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Sewage Plume in a Sand and Gravel Aquifer, Cape Cod, Massachusetts

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United States
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Prepared in cooperation
with the Massachusetts
Department of Environmental
Quality Engineering Division
of Water Pollution Control



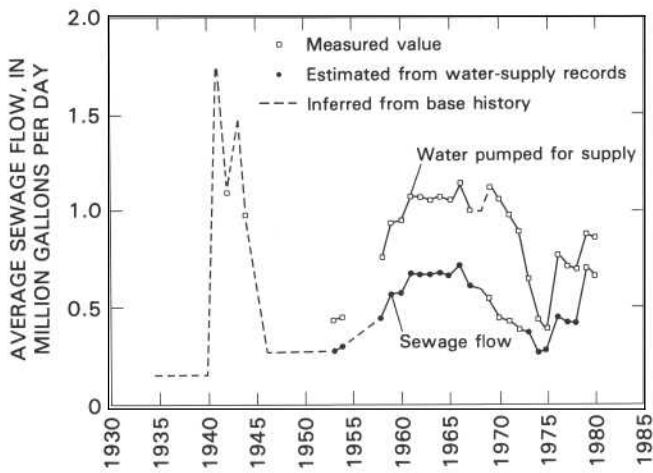


Figure 4. Volume of sewage treated at the Otis Air Force Base treatment plant from 1936 through 1980.

lic conductivity, the bedrock is assumed to be the bottom of the ground-water flow system.

Hydrology

Ground water in the aquifer occurs under unconfined, or water-table, conditions in which the top of the ground water is the water table. The water table slopes

to the south and southwest at 8 ft/mi (fig. 6). The water-table contour map shown in figure 6 is based on water levels measured in 50 wells and 6 ponds during November 1979. Water levels during this period were near average for the period of 1963–76 (Guswa and LeBlanc, 1981). Seasonal variations in aquifer recharge cause the altitude of the water table to fluctuate 1 to 3 feet each year. The altitude of the water table is highest in the spring and lowest in late fall.

The primary sources of ground water are recharge by precipitation and inflow from adjacent parts of the aquifer. Surface runoff is negligible because the sandy soils are very permeable. Therefore, precipitation which does not return to the atmosphere by evaporation and transpiration recharges the aquifer. The estimated recharge to the aquifer is 21 in/yr, or about 45 percent of the average annual precipitation. A method based on empirical correlations between evapotranspiration and climatic factors and developed by Thornthwaite and Mather (1957) was applied to climatic data to obtain this estimate.

The water-table contour map (fig. 6) shows that inflow of ground water from adjacent parts of the aquifer occurs mostly across the northern boundary of the study area. The rate of inflow, 5 to 8 Mgal/d, was estimated from Darcy's Law and flow-net analysis of a regional water-table map (LeBlanc and Guswa, 1977).

Ground water in the study area generally flows south

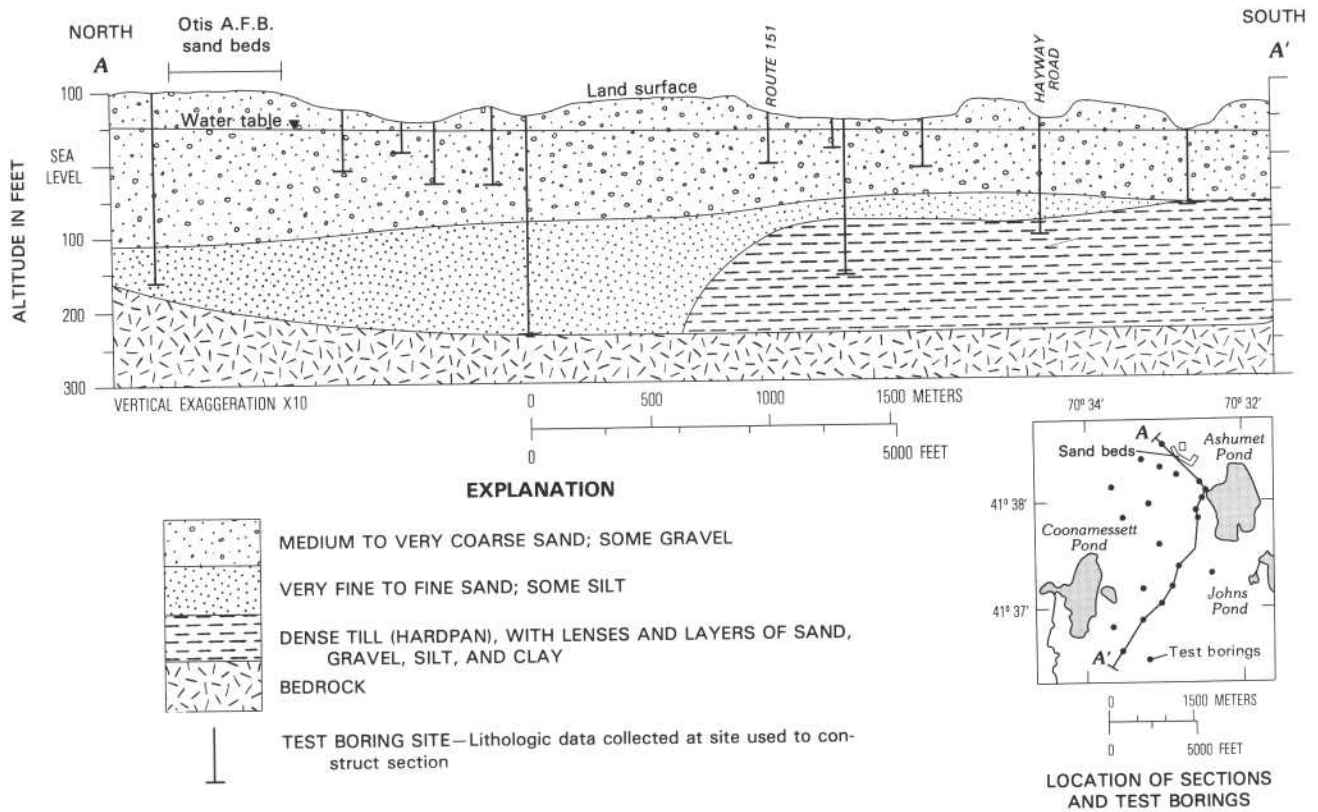
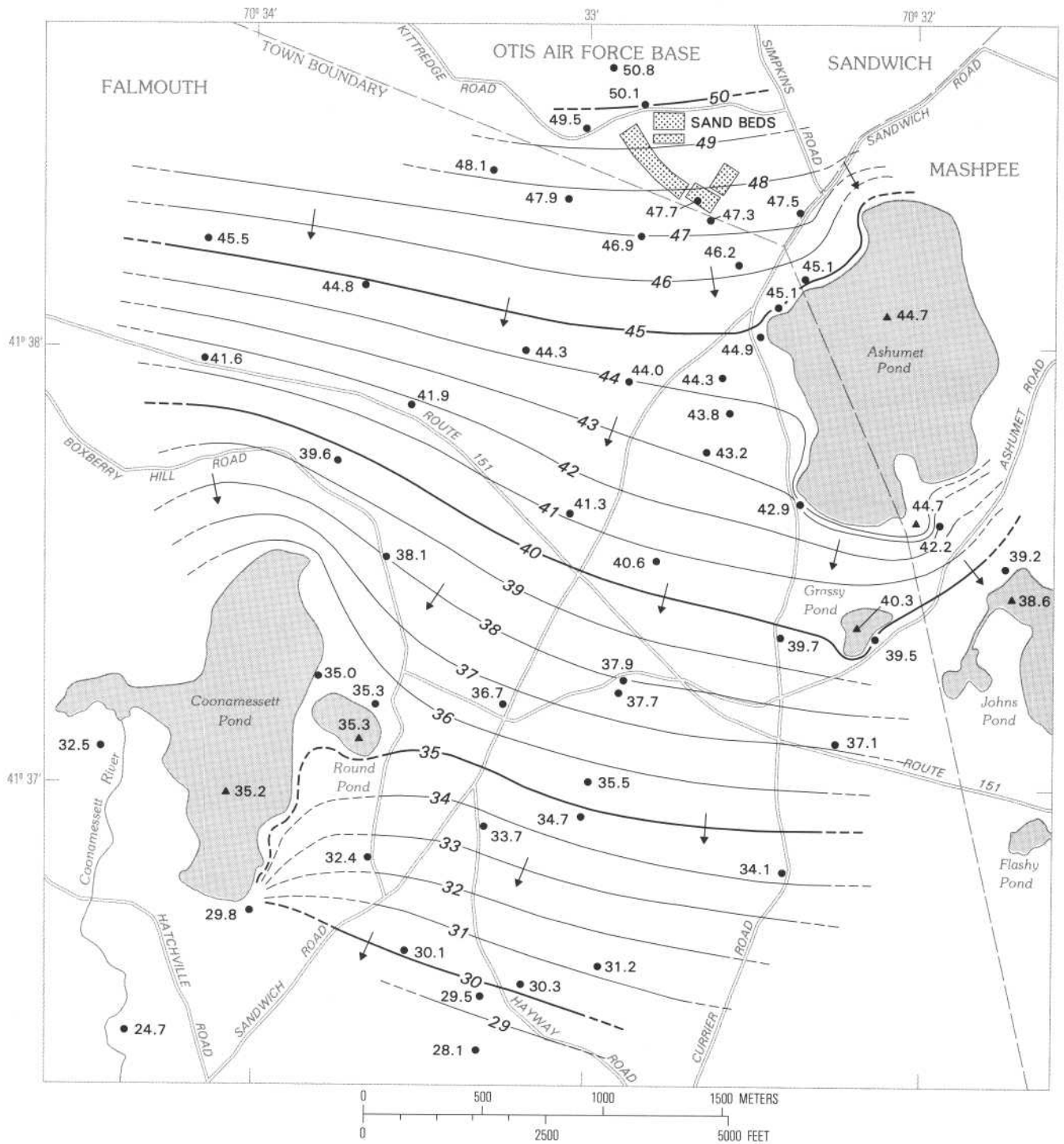


Figure 5. Geologic section showing hydrogeologic units in the study area.



EXPLANATION

- 32.0 WATER-LEVEL OBSERVATION WELL—Number is altitude of water level, in feet above sea level
- ▲ 44.7 POND LEVEL—Number is altitude of pond water level, in feet above sea level
- 35— WATER-TABLE CONTOUR, NOVEMBER 1979— Shows altitude of water table. Contour interval 1 foot. Datum is sea level. Arrows show direction of ground-water movement. Contours dashed where inferred

Figure 6. Water-table contour map and direction of ground-water flow.

and southwest, although the flow pattern is distorted near the large ponds. The direction of flow was inferred from the water-table map (fig. 6). The horizontal component

of flow is assumed to be perpendicular to the water-table contours because, in horizontal directions, the hydraulic conductivity of the sand and gravel is essentially

homogeneous and isotropic. Ground-water flow is essentially horizontal at most locations. Hydraulic head is constant with depth at the six sites where water levels have been measured in clusters of observation wells.

The estimated rate of ground-water flow through the sand and gravel is 0.8 to 2.3 ft/d. This estimate was obtained from Darcy's Law:

$$\bar{v} = \frac{K(dh/dl)}{n} \quad (1)$$

where

\bar{v} = average velocity

K = hydraulic conductivity

dh/dl = hydraulic gradient (change in water-table altitude with distance), and

n = effective porosity.

Using the values of hydraulic conductivity and water-table slope given above and assuming an effective porosity of 0.20 to 0.40 for sand and gravel,

$$\bar{v} = \frac{(200 \text{ to } 300 \text{ ft/d})(8 \text{ ft}/5280 \text{ ft})}{0.20 \text{ to } 0.40} = 0.8 \text{ to } 2.3 \text{ ft/d.} \quad (2)$$

The average velocity of ground water in the fine to very fine sand and silt and the sandy till is lower than the velocity in the sand and gravel because the hydraulic conductivity of the fine-grained sediments is much lower than the hydraulic conductivity of the sand and gravel.

Most ground water flows across the southern boundary of the area and ultimately discharges to streams, ponds, and wetlands in southern Falmouth and to Nantucket Sound. Ground water also discharges to ponds, although only Coonamessett and Johns Ponds are drained by streams (fig. 6). The net discharge through wells is small because most water is returned to the aquifer by onsite wastewater recharge and by return flows from irrigation. Direct evapotranspiration of ground water probably is small because the water table is more than 10 feet below land surface in much of the study area.

RESULTS OF CHEMICAL ANALYSES

Introduction

Water samples collected during this study were analyzed for (1) common chemical constituents, (2) physical properties, and (3) selected indicators of sewage contamination such as detergents to locate the plume and define its chemical composition. Results of chemical analyses of selected samples of (1) treated sewage discharged to the sand beds, (2) ground water in the plume, and (3) ground water outside the plume are shown in table

2. These analyses show that the concentrations of most dissolved substances in the plume are intermediate between the concentrations in the treated sewage and the concentrations in the uncontaminated ground water.

The chemical analyses of the Otis AFB treatment-plant effluent shown in table 2 (columns 1, 2, and 3) are indicative of the general chemical quality of the treated sewage, although the composition of the treated sewage varies seasonally and has varied during the 45 years that the sand beds have been in use. The chemical analysis of the uncontaminated ground water (column 6) is typical of the chemical quality of ground water on Cape Cod that has not been significantly affected by man's activities and is low in dissolved solids (Frimpter and Gay, 1979, p. 3-4); the dissolved-solids concentrations are low because the aquifer is sand and gravel composed predominantly of quartz and some feldspar derived from crystalline bedrock. The ground water has a low alkalinity because of the absence of carbonate minerals in the aquifer. The pH of uncontaminated ground water in the study area typically is less than 6.0. The samples of ground water in the plume were collected from wells located in the core of the contaminated zone, at distances along the ground-water flow path of 3,000 feet (column 4) and 7,000 feet (column 5) from the sand beds.

The water samples were collected from 66 wells during May 1978 through May 1979. Each well was sampled once, although a few wells were sampled several times during this period. Ideally, samples should be collected for chemical analyses over a much shorter period. Interpretation of the distribution of contaminants in the plume from analyses of samples collected over a 1-year period may provide an averaged or distorted view of the distributions of contaminants. However, preliminary analyses of a second set of samples collected in late 1980 indicate that the distribution of contaminants shown by the initial set of samples had not changed significantly. Collection and analysis of water samples over a longer period of time would be required to determine whether or not the distributions of dissolved substances are changing with time.

Maps and Sections Used to Present Results

Eleven chemical constituents and physical properties were selected to show the vertical and horizontal extent of the plume and to show the distribution of contaminants in the plume. These constituents and properties are: specific conductance, temperature, boron, chloride, sodium, phosphorus, nitrogen (total of all species), ammonia, nitrate, dissolved oxygen, and detergents. These constituents and properties were selected because they (1) provide a clear contrast between contaminated and uncontaminated water, (2) move through the sand and gravel

Table 2. Chemical analyses showing quality of treated sewage, contaminated ground water in the plume, and uncontaminated ground water

[Analyses by U.S. Geological Survey (columns 1, 2, 4-6) and Vaccaro and others, 1979 (column 3). Concentrations are in milligrams per liter, except as indicated.]

Constituents and properties	Treated sewage, Otis Air Force Base			Contaminated ground water		
	U.S. Geological Survey		Vaccaro and others (1979) ¹	Well FSW ² 258 3,000 feet from beds	Well FSW 264 7,000 feet from beds	Uncontaminated ground water Well FSW 242
	(1)	(2)	(3)	(4)	(5)	(6)
Collection date	11-20-79	8-29-80	1-74 to 3-78	1-23-79	2-6-79	1-23-79
Top of well screen below water table, ft	---	---	---	57	73	51
Bottom of well screen below water table, ft	---	---	---	60	76	54
Specific conductance, $\mu\text{mho/cm}$	390	394	343	377	300	46
Temperature, $^{\circ}\text{C}$	11.0	22.5	---	11.0	10.0	11.0
Dissolved oxygen	---	5.0	---	⁴ 0.0	⁶ .0	---
pH.....	6.8	5.9	6.9	7.0	6.2	5.8
Dissolved solids, sum of constituents	178	155	---	⁵ 117	⁷ 152	⁷ 39
Alkalinity (as CaCO_3).....	30	3	---	58	50	6
Bicarbonate (as HCO_3).....	36	7	---	71	61	7
Chloride (Cl).....	33	34	27	28	27	8.1
Sulfate (SO_4)	37	34	25	33	38	5.2
Fluoride (F)4	.2	---	.2	.1	<.1
Boron (B), $\mu\text{g/L}$	510	450	560	280	410	7
Calcium (Ca)	12	13	8.6	5.7	15	1.8
Magnesium (Mg).....	4.4	5.5	3.5	5.0	8.3	1.7
Sodium (Na).....	52	43	41	32	32	5.5
Potassium (K)	8.4	9.2	9.6	9.6	1.9	.6
Silica (SiO_2)	13	14	---	⁵ 6.0	⁷ 11	⁷ 9.1
Total nitrogen (N).....	19	24	---	16	3.6	.42
Nitrate (NO_3 as N).....	16	12	8.2	<.1	3.2	.42
Nitrite (NO_2 as N).....	.35	.50	.2	<.01	.02	<.01
Ammonia (NH_4 as N).....	.72	6.4	6.9	14	.13	.01
Organic nitrogen (as N).....	2.6	5.6	---	2.0	.26	<.1
Total phosphorus (P).....	6.0	9.0	---	<.01	.02	.01
Orthophosphorus (PO_4 as P).....	6.1	6.7	7.2	<.01	.01	<.01
Total organic carbon (as C).....	16	19	---	⁵ 7.0	⁷ 3.5	⁷ 2.1
MBAS ³ (detergents).....	.2	.4	---	.5	2.6	.0
Fecal coliform, colonies/100 ml ...	---	---	---	---	---	---
Iron, total recoverable (Fe), $\mu\text{g/L}$	---	590	191	⁵ 810	⁷ 140	⁷ 70
Manganese, total recoverable (Mn), $\mu\text{g/L}$	---	30	20	⁵ 880	⁷ 30	⁷ <10
Sulfide (as S)	---	---	---	.0	---	---

¹Average values

²U.S. Geological Survey well numbers

³MBAS (methylene blue active substances)

⁴Collection date, 7-12-79

⁵Collection date, 8-27-80

⁶Collection date, 7-25-79

⁷Collection date, 8-28-80

aquifer and can be used to track the contaminated ground water, or (3) indicate contamination by sewage.

The distribution of the eleven constituents and properties in three dimensions is illustrated in this report with maps and sections. A diagram showing the general relationship between the plume of contaminated ground

water and the maps and sections presented in subsequent parts of this report is shown in figure 7.

Map views of the plume were prepared from chemical analyses of water samples collected from wells with screens set in a 25-foot-thick zone of the aquifer. This zone intersects the center line of the plume (surface A

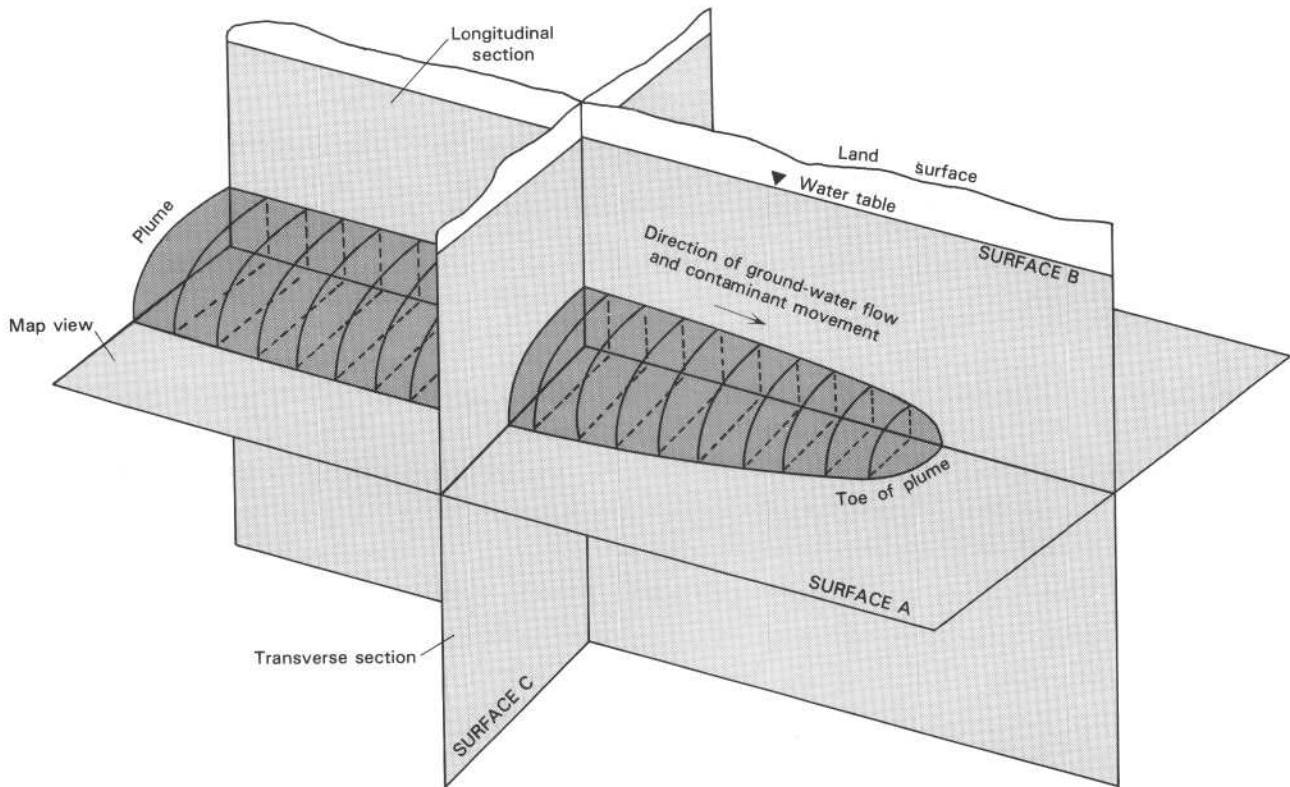


Figure 7. Idealized diagram showing relationship between the center of the plume and the map and sections used to describe the distributions of contaminants.

in fig. 7). Analyses of water collected from wells open to the aquifer above or below this lateral zone were not used to prepare the maps. Maps prepared with data collected from wells screened at all depths in the aquifer could misrepresent the areal distribution of contaminants in the aquifer.

Sections along the axis of the plume (surface B in fig. 7) and perpendicular to the axis of the plume (surface C in fig. 7) were prepared from analyses of water samples collected from clusters of wells screened at different depths in the aquifer. Most of the wells used to prepare the sections are open to 3 feet of the aquifer at the bottom of the wells. Two wells used to prepare the longitudinal sections have 10-foot-long screens.

Selected Constituents and Properties

Specific Conductance and Temperature

Specific conductance, which is easily measured in the field, was used to map the extent of the plume and to indicate the relative concentration of dissolved substances in the contaminated ground water. Specific conductance is a measure of the ability of water to conduct an electrical current, which is related to the concentrations of dissolved ionic substances in the water. Because many

of the dissolved substances in ground water are ionic substances, specific conductance is an indicator of the dissolved-solids concentration of ground water (Frimpter and Gay, 1979, p. 3).

The specific conductance of the treated sewage is four to five times higher than the maximum observed conductance of the uncontaminated ground water, 80 μmho (micromhos per centimeter at 25° Celsius), because the dissolved-solids concentration of water is increased when water is used for domestic and industrial purposes. The conductance of the ground water contaminated by the treated sewage therefore is higher than the conductance of the uncontaminated ground water. The plume of contaminated ground water is delineated by a zone of elevated conductance shown in figure 8. The conductance of ground water in the plume exceeds 200 μmho in a zone that is 2,000 to 2,500 feet wide and 8,000 feet long.

The longitudinal axis of the plume is oriented in the direction of ground-water flow shown in figure 6. This observation is consistent with descriptions of other plumes in sand and gravel (Kimmel and Braids, 1980; Hughes, 1975) which show that the contaminants are transported primarily by the flowing ground water. The plume extends to at least 11,000 feet downgradient of the sand beds. Wells were not drilled and water samples were not collected beyond 11,000 feet from the beds in this study,

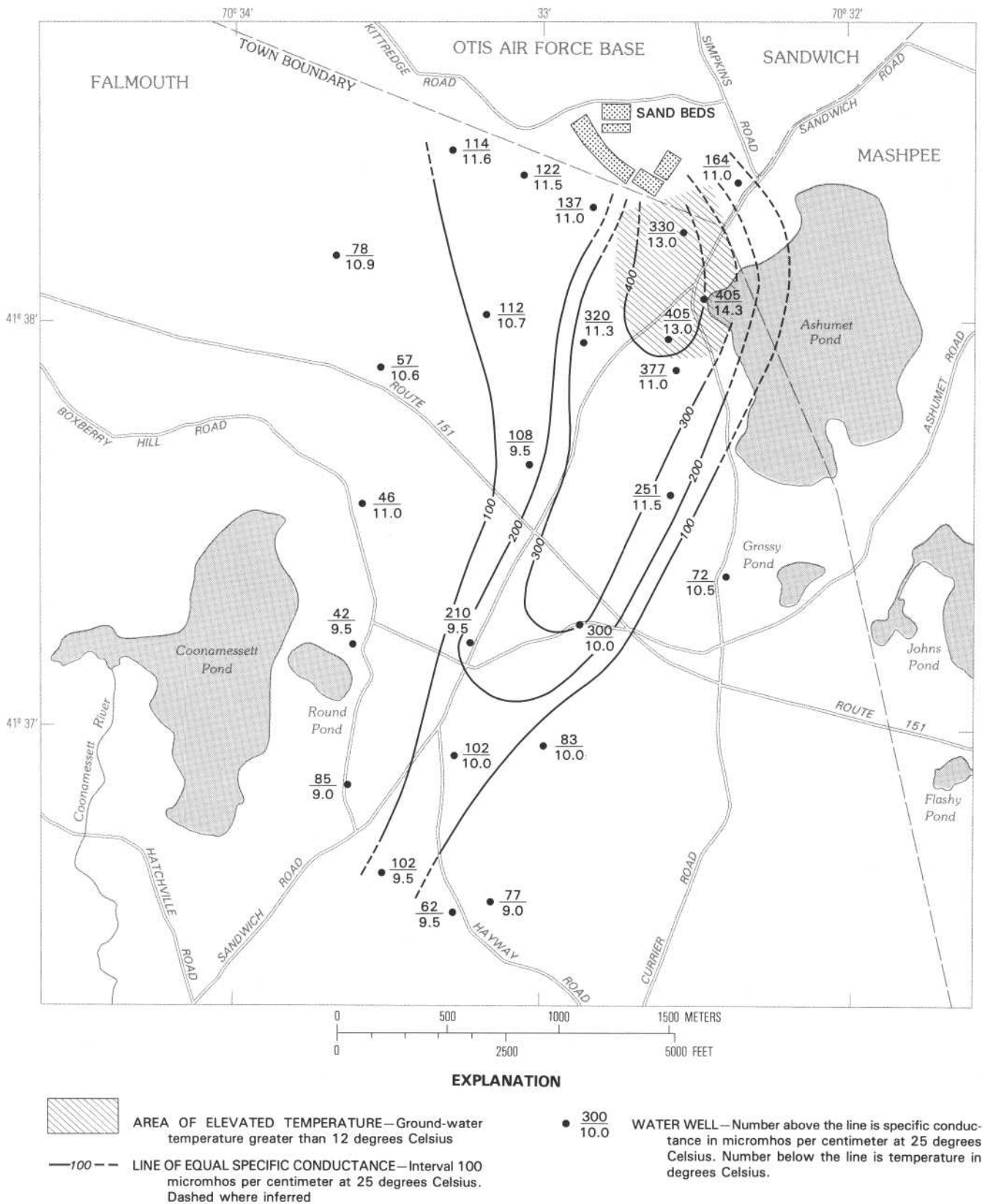


Figure 8. Areal distribution of specific conductance and temperature of ground water, May 1978 through May 1979.

so the lines of equal specific conductance in figure 8 have not been drawn beyond this distance. However, the plume undoubtedly extends farther than 11,000 feet from the sand beds. The dashed lines of equal specific conductance through Ashumet Pond are shown in figure 8 because evidence discussed later in this report suggests that the plume passes beneath the bottom of the pond.

Ground water in the center of the plume is warmer than the surrounding ground water at least as far as 2,600 feet from the sand beds (fig. 8). Temperatures as high as 14.0°C were measured in the center of the plume, while the ambient ground-water temperature generally is 9.5°C to 11.0°C. The higher temperatures in the plume may be the result of chemical and biochemical reactions occurring in the contaminated ground water. The most likely cause of the observed temperature pattern, however, is the seasonal pattern of land disposal of the treated sewage. More sewage is treated and recharged to the aquifer during the summer when the effluent is warmer than the uncontaminated ground water than during the winter when the effluent is cooler than the uncontaminated ground water.

Boron

Boron concentrations in the ground water also were used to show the extent of the plume. The longitudinal and transverse sections in figure 9 show that boron concentrations in the plume exceed 100 µg/L. The boron concentrations in the center of the plume are as high as 410 µg/L, and the uncontaminated ground water generally contains less than 50 µg/L boron. The boron content of the treated sewage (table 2) is 500 µg/L. The major sources of boron in the sewage are detergents and other cleaning agents. Human wastes and household and industrial chemicals also add some boron to the sewage.

Several characteristics of the plume are illustrated in figure 9 by the shape of the zone containing more than 100 µg/L boron. At 3,000 feet downgradient of the sand beds, the plume is 75 feet thick, and the center of the plume is 75 feet below the water table. The plume is overlain by 20 to 50 feet of uncontaminated ground water. The bottom of the plume generally coincides with the boundary between the sand and gravel and the fine to very fine sand and silt and sandy till (fig. 5).

Boron is a good indicator of the shape and extent of the plume because (1) the concentration of boron is much higher in the treated sewage than in the uncontaminated ground water, and (2) the boron moves readily in the aquifer. The longitudinal section of the plume in figure 9 shows that boron movement in the sand and gravel is not appreciably retarded by chemical reactions or adsorption onto aquifer materials. Boron adsorption onto sediments has been reported by Bassett (1976, p. 202–208).

However, the movement of boron in sand and gravel aquifers without significant retardation by chemical reactions or adsorption was also observed by Kimmel and Braids (1980, p. 20), Koerner and Haws (1979, p. 80), and Bouwer (1973, p. 172). The boron concentration of ground water in the center of the plume as far as 7,000 feet from the sand beds is as high as 80 percent of the boron concentration of the treated sewage. Thus, boron concentrations seem to be attenuated primarily by dilution, the mixing of contaminated and uncontaminated ground water.

Chloride and Sodium

The distributions of chloride and sodium also were used to delineate the plume (fig. 10). The concentrations of chloride and sodium are higher in the treated sewage than in the uncontaminated ground water partly because sodium and chloride are common constituents of the human diet. Samples of the treated sewage collected between March 1974 and August 1980 contained average concentrations of 30 mg/L chloride and 45 mg/L sodium (table 2), although the sodium content was variable. The uncontaminated ground water generally contains less than 15 mg/L chloride and less than 10 mg/L sodium.

The attenuation of chloride and sodium concentrations in the plume is due primarily to mixing of the contaminated and uncontaminated ground water. The chloride concentration in the center of the plume (fig. 10) exceeds 20 mg/L, 67 percent of the chloride concentration in the treated sewage, as far as 8,000 feet from the sand beds. The sodium concentration (fig. 10) exceeds 30 mg/L, 67 percent of the sodium concentration of the treated sewage, as far as 7,000 feet from the sand beds. The comparable attenuation of concentrations with distance suggests that both sodium and chloride are conservative species and move through the aquifer without significant retardation by chemical reactions and adsorption.

The observed conservative behavior of chloride and sodium in the plume is consistent with observations of chloride and sodium transport in sand and gravel on Long Island (Kimmel and Braids, 1980, p. 14). The conservative behavior of chloride in ground water has been described by Hem (1970, p. 172). Two factors reduce the likelihood that sodium will be removed by adsorption on the sediments. First, the sediments would be expected to have a low capacity for sodium adsorption because the sand and gravel is composed predominantly of quartz and feldspar and has a very low clay-mineral content. Second, the adsorption affinity of sodium is weaker than the adsorption affinity of the other common cations in the treated sewage (potassium, calcium, and magnesium).

Sections along the longitudinal axis of the plume

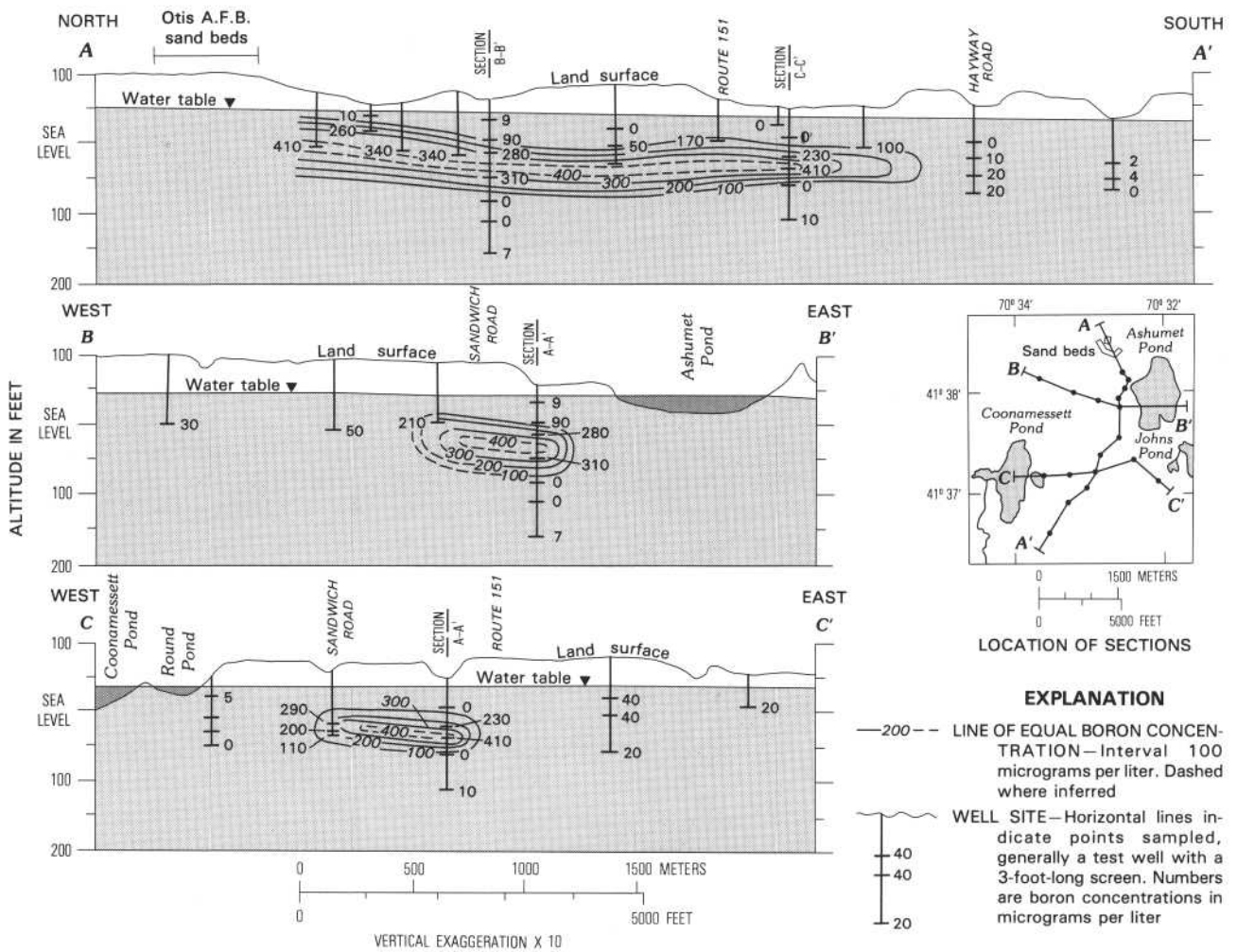


Figure 9. Vertical distribution of boron in ground water, May 1978 through May 1979.

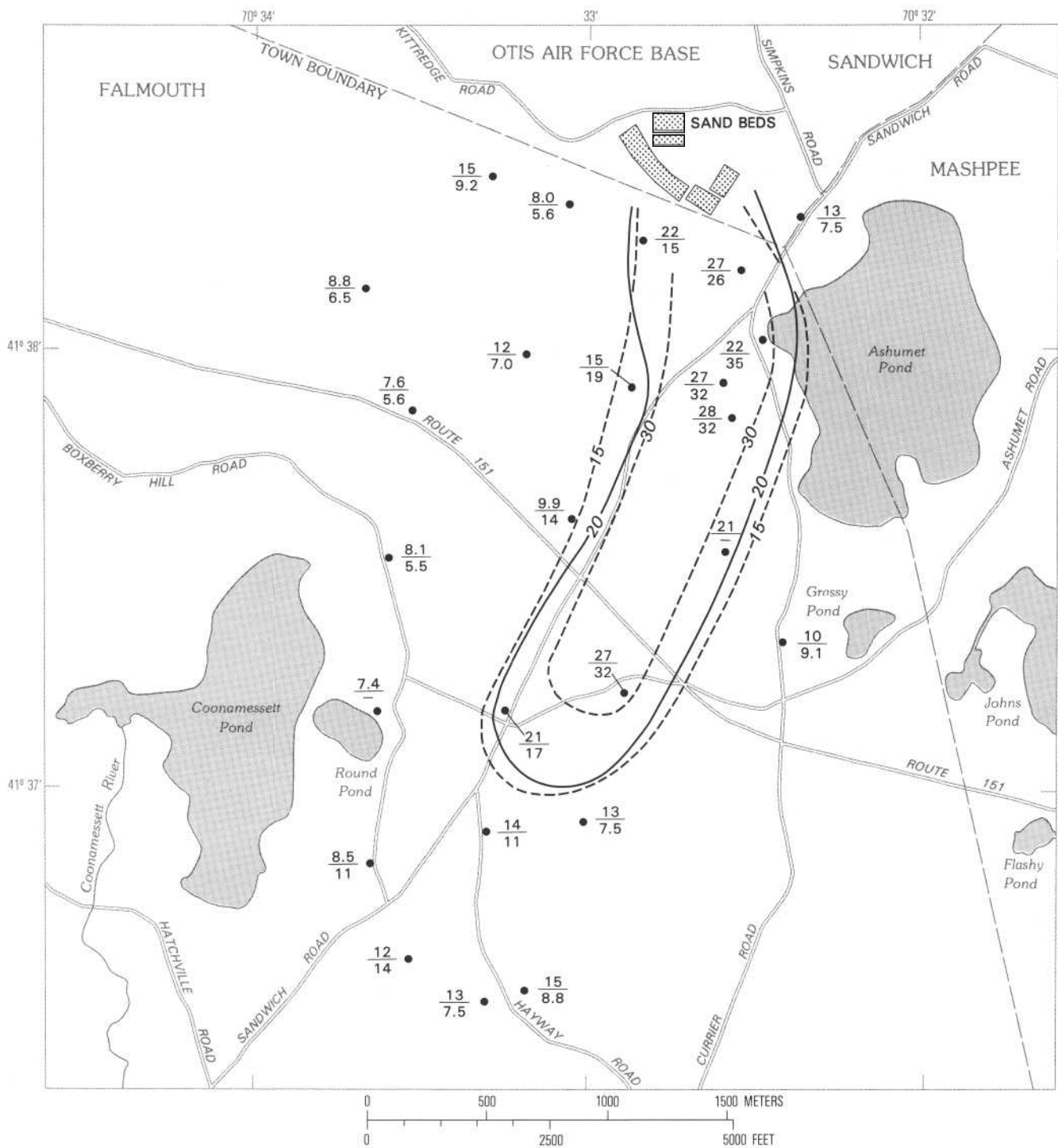
show the concentrations of chloride and sodium (fig. 11) in the contaminated ground water. The shape of the plume as defined by chloride and sodium is similar to the shape of the plume as defined by boron (fig. 9). The plume is contained in the sand and gravel aquifer and is overlain by uncontaminated ground water.

Water collected from several shallow wells south of Route 151 (fig. 11) that are screened above the plume contained more than 20 mg/L chloride and more than 15 mg/L sodium. These concentrations of chloride and sodium are higher than the concentrations in uncontaminated ground water. However, the boron concentration of water collected from these shallow wells (fig. 9) is less than 50 $\mu\text{g/L}$, the maximum boron concentration measured in the uncontaminated ground water. This combination of constituents suggests a source other than the sewage disposal.

The only known large-scale source of sodium chloride in ground water in the study area other than land disposal of sewage at Otis AFB is road salting. Several roads that cross the path of the plume are salted during the winter. These roads include Route 151, and Sandwich, Ashumet, and Hayway Roads (fig. 10). The shallow wells that contain the elevated levels of sodium and chloride are downgradient of these roads.

Phosphorus

Phosphorus (P) concentrations in the aquifer are shown in figure 12. The area in which phosphorus concentrations in the contaminated ground water exceed concentrations in the uncontaminated ground water is much smaller than the area of the plume delineated by specific conductance (fig. 8) and by chloride and sodium (fig. 10).



EXPLANATION

- 20— LINE OF EQUAL CHLORIDE CONCENTRATION—Concentration in milligrams per liter.
- 15-- LINE OF EQUAL SODIUM CONCENTRATION—Interval 15 milligrams per liter

- $\frac{27}{32}$ WATER WELL—Number above line is chloride concentration in milligrams per liter. Number below line is sodium concentration in milligrams per liter

Figure 10. Areal distribution of chloride and sodium in ground water, May 1978 through May 1979.