4.00	1.0	10.39	7-11-84
G35S	595.45	14.0	2.00	1.0	10.35	7-11-84
G36D	--	[a]60.0	--	--	--	--
G36S	592.27	14.0	2.00	1.0	7.17	7-11-84
G37D	591.81	26.0	4.00	1.0	3.49	7-11-84
G37S	591.52	14.0	2.00	1.0	5.22	7-11-84
G38D	592.58	31.0	4.00	1.0	3.93	7-11-84
G38S	592.62	14.0	2.00	1.0	6.79	7-11-84
G39D	592.59	31.0	4.00	0.5	2.38	7-11-84
G39S	592.62	14.0	2.00	0.5	7.52	7-11-84
G40D	592.92	26.0	4.00	1.0	1.01	7-11-84
G40S	593.80	14.0	2.00	1.9	7.59	7-11-84
G41S	633.08	34.0	2.00	1.8	30.70	7-10-84
H15S	621.07	34.0	4.00	1.8	17.36	5-12-82
H16S	618.26	34.0	4.00	2.1	15.71	5-12-82
H17S	619.66	34.0	4.00	1.9	17.16	5-12-82
H18D	619.88	65.0	4.00	1.8	17.85	5-12-82
H18S	619.81	34.0	4.00	1.8	17.75	5-12-82
H19S	618.54	34.0	4.00	1.9	16.87	5-12-82
H20S	618.89	34.0	4.00	1.8	17.88	5-12-82
H21D	618.90	65.0	4.00	1.7	18.15	5-12-82
H21S	618.86	34.0	4.00	1.9	18.31	5-12-82
H22D	617.92	56.0	4.00	1.7	21.06	4-07-83
H22S	617.56	34.0	4.00	1.9	17.12	5-12-82
H23D	623.02	62.0	4.00	1.7	25.66	4-07-83
H23S	622.93	41.0	4.00	1.7	25.59	4-07-83
H24D	619.27	56.0	4.00	1.8	22.44	4-07-83
H24S	618.81	34.0	4.00	1.7	22.18	4-07-83
H25D	619.23	56.0	4.00	1.8	23.03	4-06-83
H25S	619.02	34.0	4.00	1.8	22.87	4-06-83
H26D	617.02	56.0	4.00	1.8	20.93	4-06-83
H26S	616.74	34.0	4.00	1.7	20.73	4-06-83
H27D	616.77	56.0	4.00	1.8	20.77	4-07-83
H27S	615.57	34.0	4.00	1.8	20.57	4-07-83
H28S	618.71	38.0	4.00	1.7	28.90	4-06-83
H29S	615.66	38.0	4.00	1.8	27.30	4-06-83
H30S	611.74	32.0	4.00	1.8	21.62	4-06-83
H31S	611.91	34.0	4.00	1.8	22.24	4-08-83

[a] Clay from 20 feet to 60 feet; still in clay when drilling stopped, well abandoned.

Table 1.--Selected data for wells at Wurtsmith Air Force Base--Continued

Well number	Altitude of measuring point (feet)	Depth of well below land surface (feet)	Casing diameter (inches)	Height of measuring point above land surface (feet)	Water level below measuring point (feet)	Date water level measured
H32S	613.35	34.0	4.00	1.6	27.72	4-06-83
H33S	609.78	28.0	4.00	1.7	17.13	4-08-83
H34S	610.50	34.0	4.00	1.8	18.04	4-08-83
H35S	610.52	31.0	4.00	1.8	18.54	4-08-83
H36S	607.75	34.0	4.00	1.8	19.88	4-06-83
H37S	608.23	34.0	4.00	1.9	21.13	4-06-83
H38D	626.88	59.0	4.00	1.6	30.25	9-29-83
H39D	628.64	62.0	4.00	2.0	32.12	9-29-83
H40S	614.31	34.0	4.00	1.8	23.95	11-07-83
H41S	614.85	34.0	4.00	1.7	24.58	11-07-83
H42S	614.71	34.0	4.00	1.8	22.80	11-07-83
H43D	616.68	60.0	4.00	1.9		
H43S	616.67	34.0	4.00	1.8	22.28	11-07-83
H44D	615.52	60.0	4.00	1.7	22.35	11-08-83
H44S	615.43	34.0	4.00	1.7	--	--
H45D	614.39	60.0	4.00	1.8	21.75	11-08-83
H45S	614.25	34.0	4.00	1.7	--	--
H46D	614.50	59.0	4.00	1.7	--	--
H46S	614.58	34.0	4.00	1.8	23.07	11-08-83
H47S	614.19	34.0	4.00	1.8	20.73	11-07-83
H48S	616.30	34.0	4.00	1.9	19.63	12-01-83
H49D	615.95	54.0	4.00	1.7	19.06	12-01-83
H49S	615.94	34.0	4.00	1.8	19.07	12-01-83
H50D	619.61	[b]65.0	4.00	1.7	19.94	1-24-84
H50S	619.68	[c]44.0	4.00	1.7	--	--
H51D	614.96	54.0	4.00	1.6	19.67	1-24-84
H51S	615.10	34.0	4.00	1.7	--	--
H52D	615.27	54.0	4.00	1.7	19.85	1-24-84
H52S	615.22	34.0	4.00	1.7	20.16	12-01-83
H53D	615.55	54.0	4.00	1.5	20.10	12-01-83
H53M	615.76	44.0	4.0	1.5	19.99	5-16-84
H53S	615.76	34.0	4.00	1.8	--	--
H54D	622.20	54.0	4.00	1.8	26.13	1-24-84
H54S	621.75	34.0	4.00	1.3	--	--
H55D	612.25	56.0	4.00	1.8	22.90	1-25-84
H55S	611.79	34.0	4.00	1.6	22.44	1-25-84
H56D	615.56	56.0	4.00	1.6	25.35	1-26-84
H56S	615.90	34.0	4.00	1.8	25.41	1-26-84
H57D	614.71	56.0	4.00	1.7	23.96	7-11-84
H57S	614.78	34.0	4.00	1.9	--	--
H58D	614.23	56.0	4.00	1.9	--	--
H58S	614.20	34.0	4.00	1.9	--	--
H59D	614.49	56.0	4.00	1.6	23.25	1-27-84
H59S	614.25	34.0	4.00	1.5	23.03	1-27-84
H60D	612.90	56.0	4.00	1.8	22.18	1-26-84
H60S	612.97	34.0	4.00	1.9	22.23	1-26-84
H61D	611.47	56.0	4.00	1.9	20.23	7-11-84
H61S	611.56	34.0	4.00	1.8	--	--
H62D	612.17	56.0	4.00	1.7	22.27	1-25-84
H62S	612.06	34.0	4.00	1.7	22.17	1-25-84
H63D	617.19	55.0	4.00	1.8	20.70	4-11-84

[b] Reset screen; new depth, 56.0 feet
[c] Reset screen; new depth, 35.0 feet

Table 1.--Selected data for wells at Wurtsmith Air Force Base--Continued

Well number	Altitude of measuring point (feet)	Depth of well below land surface (feet)	Casing diameter (inches)	Height of measuring point above land surface (feet)	Water level below measuring point (feet)	Date water level measured
H63M	617.45	45.0	4.00	1.9	--	--
H63S	617.38	34.0	4.00	1.9	--	--
H64D	616.34	49.0	4.00	1.7	22.12	4-11-84
H64S	616.41	30.0	4.00	1.6	--	--
H65D	615.11	49.0	4.00	1.8	20.87	7-12-84
H65S	615.04	30.5	4.00	1.7	--	--
H66D	620.34	52.0	4.00	1.6	20.48	7-10-84
H66S	620.04	30.0	4.00	1.8	--	--
H67D	616.11	52.0	4.00	1.8	24.52	7-11-84
H68S	609.86	33.0	4.00	1.8	24.40	7-11-84
H69D	608.36	41.0	4.00	2.1	16.80	5-17-84
H69S	608.20	20.0	4.00	1.9	16.69	5-17-84
H70D	606.97	41.0	4.00	1.9	15.83	7-12-84
H70M	606.82	31.0	4.00	2.0	15.55	5-17-84
H70S	607.06	20.0	4.00	1.8	15.85	5-17-84
H71D	605.66	41.0	4.00	1.9	14.20	5-17-84
H71S	605.43	20.0	4.00	1.7	14.05	5-17-84
H72D	617.71	55.0	4.00	1.9	18.27	5-16-84
H72S	617.69	32.0	4.00	1.9	18.26	5-16-84
H73D	617.00	55.0	4.00	1.8	18.25	7-10-84
H73M	616.97	44.0	4.00	1.8	17.83	5-16-84
H73S	616.14	32.0	4.00	1.9	18.00	5-16-84
H74D	616.28	55.0	4.00	1.8	25.06	7-11-84
H74M	616.32	44.0	4.00	1.8	26.13	7-16-84
H74S	616.48	32.0	4.00	2.0	26.33	7-16-84
H75S	607.96	28.0	4.00	1.9	16.26	7-12-84
H76D	614.16	54.0	4.00	1.9	18.10	7-12-84
H76S	614.16	33.0	4.00	1.8	18.11	6-26-84
H77D	617.89	54.0	4.00	2.1	22.39	7-12-84
H77S	617.47	33.0	4.00	1.7	21.98	6-26-84
H78D	618.76	54.0	4.00	1.9	23.36	7-12-84
H78S	618.78	33.0	4.00	1.9	23.32	6-26-84
H79D	618.66	54.0	4.00	1.9	23.00	7-12-84
H79S	618.56	33.0	4.00	1.9	22.83	6-26-84
H80D	616.14	44.1	4.00	1.9	18.34	5-09-85
H80S	616.16	33.4	4.00	2.1	--	--
H81D	616.21	44.1	4.00	1.9	18.94	5-09-85
H81S	616.19	33.5	4.00	2.0	--	--
H82D	616.39	44.0	4.00	2.0	19.41	5-08-85
H82S	616.39	33.5	4.00	2.0	--	--
H83D	616.62	43.9	4.00	2.1	19.85	5-08-85
H83S	616.62	33.4	4.00	2.1	--	--
H84D	616.67	44.0	4.00	2.0	20.18	5-08-85
H84S	616.68	33.4	4.00	2.1	--	--
H85D	616.41	43.8	4.00	2.2	20.55	5-08-85
H85S	616.22	33.6	4.00	1.9	--	--

Table 1.--Selected data for wells at Wurtsmith Air Force Base--Continued

Well number	Altitude of measuring point (feet)	Depth of well below land surface (feet)	Casing diameter (inches)	Height of measuring point above land surface (feet)	Water level below measuring point (feet)	Date water level measured
GST1	615.24	59.0	8.00	2.0	21.12	7-11-84
GST2	613.56	32.0	6.00	1.5	18.70	7-10-84
GST3	614.00	190.0	6.00	1.7	5.2	12-17-85
PB	615.07	50.0	6.00	2.1	20.93	4-25-84
PC	615.83	47.0	6.00	2.1	21.99	4-25-84
PW1	--	69.0	10.00	0.0	19.0	12-17-80
PW2	--	67.0	10.00	0.0	21.1	12-18-80
PW3	--	67.0	10.00	0.0	21.0	12-22-80
PW4	--	70.0	8.00	0.0	--	--

Table 2.--Analyses of volatile organic compounds in ground water at Wurtsmith Air Force Base

[Analyses by U.S. Geological Survey. Results in micrograms per liter (μg/L). ND indicates not detected.]

Well number	Date	Trichloroethylene	1,2 Dichloroethylene	Benzene	Toluene	Xylene	Ethyl benzene	Tetrachloroethylene	Methylene chloride	Other
AF1	March 8, 1984	52	24	ND	ND	ND	ND	ND	ND	ND
	May 8, 1985	50	8.2	ND	ND	ND	ND	4.1	ND	ND
AF3	April 27, 1983	83	57	ND	ND	ND	ND	12	ND	(a)
	September 27, 1983	38	19	ND	ND	ND	ND	6.4	ND	ND
AF4	December 1, 1983	ND	14	ND	ND	ND	ND	ND	ND	ND
AF18	May 12, 1982	ND	ND	ND	ND	ND	ND	ND	ND	ND
	June 11, 1982[b]	ND	ND	ND	ND	ND	ND	ND	ND	ND
	June 11, 1982[c]	ND	ND	ND	ND	ND	ND	ND	ND	ND
AF19	May 12, 1982	16	ND	ND	ND	ND	ND	ND	ND	ND
	June 11, 1982[d]	ND	ND	ND	ND	ND	ND	ND	ND	(e)
AF69	November 7, 1983	ND	ND	ND	ND	ND	ND	ND	17	ND
AF73	November 7, 1983	ND	ND	1,050	ND	ND	4,020	ND	574	(f)
AF74	November 8, 1983	18	ND	ND	ND	ND	ND	ND	42	ND
AF75	November 8, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
AF76	November 8, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
G20S	June 11, 1982	ND	ND	ND	ND	ND	ND	ND	ND	(d)
G27	December 1, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
G28	December 1, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
G35S	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
G35D	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
G36S	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
G37S	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
G37D	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
G38S	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
G38D	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
G39S	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
G39D	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
G40S	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
G40D	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H15S	May 12, 1982	ND	ND	ND	ND	ND	ND	ND	ND	ND
	June 10, 1982	ND	ND	ND	ND	ND	ND	ND	ND	ND
H16S	May 12, 1982	ND	ND	ND	ND	ND	ND	ND	ND	ND
	June 10, 1982	ND	ND	ND	ND	ND	ND	ND	ND	ND

[a] Water also contained 7.5 μg/L chloroform
[b] Sample collected at 0800
[c] Sample collected at 0900
[d] Sample collected at 0830
[e] Water also contained undifferentiated hydrocarbons, <20 μg/L
[f] Water also contained undifferentiated hydrocarbons

Table 2.--Analyses of volatile organic compounds in ground water at Wurtsmith Air Force Base--Continued

Well number	Date	Tri-chloro-ethylene	1,2 Di-chloro-ethylene	Benzene	Toluene	Xylene	Ethyl benzene	Tetra-chloro-ethylene	Methylene chloride	Other
H17S	May 12, 1982	ND	ND	ND	ND	ND	ND	ND	ND	ND
	June 10, 1982	ND	ND	ND	ND	ND	ND	ND	ND	ND
H18S	May 12, 1982	ND	ND	ND	ND	ND	ND	ND	ND	ND
	June 10, 1982	ND	ND	ND	ND	ND	ND	ND	ND	ND
H18D	May 12, 1982	ND	6.4	ND	ND	ND	ND	ND	ND	ND
	June 10, 1982	ND	5.0	ND	ND	ND	ND	ND	ND	ND
H19S	May 12, 1982	ND	ND	ND	ND	ND	ND	<1	ND	ND
	June 10, 1982	ND	ND	ND	ND	ND	ND	ND	ND	ND
H20S	May 12, 1982	5.5	ND	ND	ND	ND	ND	ND	ND	ND
	June 10, 1982	ND	ND	ND	ND	ND	ND	ND	ND	ND
H21S	May 12, 1982	134	ND	ND	ND	ND	ND	ND	ND	ND
	June 10, 1982	120	ND	ND	ND	ND	ND	ND	ND	ND
	April 27, 1983	69	ND	ND	ND	ND	ND	ND	ND	ND
H21D	May 12, 1982	123	12	ND	ND	ND	ND	ND	ND	ND
	June 10, 1982[a]	80	<1	4.0	ND	ND	ND	ND	ND	ND
	June 10, 1982[b]	110	3.0	ND	ND	ND	ND	ND	ND	ND
	April 27, 1983	79	11	ND	ND	ND	ND	ND	ND	ND
H22S	May 12, 1982	1,360	7.1	ND	ND	ND	ND	ND	ND	ND
	June 10, 1982[c]	1,430	ND	ND	ND	ND	ND	ND	ND	ND
	June 10, 1982[d]	1,720	ND	ND	ND	ND	ND	ND	ND	ND
	April 27, 1983	735	ND	ND	ND	ND	ND	ND	ND	ND
H22D	April 27, 1983	540	8.8	ND	ND	ND	ND	ND	ND	ND
H23S	April 27, 1983	131	ND	ND	ND	ND	ND	27	ND	ND
H23D	April 27, 1983	232	124	ND	ND	ND	ND	ND	ND	ND
H24S	April 27, 1983	892	6.7	ND	ND	ND	ND	ND	ND	ND
H24D	April 27, 1983	1,190	43	ND	ND	ND	ND	ND	ND	(e)
H25S	April 27, 1983	10	81	ND	ND	ND	ND	ND	ND	(f)
H25D	April 27, 1983	44	222	ND	ND	ND	ND	ND	ND	(g)
	September 27, 1983	193	191	ND	ND	ND	ND	ND	ND	(h)
H26S	April 27, 1983	18	79	ND	ND	ND	ND	ND	ND	ND
H26D	April 27, 1983	1,270	1,450	ND	ND	ND	ND	ND	ND	(i)
	September 27, 1983	1,190	724	ND	ND	ND	ND	ND	ND	(j k)

[a] Sample collected at 1718

[b] Sample collected at 1730

[c] Sample collected at 1800

[d] Sample collected at 1815

[e] Water also contained 41 μg/L chloroform

[f] Water also contained 15 μg/L 1,1,1 trichloroethane

[g] Water also contained 16 μg/L 1,1,1 trichloroethane

[h] Water also contained 17 μg/L 1,1,1 trichloroethane

[i] Water also contained 27 μg/L 1,1,1 trichloroethane

[j] Water also contained 31 μg/L 1,1,1 trichloroethane

[k] Water also contained 86 μg/L chloroform

Table 2.--Analyses of volatile organic compounds in ground water at Wurtsmith Air Force Base--Continued

Well number	Date	Tri-chloro-ethylene	1,2 Di-chloro-ethylene	Benzene	Toluene	Xylene	Ethyl benzene	Tetra-chloro-ethylene	Methylene chloride	Other
H27S	April 27, 1983	14	ND	ND	ND	ND	ND	ND	ND	ND
H27D	April 27, 1983	3,290	1,410	ND	ND	ND	ND	ND	ND	ND
	September 27, 1983	1,890	355	ND	ND	ND	ND	ND	ND	(a)
H28S	April 27, 1983	ND	22	24	ND	ND	33	ND	ND	ND
	November 7, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
H29S	April 27, 1983	4.3	ND	ND	ND	ND	3.3	ND	ND	ND
	November 7, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
H30S	April 27, 1983	27	ND	ND	ND	ND	ND	ND	ND	ND
H31S	April 27, 1983	4.2	ND	ND	ND	ND	ND	ND	ND	ND
H33S	April 27, 1983	ND	24	12	ND	ND	ND	ND	ND	ND
	June 27, 1984	11	19	ND	ND	ND	ND	ND	ND	ND
H34S	April 27, 1983	ND	6.8	11	ND	ND	ND	ND	ND	ND
	June 27, 1984	ND	29	ND	ND	ND	ND	ND	ND	ND
H35S	April 27, 1983	ND	6.7	4.8	ND	ND	ND	ND	ND	ND
	June 27, 1984	ND	71	ND	ND	ND	ND	ND	ND	(b)
H36S	April 27, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
H37S	April 27, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
H38D	September 27, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
H39D	September 27, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
H40S	November 7, 1983	24	ND	ND	ND	ND	ND	53	ND	ND
H41S	November 7, 1983	27	ND	ND	ND	ND	ND	14	ND	ND
H42S	November 7, 1983	16	11	18	ND	ND	ND	ND	ND	ND
H43S	November 7, 1983	ND	ND	2,870	ND	ND	ND	ND	37	(c,d)
H43D	November 7, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
H44S	November 8, 1983	ND	ND	684	ND	ND	80	ND	ND	ND
H44D	November 8, 1983	ND	ND	3.4	ND	ND	ND	ND	ND	(c)
H45S	November 8, 1983	ND	ND	161	ND	1,030	284	ND	83	ND
H45D	November 8, 1983	ND	ND	103	ND	ND	ND	ND	ND	ND
H46S	November 8, 1983	11	ND	ND	ND	ND	ND	5.3	ND	ND
H46D	November 8, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
H47S	November 7, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
H48S	December 1, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND

[a] Water also contained 53 μg/L chloroform

[b] Water also contained 15 μg/L 1,1 dichloroethane

[c] Water also contained other undifferentiated hydrocarbons

[d] Water also contained 25 μg/L chloroform

Table 2.--Analyses of volatile organic compounds in ground water at Wurtsmith Air Force Base--Continued

Well number	Date	Trichloroethylene	1,2 Dichloroethylene	Benzene	Toluene	Xylene	Ethyl benzene	Tetrachloroethylene	Methylene chloride	Other
H49S	December 1, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
H49D	December 1, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
H50S	December 1, 1983	107	ND	ND	ND	ND	ND	ND	ND	ND
	June 27, 1984[a]	13	ND	ND	ND	ND	ND	ND	ND	ND
H50D	December 1, 1983	ND	45	ND	ND	ND	ND	ND	ND	ND
	March 8, 1984[a]	73	36	ND	ND	ND	ND	ND	ND	ND
H51S	December 1, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
H51D	December 1, 1983	3.1	ND	ND	ND	ND	ND	ND	ND	ND
H52S	December 1, 1983	16	ND	ND	ND	ND	ND	ND	ND	ND
H52D	December 1, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
H53S	December 1, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
H53M	May 16, 1984	20	43	ND	ND	ND	ND	ND	ND	ND
H53D	December 1, 1983	8.3	756	ND	ND	ND	ND	ND	ND	ND
H54S	December 1, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
H54D	December 1, 1983	92	12	ND	ND	ND	ND	ND	ND	ND
H55S	January 25, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H55D	January 25, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H56S	January 25, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H56D	January 25, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H57S	February 14, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H57D	February 14, 1984	ND	ND	5.3	ND	ND	ND	ND	ND	ND
H58S	February 14, 1984	7.3	ND	ND	ND	ND	ND	ND	ND	ND
	May 8, 1985	ND	ND	ND	ND	ND	ND	ND	ND	ND
H58D	February 14, 1984	ND	6.7	15	ND	ND	ND	ND	ND	ND
	May 8, 1985	ND	ND	ND	ND	ND	ND	ND	ND	ND
H59S	January 25, 1984	49	ND	7.3	ND	ND	ND	9.5	ND	ND
	May 8, 1985	23	ND	ND	ND	ND	ND	ND	ND	ND
H59D	January 25, 1984	ND	14	184	ND	ND	ND	ND	ND	ND
	May 8, 1985	ND	18	128	ND	ND	ND	ND	ND	ND
H60S	January 25, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H60D	January 25, 1984	ND	19	ND	ND	ND	ND	ND	ND	ND
H61S	February 14, 1984	4.6	ND	ND	ND	ND	ND	ND	ND	ND
H61D	February 14, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H62S	January 25, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H62D	January 25, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H63S	March 8, 1984	ND	6.5	ND	ND	ND	ND	ND	ND	ND
H63M	March 8, 1984	3,240	1,480	ND	ND	ND	ND	ND	ND	ND
H63D	March 8, 1984	100	749	ND	ND	ND	ND	ND	ND	ND

[a] Well screen set at a shallower depth

Table 2.--Analyses of volatile organic compounds in ground water at Wurtsmith Air Force Base--Continued

Well number	Date	Tri-chloro-ethylene	1,2 Di-chloro-ethylene	Benzene	Toluene	Xylene	Ethyl benzene	Tetra-chloro-ethylene	Methylene chloride	Other
H64S	March 8, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H64D	March 8, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H65S	March 8, 1984	4.4	ND	ND	ND	ND	ND	ND	ND	ND
H65D	March 8, 1984	279	624	ND	4.0	ND	ND	ND	ND	ND
H66S	March 8, 1984	54	ND	ND	ND	ND	ND	ND	ND	ND
H66D	March 8, 1984	ND	9.1	ND	ND	ND	ND	ND	ND	ND
H67D	March 8, 1984	4.4	ND	16	ND	ND	ND	ND	ND	ND
	May 8, 1985	ND	125	ND	ND	ND	ND	ND	ND	ND
H68S	March 8, 1984	18	ND	ND	ND	ND	ND	ND	ND	ND
H69S	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H69D	May 17, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H70S	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H70M	May 17, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H70D	May 17, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H71S	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H71D	May 17, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H72S	May 16, 1984	179	563	ND	ND	ND	ND	ND	ND	(a)
H72D	May 16, 1984	7.5	47	ND	ND	ND	ND	ND	ND	ND
H73S	May 16, 1984	84	ND	ND	ND	ND	ND	ND	ND	(b)
H73M	May 16, 1984	ND	18	ND	ND	ND	ND	ND	ND	ND
H73D	May 16, 1984	ND	10	ND	ND	ND	ND	ND	ND	ND
H74S	May 16, 1984	18	ND	ND	ND	ND	ND	12	ND	ND
	May 8, 1985	18	ND	ND	ND	ND	ND	46	ND	ND
H74M	May 16, 1984	ND	ND	700	ND	ND	ND	ND	ND	ND
	May 8, 1985	ND	ND	ND	ND	ND	ND	ND	ND	ND
H74D	May 16, 1984	3.4	41	ND	ND	ND	ND	ND	ND	ND
	May 8, 1985	ND	ND	ND	ND	ND	ND	ND	ND	(c)
H75S	June 27, 1984	7.2	ND	ND	ND	ND	ND	ND	ND	(d)
H76S	June 27, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H76D	June 27, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H77S	June 27, 1984	ND	45	ND	ND	ND	ND	ND	ND	ND
	August 30, 1984	ND	95	ND	ND	ND	ND	ND	ND	ND
H77D	June 27, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
H78S	June 27, 1984	ND	36	218	9.3	ND	188	ND	ND	(e)
H78D	June 27, 1984	ND	252	7.2	ND	ND	ND	ND	ND	ND

[a] Water also contained 15 μg/L 1,1,1 trichloroethane

[b] Water also contained 7.1 μg/L 1,1,1 trichloroethane

[c] Water also contained 18 μg/L 1,1,1 trichloroethane

[d] Water also contained 12 μg/L bromoform

[e] Water also contained 54 μg/L 1,1,1 trichloroethane; 22 μg/L 1,1 dichloroethane

Table 2.--Analyses of volatile organic compounds in ground water at Wurtsmith Air Force Base--Continued

Well number	Date	Tri-chloro-ethylene	1,2 Di-chloro ethylene	Benzene	Toluene	Xylene	Ethyl benzene	Tetra-chloro-ethylene	Methylene chloride	Other
H79S	June 27, 1984	ND	20	ND	ND	ND	ND	ND	ND	ND
H79D	June 27, 1984	ND	6.0	ND	ND	ND	ND	ND	ND	ND
H80S	May 9, 1985	ND	15	ND	ND	ND	ND	ND	ND	ND
H80D	May 9, 1985	ND	134	ND	ND	ND	ND	ND	ND	ND
H81S	May 9, 1985	ND	ND	ND	27	ND	ND	ND	ND	ND
H81D	May 9, 1985	ND	65	ND	ND	ND	ND	ND	ND	ND
H82S	June 10, 1985	5	16	ND	ND	ND	ND	ND	ND	ND
H82D	May 8, 1985	ND	139	ND	ND	ND	ND	ND	ND	ND
H83S	May 8, 1985	ND	9.5	157	ND	19	98	ND	ND	ND
H83D	May 8, 1985	ND	32	ND	ND	46	67	ND	ND	ND
H84S	May 8, 1985	ND	ND	139	ND	ND	ND	ND	ND	ND
H84D	May 8, 1985	5.4	ND	ND	ND	ND	ND	ND	ND	ND
H85S	May 8, 1985	ND	ND	917	ND	17	7.5	ND	ND	ND
H85D	May 8, 1985	ND	ND	ND	ND	ND	ND	ND	ND	ND
O4S	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
O4D	June 26, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
O6S	April 27, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
PW1,2	September 27, 1983	155	36	ND	ND	ND	ND	3.9	ND	ND
PW1,2,4	April 27, 1984	357	34	ND	ND	ND	ND	ND	ND	ND
PW2	April 27, 1983	508	37	ND	ND	ND	ND	6.0	ND	ND
	September 27, 1983	206	40	ND	ND	ND	ND	4.9	ND	ND
	April 25, 1984	318	108	ND	ND	ND	ND	6.8	ND	ND
PW4	April 27, 1983	224	22	ND	ND	ND	ND	ND	ND	ND
	January 25, 1984	240	29	10	ND	ND	ND	ND	ND	ND
	April 25, 1984	388	82	27	ND	ND	ND	7.8	ND	ND
	May 8, 1985	293	38	ND	ND	ND	ND	ND	ND	ND
Pc[a]	September 27, 1983	162	23	ND	ND	ND	ND	4.8	ND	ND
	January 25, 1984	246	42	ND	ND	ND	ND	4.4	ND	ND
	April 25, 1984	308	108	13	ND	ND	ND	ND	ND	ND
	May 8, 1985	201	25	6.6	ND	ND	ND	6.2	ND	ND
PC	April 25, 1984	6.4	16	300	ND	ND	ND	7.1	ND	ND
R4D	April 27, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
R5S	May 7, 1985	5.7	ND	59	ND	ND	ND	ND	ND	ND
R5D	May 7, 1985	ND	51	ND	ND	ND	ND	ND	ND	ND
R6S	April 27, 1983	5.0	ND	ND	ND	ND	ND	13	ND	ND
R6D	May 7, 1985	ND	2.5	ND	ND	ND	ND	ND	ND	ND

[a] Composite of PW1, PW2, PW3 and PW4

Table 2.--Analyses of volatile organic compounds in ground water at Wurtsmith Air Force Base--Continued

Well number	Date	Tri-chloro-ethylene	1,2 Di-chloro-ethylene	Benzene	Toluene	Xylene	Ethyl benzene	Tetra-chloro-ethylene	Methylene chloride	Other
R7D	April 27, 1983	25	ND	ND	ND	ND	ND	ND	ND	ND
	September 27, 1983	30	3.6	ND	ND	ND	ND	ND	ND	ND
	May 7, 1985	18	6.6	3.3	ND	ND	ND	ND	ND	ND
R10S	April 27, 1983	ND	ND	381	ND	ND	474	ND	ND	(a)
	November 7, 1983	ND	ND	775	ND	272	363	ND	ND	ND
R10D	April 27, 1983	7.1	ND	39	ND	ND	ND	ND	ND	ND
	November 7, 1983	ND	ND	12	ND	ND	4.5	ND	5.3	ND
R13D	April 10, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
R17S	April 27, 1983	18	ND	ND	ND	ND	ND	11	ND	ND
	December 1, 1983	6.3	ND	ND	ND	ND	ND	ND	5.3	ND
R17D	April 27, 1983	90	ND	ND	ND	ND	ND	ND	ND	ND
	September 27, 1983	25	13	ND	ND	ND	ND	ND	ND	ND
	November 12, 1983	40	ND	ND	ND	ND	ND	ND	4.5	ND
R18S	April 27, 1983	ND	7.8	ND	2.8	ND	ND	ND	ND	ND
	November 8, 1983	33	8.8	ND	ND	ND	ND	ND	ND	ND
R18D	November 8, 1983	ND	ND	ND	3.3	ND	ND	ND	5.7	ND
R19D	April 10, 1984	7.6	ND	ND	ND	ND	ND	ND	ND	ND
R27D	April 10, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
R29S	April 10, 1984	20	ND	ND	ND	ND	ND	ND	ND	ND
R34S	April 10, 1984	31	ND	ND	ND	ND	ND	11	ND	ND
R36S	April 10, 1984	65	ND	ND	ND	ND	ND	ND	ND	ND
R36D	April 10, 1984	135	ND	ND	ND	ND	ND	ND	ND	ND
R39S	October 19, 1982	ND	ND	ND	ND	ND	ND	ND	ND	ND
	June 27, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
R49S	April 10, 1984	50	ND	ND	ND	ND	ND	ND	ND	ND
R59S	April 10, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
R79S	April 27, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
R80S	April 27, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
R81S	April 27, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
R82S	April 27, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
R83S	April 27, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
R84S	April 27, 1983	ND	ND	ND	ND	ND	ND	ND	ND	ND
R85S	April 27, 1983	5.4	ND	ND	ND	ND	ND	33	ND	ND
	November 8, 1983	ND	ND	ND	3.1	ND	ND	16	ND	ND
R86S	November 7, 1983	ND	ND	ND	3.4	ND	ND	ND	ND	ND
R86D	November 7, 1983	ND	ND	ND	3.3	ND	ND	ND	ND	ND

[a] Water also contained other hydrocarbons

Table 2.--Analyses of volatile organic compounds in ground water at Wurtsmith Air Force Base--Continued

Well number	Date	Trichloroethylene	1,2 Dichloroethylene	Benzene	Toluene	Xylene	Ethyl benzene	Tetrachloroethylene	Methylene chloride	Other
R87D	November 8, 1983	ND	ND	ND	62	ND	ND	ND	ND	ND
R88S	April 27, 1983	ND	349	10	ND	ND	ND	ND	ND	(a)
	June 27, 1984	ND	34	8.3	ND	ND	ND	ND	ND	(b)
R88D	April 27, 1983	ND	222	7.2	ND	ND	ND	ND	ND	(c)
	June 27, 1984	ND	52	ND	ND	ND	ND	ND	ND	ND
NR	October 19, 1982	ND	ND	ND	ND	ND	ND	ND	ND	ND
NS	October 19, 1982	ND	ND	ND	ND	ND	ND	ND	ND	ND
	August 30, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
NK	August 30, 1984	ND	ND	ND	ND	ND	ND	ND	ND	ND
KC	April 27, 1983	4.2	ND	ND	ND	ND	ND	ND	ND	ND
Treatment effulent plant	May 12, 1982	ND	ND	ND	ND	ND	ND	ND	ND	ND
Three Pipes Drain (Site 2)	December 1, 1983	ND	ND	ND	2.7	ND	ND	ND	ND	ND

[a] Water also contained 105 μg/L 1,1 dichloroethane

[b] Water also contained 23 μg/L 1,1 dichloroethane

[c] Water also contained 11 μg/L 1,1 dichloroethane; 5.4 μg/L 1,2 dichloroethane

Table 6.--Chemical and physical analyses of ground water
[Analyses by U.S. Geological Survey.]

Well number	Date	Specific conductance (µS/cm)	Temp-erature (°C)	Calcium, total (mg/L)	Chloride, dissolved (mg/L)	Ammonia (mg/L as N)	Nitrite (mg/L as N)	Nitrate (mg/L as N)	Organic nitrogen (mg/L as N)	Nitrogen, total (mg/L as N)	Iron, total (µg/L)	Lead, total (µg/L)	Man-ganese, total (µg/L)	Oil and grease, total (µg/L)
AF18	June 11, 1982[a]	313	--	--	2.2	0.18	0.02	0.38	0.72	1.3	--	--	--	--
AF19	May 12, 1984	250	--	--	1.6	--	.06	3.3	--	--	--	--	--	--
	June 11, 1982[b]	240	--	--	1.7	2.7	.38	3.8	.20	7.1	--	--	--	--
G20S	June 11, 1982	345	--	--	2.6	.02	.01	2.9	19	22	--	--	--	--
H15S	May 12, 1982	287	--	--	2.0	--	.01	6.0	--	--	--	--	--	--
	June 10, 1982	278	--	--	.8	.01	.01	6.5	.70	7.2	--	--	--	--
H16S	May 12, 1982	307	--	--	1.8	--	.01	2.6	--	--	--	--	--	--
	June 10, 1982	313	--	--	1.4	.01	.01	3.5	.30	3.8	--	--	--	--
H17S	May 12, 1982	312	--	--	5.3	--	.01	2.4	--	--	--	--	--	--
	June 10, 1982	309	--	--	4.7	.01	.01	2.8	2.0	4.8	--	--	--	--
H18S	May 12, 1982	429	--	--	3.8	--	.01	13	--	--	--	--	--	--
	June 10, 1982	405	--	--	2.9	.01	.01	12	.60	13	--	--	--	--
H18D	May 12, 1982	340	--	--	2.9	--	.41	6.9	--	--	--	--	--	--
	June 10, 1982	275	--	--	1.5	.01	.17	1.6	.90	2.7	--	--	--	--
H19S	May 12, 1982	218	--	--	.8	--	.01	.40	--	--	--	--	--	--
	June 10, 1982	226	--	--	.6	.01	.01	.40	.60	1.0	--	--	--	--
H20S	May 12, 1982	276	--	--	2.1	--	.01	1.7	--	--	--	--	--	--
	June 10, 1982	277	--	--	2.0	.01	.01	1.7	.20	1.9	--	--	--	--
H21S	May 12, 1982	283	--	--	2.8	--	.02	.88	--	--	--	--	--	--
	June 10, 1982	270	--	--	1.1	.01	.01	.30	1.9	2.2	--	--	--	--
H21D	May 12, 1982	740	--	--	73	--	.01	.09	--	--	--	--	--	--
	June 10, 1982[c]	461	--	--	--	--	--	--	--	--	--	--	--	--
	June 10, 1982[d]	748	--	--	60	.10	.01	.10	1.1	1.3	--	--	--	--
H22S	May 12, 1982	493	--	--	4.0	--	.02	4.1	--	--	--	--	--	--
	June 10, 1982[e]	457	--	--	--	--	--	--	--	--	--	--	--	--
	June 10, 1982[f]	499	--	--	1.9	.02	.01	3.7	.58	4.3	--	--	--	--

[a] Sample collected at 0900
[b] Sample collected at 0830
[c] Sample collected at 1718
[d] Sample collected at 1730
[e] Sample collected at 1800
[f] Sample collected at 1815

Table 6.--Chemical and physical analyses of ground water--Continued

Well number	Date	Specific conductance (µS/cm)	Temp-erature (°C)	Calcium, total (mg/L)	Chloride, dissolved (mg/L)	Ammonia (mg/L as N)	Nitrite (mg/L as N)	Nitrate (mg/L as N)	Organic nitrogen (mg/L as N)	Nitrogen, total (mg/L as N)	Iron, total (µg/L)	Lead, total (µg/L)	Man-ganese, total (µg/L)	Oil and grease, total (mg/L)
H28S	November 7, 1983	515	13.0	--	--	--	--	--	--	--	370	1	1,300	<1
H29S	November 7, 1983	482	13.0	--	--	--	--	--	--	--	300	5	460	<1
H40S	November 7, 1983	484	11.5	--	--	--	--	--	--	--	270	4	370	<1
H41S	November 7, 1983	832	13.0	--	--	--	--	--	--	--	280	3	10	<1
H42S	November 7, 1983	779	13.0	--	--	--	--	--	--	--	2,300	4	1,200	2
H43S	November 7, 1983	572	13.0	--	--	--	--	--	--	--	4,800	4	260	<1
H43D	November 7, 1983	286	10.5	--	--	--	--	--	--	--	350	5	150	2
H44S	November 8, 1983	792	13.0	--	--	--	--	--	--	--	610	3	2,200	<1
H44D	November 8, 1983	456	12.0	--	--	--	--	--	--	--	470	5	200	<1
H45S	November 8, 1983	481	12.0	--	--	--	--	--	--	--	5,000	4	490	3
H46S	November 8, 1983	383	13.0	--	--	--	--	--	--	--	320	4	30	1
R10S	November 7, 1983	755	14.0	140	--	--	--	--	--	--	29,000	8	290	<1
R10D	November 7, 1983	1,390	11.0	210	--	--	--	--	--	--	18,000	9	120	2
R86S	November 7, 1983	378	14.5	60	--	--	--	--	--	--	350	3	<10	<1
R87D	November 8, 1983	559	11.0	98	--	--	--	--	--	--	4,600	5	170	3
Treatment plant effluent	May 12, 1982	782	--	--	40	--	0.11	0.57	--	--	--	--	--	--
	June 11, 1982	787	--	--	36	31	.09	.21	1.1	32	--	--	--	--

APPENDIX B: DEVELOPMENT AND CALIBRATION OF GROUND-WATER-FLOW MODEL

A description of the development and calibration of three ground-water-flow models of the ground-water system at Wurtsmith Air Force Base is given in Stark and others (1983), and no detailed treatment of the subject is included in this report. Mathematical simulation of ground-water flow was based on steady-state, two-dimensional, finite-difference models. These models were developed using a computer program described by Trescott, Pinder, and Larson (1976). One model, referred to in the earlier report as the "Base model," was used to describe general ground-water flow conditions for the entire Base. Models of two areas--the Building 43 plume area and the Alert Apron plume area--were developed for detailed evaluations. Each model was used to refine estimates of the aquifer's hydraulic parameters and to aid in calculating the rate and direction of ground-water flow.

As part of 1982-85 work, the "Base model" previously developed was modified by using a finer grid over the entire Base, extending the southern boundary of the modeled area, and using a single value of hydraulic conductivity.[7] Refinement of the Base model was possible largely because an additional 124 wells (and associated water levels) were available for calibration. In calibration, calculated water levels were compared to observed water levels. If the levels did not match, the hydraulic parameters were adjusted and new water levels were calculated. This procedure was repeated until a new "Base model" was calibrated. Figure 55 shows the boundary characteristics of the new Base model.

Hydraulic conductivity, which ranges from 100 ft/d in the eastern part of the Base to 150 ft/d in the western part in earlier model, was changed to 120 ft/d in the new Base model. Recharge was changed from 15 in/yr to 17 in/yr.

The Base model, enclosed by an impermeable boundary, covers an area of about 13 mi^2. It encompasses the entire Base and an area to the east and south including Van Etten Lake, Van Etten Creek, and part of the Au Sable River. Flow in the sand and gravel aquifer that underlies the Base was simulated by dividing the area into cells. All cells were represented by squares that measured 120 ft along a side, rather than 742 ft used in the earlier model.

The western side of the model area is bounded at some places by cells that represent constant heads (water levels) and at other places by cells that represent no-flow conditions. Constant-head cells were located to coincide with the 620-foot equipotential line that as determined from field data. No-flow cells were located along ground-water-flow lines.

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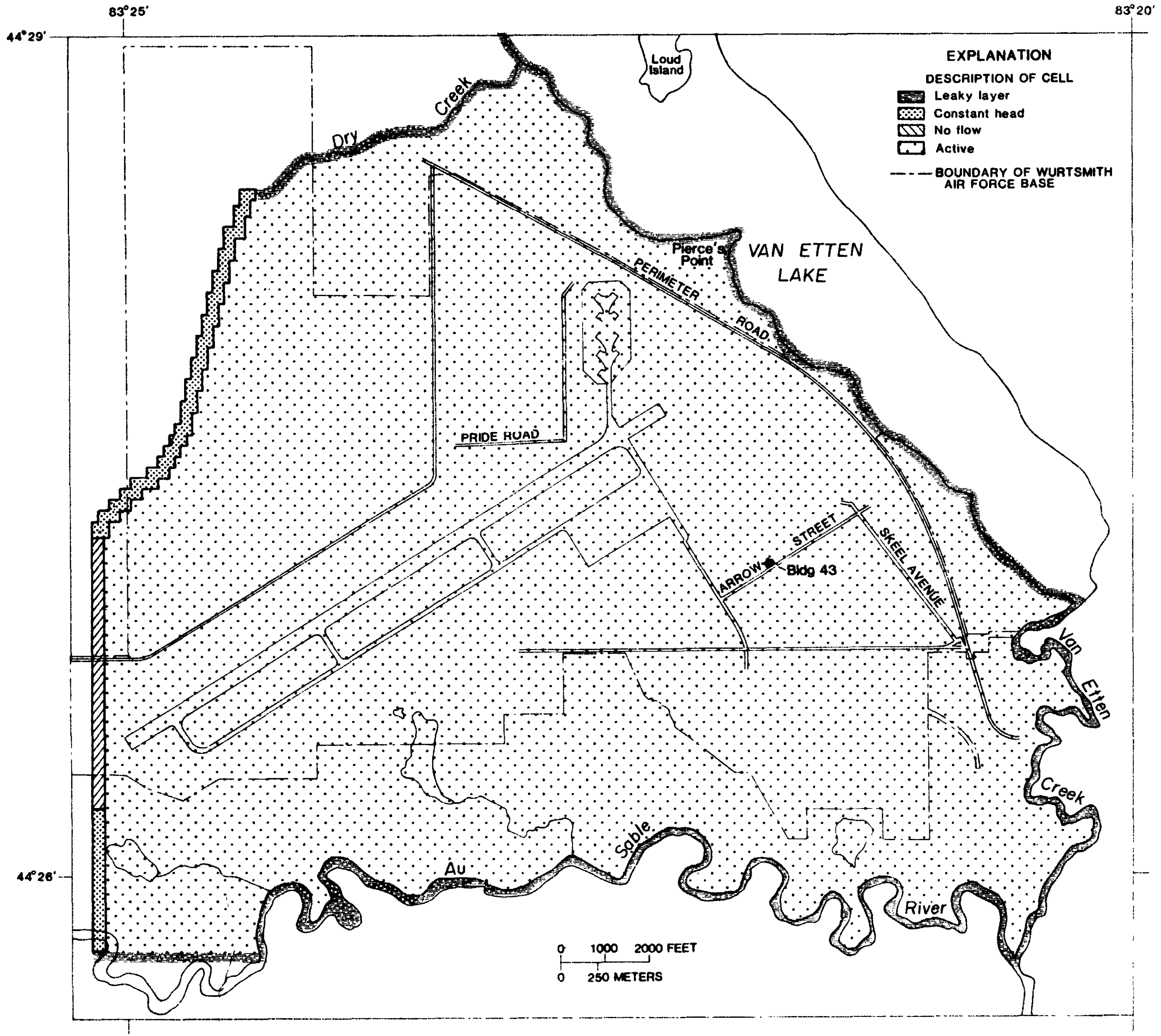
[7] Gary C. Huffman, assisted by Norman G. Grannemann, modified and calibrated the Base model used in this study.



Base from U.S. Geological Survey 1:62,500 quadrangle and Wurtsmith Air Force Base 1:7,200 map

Figure 55.--Boundary characteristics of 1982-85 Wurtsmith Air Force Base model.

The southern side of the model area represents the Au Sable River. The Au Sable River was simulated as leaky-streambed cells rather than as constant-head cells used in the earlier model. Leaky-streambed cells simulate flow from the aquifer through confining beds to an overlying surface-water feature. Three-Pipes Drain, Allen Lake, Duel Lake, and one unnamed lake were added to the model and simulated as leaky-streambed cells.

The eastern side of the model area represents Van Etten Lake and Van Etten Creek. The lake and creek bottoms were simulated as leaky-streambed cells. Hydraulic head values for those parts of the leaky-streambed cells overlying the confining bed were set to a level that represented the water surface of the lake and stream. Use of leaky-streambed cells was justified because simulations showed that the hydraulic conductivity of the streambed and lakebed influenced the shape of the water table in the vicinity of the shores. The streambed and lakebed were simulated as having a uniform thickness of 1 ft. Model results best matched field data when the values of hydraulic conductivity assigned the leaky-streambed cells were 0.02 ft/d for confining beds under Van Etten Creek and the southeastern part of Van Etten Lake, and 0.07 ft/d for confining beds under the northwestern part of the lake.

Dry Creek, along the northern side of the model area, was simulated as a leaky-streambed rather than as a no-flow boundary.

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