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

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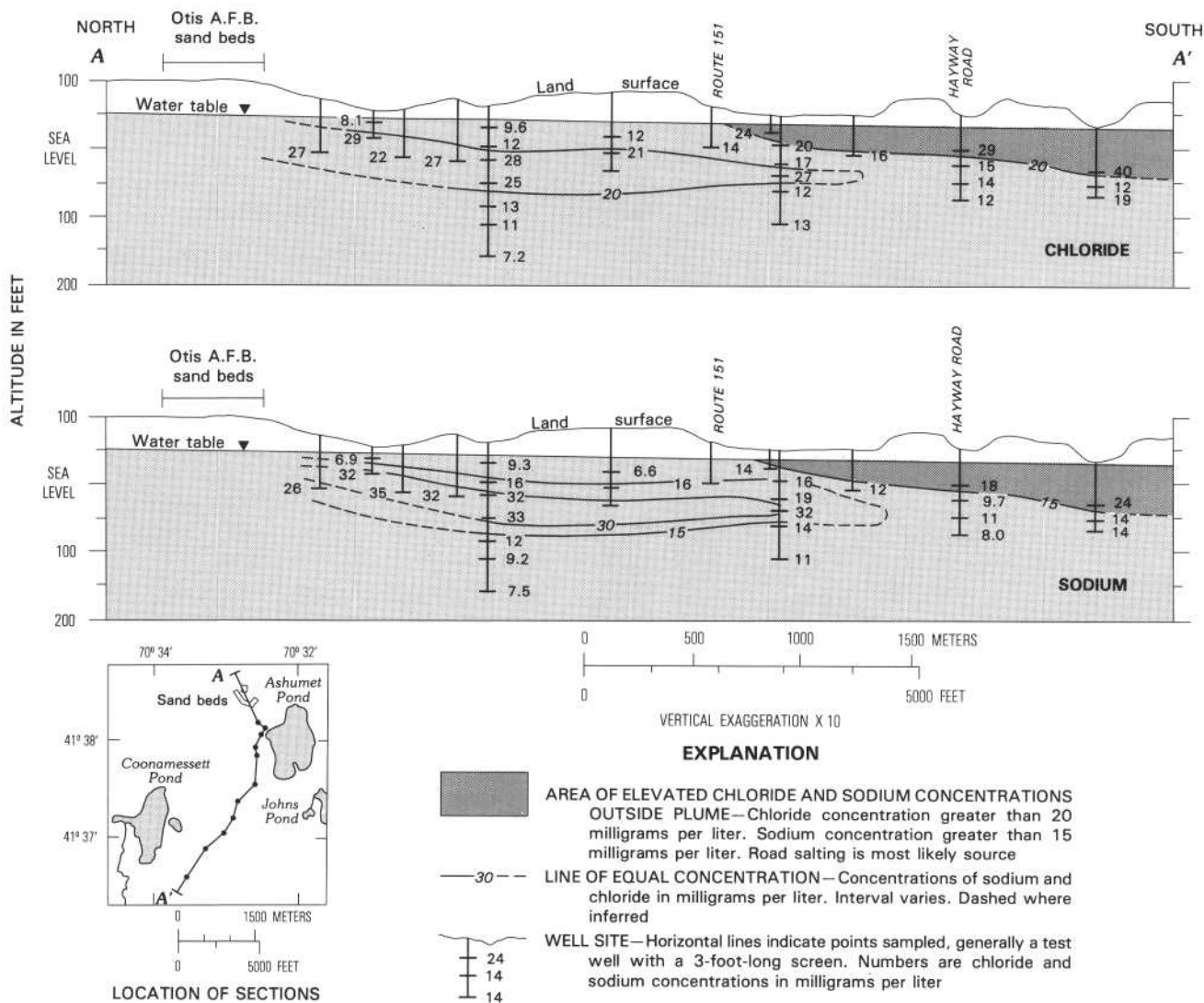


Figure 11. Vertical distribution of chloride and sodium in ground water, May 1978 through May 1979.

The phosphorus concentrations in the contaminated ground water do not exceed 0.05 mg/L farther than 2,500 feet downgradient of the sand beds. Uncontaminated ground water in the study area generally contains less than 0.05 mg/L phosphorus. Most phosphorus in the secondarily treated sewage is in the form of orthophosphate (PO_4^{3-}), the predominant form of dissolved inorganic phosphorus in water. Between 1974 and 1980, the average concentration of orthophosphate (as phosphorus) in the treated sewage was 7 mg/L (table 2).

The limited extent of elevated phosphorus concentrations in the plume compared to boron, sodium, and chloride most likely is caused by adsorption of phosphorus on the sediments and by the formation of insoluble phosphorus compounds. Phosphorus is adsorbed on metal

oxides, particularly ferric hydroxide (Hem, 1970, p. 185), which typically coat the sediment grains of sand and gravel. Phosphorus also has a strong tendency to form phosphorus compounds of low solubility by reacting with the iron and aluminum which are available in the aquifer. The effect of these two processes, jointly referred to as sorption, is to remove phosphorus from solution and to retard the movement of the phosphorus front through the aquifer. Therefore, phosphorus appears to move much more slowly from the contamination source than conservative species such as chloride. The retardation of phosphorus movement away from sewage-disposal sites in sand and gravel has also been observed by Koerner and Haws (1979, p. 84–86), Aulenbach and Tofflemire (1975, p. 166), and Bouwer (1973, p. 172).

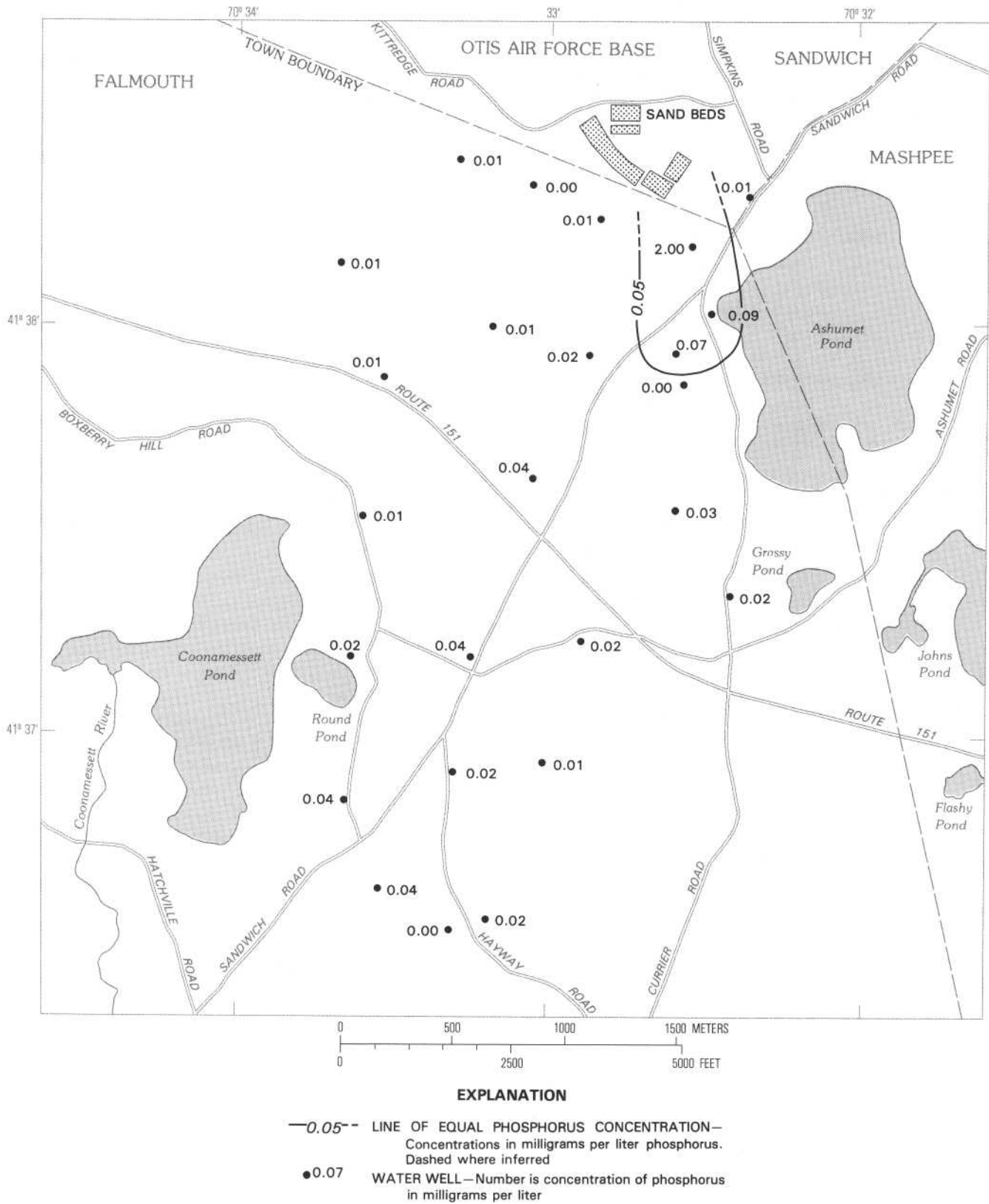


Figure 12. Areal distribution of phosphorus in ground water, May 1978 through May 1979.

Nitrogen

Nitrogen is an important component of domestic sewage that is derived from human and food wastes. The concentrations of nitrogen in ground water are shown in figure 13. Nitrogen concentrations as high as 24 mg/L were measured in water samples collected from the plume. The treated sewage from the Otis AFB facility contained 20 to 25 mg/L total nitrogen during 1979–80 (table 2). Ground water outside the plume which has not been contaminated by other activities of man generally contains less than 0.5 mg/L nitrogen (Frimpter and Gay, 1979, p. 9).

The area in which the contaminated ground water contains more than 2 mg/L nitrogen (fig. 13) delineates a plume that is similar in shape and location to the area delineated by specific conductance (fig. 8) and by chloride and sodium (fig. 10). Nitrogen exceeds 2.0 mg/L in water samples collected from two wells located near the intersection of Boxberry Hill Road and Sandwich Road (fig. 13), 11,000 feet downgradient of the sand beds. These wells are located at the farthest point from the sand beds at which water samples were collected. The zone in the plume that contains more than 2.0 mg/L nitrogen most likely extends more than 11,000 feet from the sand beds in the southwesterly direction of ground-water flow.

Septic tank and cesspool effluents, fertilizers applied to golf courses and food crops, and sewage sludges that may have been buried in the past near the Otis AFB treatment plant also are potential sources of nitrogen in the ground water. Elevated nitrogen concentrations in water samples collected from wells located outside the plume probably result from these additional sources. Most of these wells are shallow and are located on or near the two golf courses (fig. 2) or are adjacent to onsite wastewater disposal systems. Water collected from several deeper wells which seem to be outside the plume (for example, well FSW 234 in fig. 13) contained more than 1.0 mg/L nitrogen. Data presently available are insufficient to identify the source of the nitrogen at these locations.

Ammonia, Nitrate, and Dissolved Oxygen

Nitrogen (N) occurs in several forms in ground water. The vertical distributions of the two predominant species of nitrogen in the plume, nitrate (NO_3^-) and ammonia as the ammonium (NH_4^+), are shown in figure 14. Nitrogen in the center of the plume as far as 5,000 feet from the sand beds is mostly in the form of ammonia. A thin zone of ground water containing more than 1 mg/L nitrate-nitrogen overlies the center of the plume in this region. Between 5,000 feet and 8,000 feet from the sand beds, the predominant species of nitrogen in the plume changes from ammonia to nitrate. Nitrogen is in the nit-

rate form farther than 8,000 feet from the sand beds. In this region, ammonia concentrations are less than 0.05 mg/L.

The observed change in the species of nitrogen in the plume as the contaminated ground water moves away from the sand beds is the result of oxidation of ammonia to nitrite (NO_2^-) and nitrate (NO_3^-) in the presence of dissolved oxygen. This oxidation process, called nitrification, is mediated by bacteria which occur naturally in ground water (Behnke, 1975). Because oxygen combines chemically with nitrogen during oxidation, the distributions of ammonia and nitrate in the plume are closely related to the distribution of dissolved oxygen (fig. 14).

In the center of the plume, within 5,000 feet of the sand beds, dissolved oxygen is absent. In this zone, most nitrogen is in the form of ammonia, and nitrate is absent. Small amounts of nitrogen also are present in organic compounds and as nitrite but the distributions of these other forms are not shown in figure 14.

Ammonia is oxidized to nitrate in a thin boundary zone along the top and sides of the plume within 5,000 feet of the sand beds (fig. 14). In this zone, ground water outside the plume which contains as much as 11 mg/L dissolved oxygen mixes with the contaminated ground water that contains elevated levels of ammonia. Uncontaminated ground water on Cape Cod typically contains dissolved oxygen (Frimpter and Gay, 1979, p. 7–8). The dissolved oxygen is introduced with recharge through the sandy and gravelly soils that have a low organic matter content.

The oxidation of ammonia to nitrate also occurs in the center of the plume between 5,000 and 8,000 feet from the sand beds as the contaminated and uncontaminated ground water mix by hydrodynamic dispersion. The oxidation of ammonia to nitrate in the center of the plume is most evident in water samples collected from wells FSW 262–266 located 7,000 feet from the sand beds (fig. 14). Both ammonia and nitrate are present at concentrations greater than 1 mg/L at this site. The oxidation of ammonia is essentially complete 8,000 feet downgradient of the sand beds.

Dissolved oxygen was not detected in the fine-grained sediments beneath the sand and gravel (fig. 5), but there is no evidence that ground water in these sediments has been contaminated by the sewage disposal at Otis AFB. The lack of dissolved oxygen in the deeper part of the aquifer below the plume may reflect the natural tendency for dissolved oxygen to be depleted in ground-water systems as the residence time of water in the aquifer increases.

The distributions of ammonia and nitrate (fig. 14) show that ammonia has moved readily in the aquifer and that oxidation of ammonia to nitrate is the primary cause

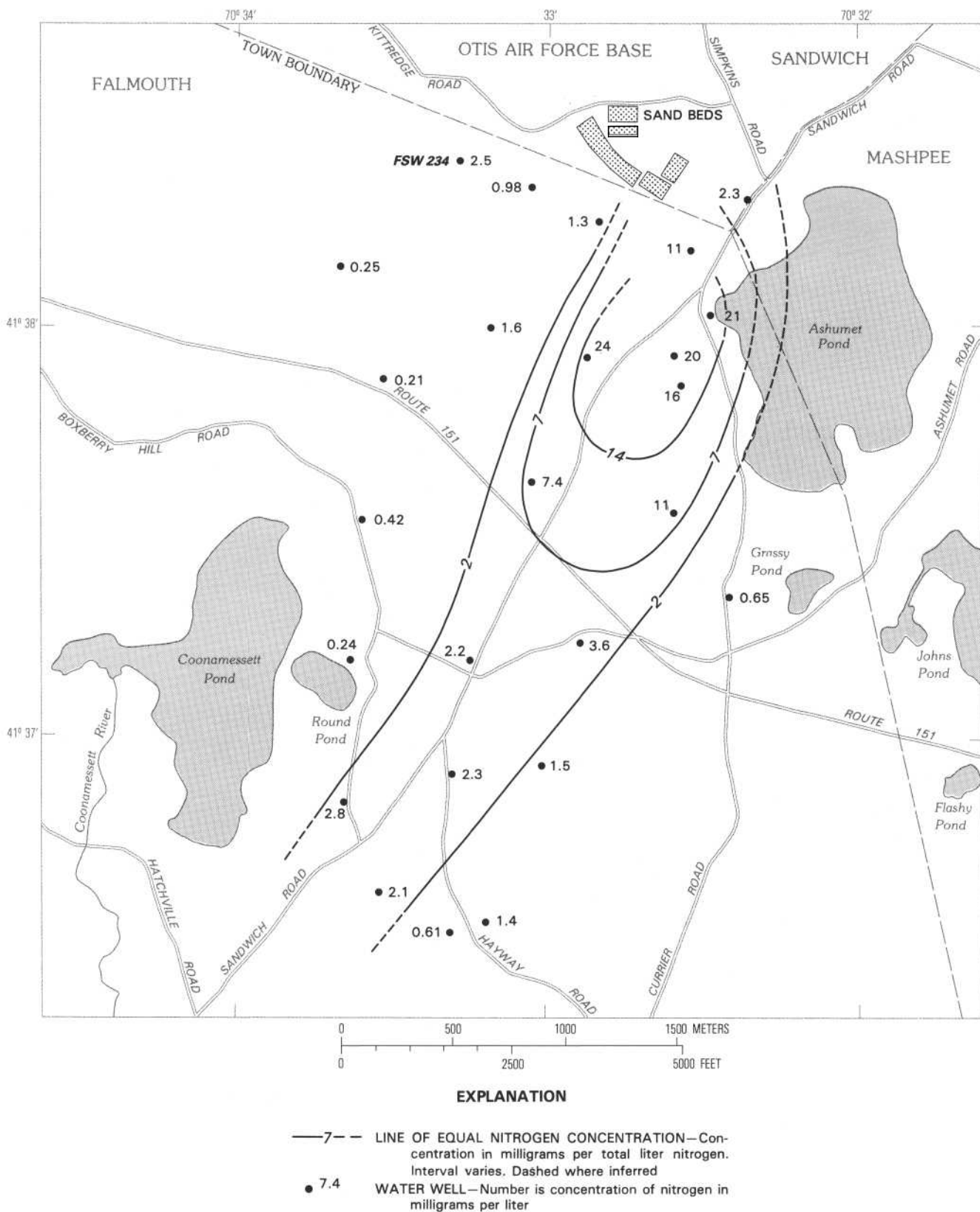


Figure 13. Areal distribution of nitrogen in ground water, May 1978 through May 1979.

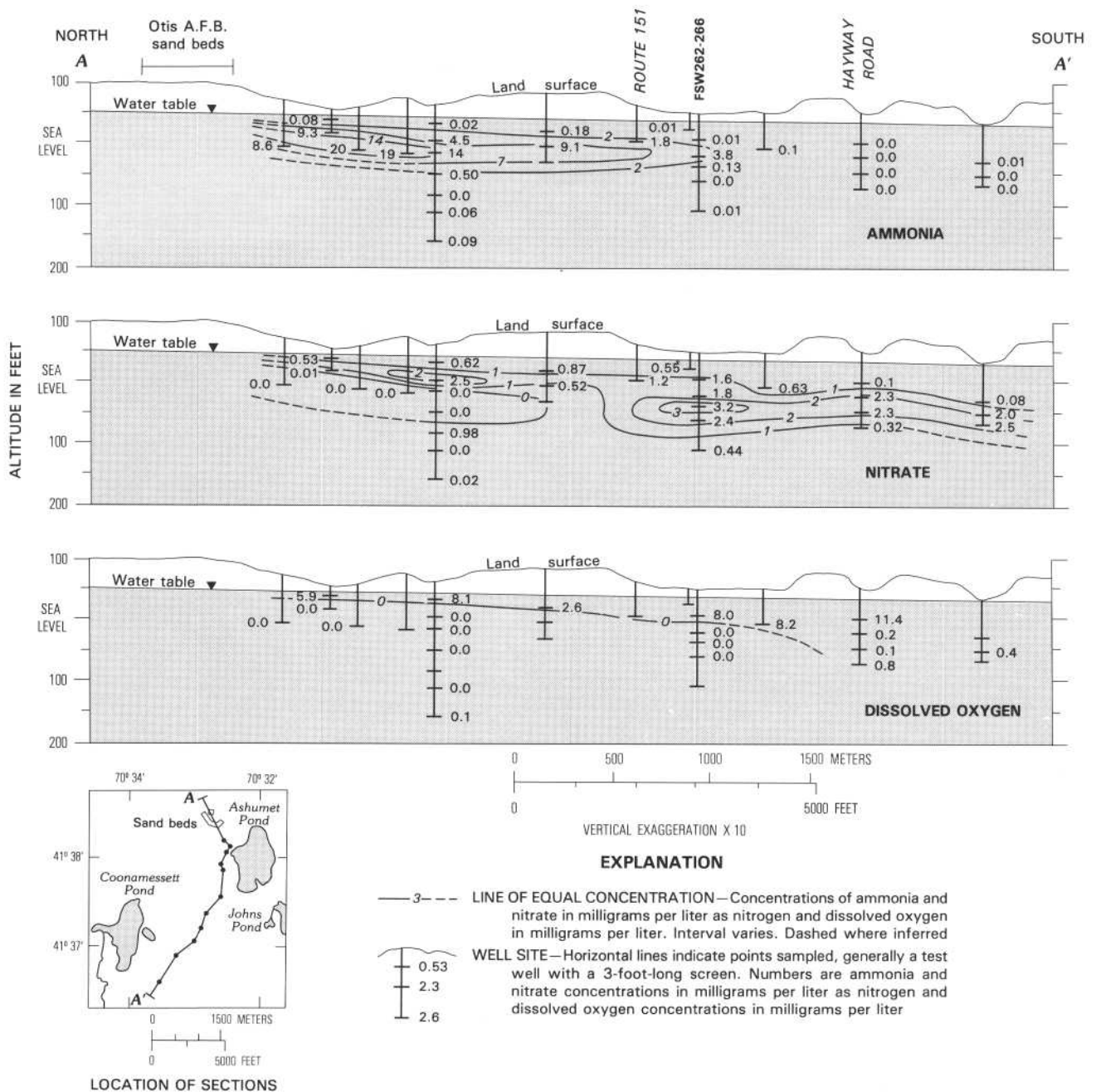


Figure 14. Vertical distribution of ammonia, nitrate, and dissolved oxygen in ground water, May 1978 through May 1979.

of attenuation of ammonia concentrations in the plume. Nitrate, the end product of nitrification, is the stable species of nitrogen in an oxidizing ground-water environment and moves through the aquifer without reacting with other chemical constituents or with the sediments (Freeze and Cherry, 1979, p. 413).

Detergents

Detergents in ground water are a definite indication of contamination by wastewater disposal. Sewage typically contains detergents introduced into water from laundry and

dishwashing wastes. Because detergents are manmade chemicals, they do not exist in ground water that has not been contaminated by wastewater disposal.

Detergents were first used in the United States around 1946 (Hughes, 1975, p. 22), and became the dominant cleaning agent, exceeding the use of soaps, in 1953 (Wayman and others, 1965, p. 2). The primary active agents in detergents are surface active agents, or surfactants. Prior to 1964, the most common surfactant used in detergents was alkyl benzene sulfonate (ABS). ABS is nonbiodegradable. Numerous instances of ABS con-

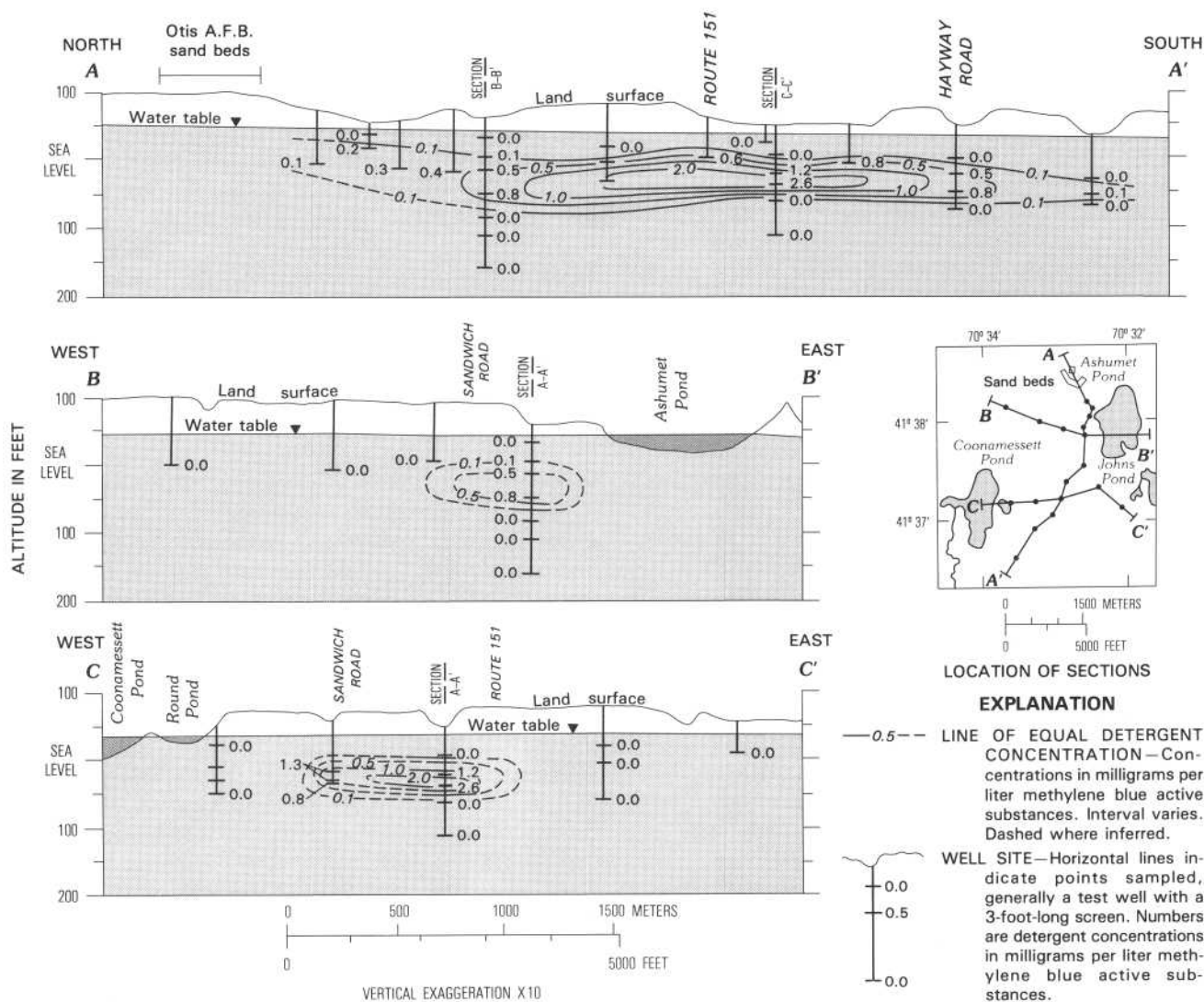


Figure 15. Vertical distribution of detergents in ground water, May 1978 through May 1979.

tamination of ground water have been reported (Suess, 1964, p. 89; Perlmutter and Lieber, 1970). In 1964, ABS was replaced by LAS (linear alkyl sulfonates) to reduce the environmental impacts of detergent use. LAS is biodegradable and secondary sewage treatment plants can remove LAS effectively under favorable conditions.

The concentration of detergents in water is measured by the MBAS (methylene blue active substances) test and is expressed in milligrams per liter MBAS (American Public Health Association and others, 1975, p. 600). This test determines the concentration of surfactants in the water but does not distinguish between the nonbiodegradable (ABS) and the biodegradable (LAS) surfactants.

Although data are not available that show the detergent content of the Otis AFB treated sewage between 1946 and 1979, chemical analyses of treated sewage from similar treatment plants (Kardos and Sopper, 1973, p. 150–151; Hunter and Kotalik, 1973, p. 11; Wayman and

others, 1965, p. 8; Hughes, 1975, p. 12–13) show detergent concentrations of 3 to 10 mg/L MBAS prior to 1966 and 0.2 to 1.0 mg/L MBAS after the biodegradable forms became prevalent. Samples of the treated sewage collected at the Otis AFB facility in November 1979 and August 1980 (table 2) contained 0.2 and 0.4 mg/L MBAS.

The distribution of detergents in the aquifer is shown in figure 15. Detergent concentrations exceed 0.5 mg/L MBAS in a zone between 3,000 and 10,000 feet downgradient of the sand beds. A water sample collected from a well located 7,000 feet from the sand beds contained 2.6 mg/L MBAS, the highest detergent concentration detected during this study. Detergents were not detected in ground water outside the plume.

The observed distribution of detergents in the plume may be the result of one or more factors which include: (1) Historical changes in the volume of sewage applied to the beds, (2) historical changes in the detergent concen-

trations in the sewage, (3) changes in the treatment or disposal processes at the sewage treatment plant such as sand-bed rotation and bed loading rates that changed the detergent concentrations in the treated sewage, and (4) spatial or temporal changes in adsorption and degradation of surfactants in the aquifer. Available data are insufficient to evaluate these potential factors in detail. However, the distribution of detergents in the plume (fig. 15) most likely is related to the change in 1964 from nonbiodegradable (ABS) to biodegradable (LAS) surfactants.

Detergents in the zone of the plume that contains elevated detergent concentrations are derived from pre-1964 disposal of treated sewage containing non-biodegradable detergents. These nonbiodegradable detergents have moved more than 3,000 feet downgradient of the sand beds. The lower concentration of detergents (less than 0.5 mg/L MBAS) in the plume within 3,000 feet of the sand beds is the result of the lower detergent content of the treated sewage following the introduction of biodegradable surfactants. The decrease in the volume of sewage treated at the Otis AFB plant between 1968 and 1978 (fig. 4) also may have contributed to the lower detergent concentrations in this zone.

Detergents have moved readily in the aquifer. Unlike phosphorus (fig. 12), attenuation of detergent concentrations in the plume by chemical reactions and adsorption is not evident in figure 15. This observation is consistent with laboratory studies by Wayman and others (1965, p. 49-96) which showed that ABS does not degrade chemically in most ground-water environments and is not adsorbed significantly on sand and gravel composed predominantly of quartz. LAS is more likely to degrade chemically (Wayman and others, 1965) or to be adsorbed on the sediments (Freeze and Cherry, 1979, p. 440). However, Wayman and others (1965, p. 56) showed that biodegradation of LAS is very slow in oxygen-containing ground water at 10°C and may be insignificant in ground water that is devoid of dissolved oxygen. Therefore, detergents, particularly nonbiodegradable (ABS) surfactants, most likely behave conservatively in the aquifer and can be used to determine the extent of the contaminated ground water.

DISCUSSION

Processes that Affect the Distribution of Contaminants in the Plume

The transport of contaminants in the plume is affected by processes which tend to spread the contaminants in the aquifer and by processes which tend to retard or restrict the movement of the dissolved substances. Two processes that tend to spread the contaminants in the

aquifer are advection and hydrodynamic dispersion. The contaminants introduced into the aquifer by land disposal of treated sewage at the sand beds are carried away from the disposal site primarily by flowing ground water, a process called advection. The large extent of the plume (fig. 16) shows that advection is very effective in moving the contaminants through the aquifer. Because the contaminants are transported primarily by the flowing ground water, the plume is aligned with the direction of ground-water flow shown by arrows drawn perpendicular to the water-table contours (fig. 16).

Hydrodynamic dispersion is the other process that spreads the contaminants in the aquifer. Dispersion results from mechanical mixing as ground water moves through the tortuous, branching, and interfingering pores of different sizes between the sediment grains and from molecular diffusion in the pore water. The effect of hydrodynamic dispersion is the dilution of contaminated ground water by uncontaminated ground water as the plume spreads in the direction of ground-water flow and, to a much lesser extent, perpendicular to the direction of flow. The distribution of boron in the plume (fig. 16) shows that the concentration of boron decreases gradually from greater than 300 µg/L in the center of the plume to less than 100 µg/L along the sides of the plume. If the dissolved substances were transported only by advection, a sharp boundary instead of a gradual transition would separate contaminated from uncontaminated ground water.

Processes which tend to retard the movement of contaminants in the aquifer include chemical and biochemical reactions between the contaminant and other dissolved substances in the ground water and between the contaminant and the sediments. The removal of phosphorus from the plume by precipitation and adsorption (fig. 12) and the oxidation of ammonia to nitrate (fig. 14) are examples of these processes. The net effect of these processes is that some substances, such as boron (fig. 16), move through the aquifer at approximately the same velocity as the ground water and other substances, such as phosphorus (fig. 16), appear to move much more slowly than the ground water.

In addition to advection, dispersion, and retardation, changes in the chemical quality and volume of the treated sewage applied to the sand beds also affect the extent and composition of the plume. For example, the distribution of detergents (fig. 16) reflects the decrease in detergent content of the treated sewage following the conversion from nonbiodegradable (ABS) to biodegradable (LAS) surfactants in 1964. Past changes in the concentrations of other contaminants in the treated sewage also may be reflected in the distributions of contaminants in the plume. However, historical data on the chemical quality of the treated sewage generally are insufficient to document these variations and their effects on the extent and composition of the plume.