A Nitrogen-Rich Septage-Effluent Plume in a Coastal Aquifer, Marsh, and Creek System, Orleans, Massachusetts: Project Summary, 1988-95

By Peter K. Weiskel, Leslie A. DeSimone, and Brian L. Howes

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CONVERSION FACTORS, WATER-QUALITY INFORMATION, AND VERTICAL DATUM

CONVERSION FACTORS

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
inch (in.)	2.54	centimeter
mile (mi)	1.609	kilometer
cubic foot per second (ft^3/s)	28.32	liter per second
gallon per square foot per day ($(gal/ft^2)/d$)	40.73	liter per meter squared per day

Temperature is given in degree Celsius (°C), which can be converted to degree Fahrenheit (°F) by the following equation:

°F = 1.8 (°C) + 32.

WATER-QUALITY INFORMATION

Chemical concentration is given in units of milligrams per liters (mg/L) or micrograms per liter (µg/L). Milligrams and micrograms per liter are units expressing the mass of the solute per unit volume (liter) of solution. One thousand micrograms per liter is equivalent to 1 milligram per liter. Salinity is given in units of parts per thousand (ppt). Salinity values are commonly reported for marine and estuarine samples. Parts per thousand are units expressing the mass of solute per unit mass of solution. One part per thousand is equivalent to 1 gram per kilogram of solution.

VERTICAL DATUM

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

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Abstract

A nitrogen-rich septage-effluent plume was monitored in order to quantify the movement, chemistry, and possible ecological effects of nitrogen in a coastal aquifer underlying Namskaket Marsh and Creek in Orleans, Massachusetts. The plume originates at a septage-treatment facility that discharges a treated, nitrogen-rich effluent to the ground. The part of Namskaket Marsh and Creek where the plume is expected to discharge is about 1,000 feet downgradient of the facility and 1 mile inland from Cape Cod Bay.

By late-1995, the leading edge of the effluent plume extended about 800 feet downgradient from the effluent disposal area and was about 200 feet from the marsh. In late 1992, after 2 years of effluent discharge, concentrations of nitrate ranged from 10 to 40 mg/L (milligrams per liter) as nitrogen, and dissolved ammonium concentrations ranged from 2 to more than 8 mg/L as nitrogen. The center of the plume was anoxic by late 1992 because of oxygen consumption by subsurface bacteria. About 25 percent of the total mass of nitrogen discharged from the facility has been removed by subsurface processes in the unsaturated zone and aquifer beneath the site. Seepage zones near the marsh-upland boundary and the bottoms of Namskaket Creek and tributaries are the most likely discharge areas for the effluent plume. High rates of ground-water discharge (averaging 0.30 gallon per square foot per hour) were measured in these zones during the ebb portion of the tidal cycle. Measurements of ambient (background) nitrate uptake by the sediments of the creek and marsh indicate significant potential for removal of plume nitrogen by these sediments after the expected arrival of the plume in the marsh.

Baseline monitoring of water quality in Namskaket Creek from March 1993 through September 1995 showed a seasonal pattern in dissolved ammonium and orthophosphate concentrations, with peak concentrations in the mid to late summer. Ammonium concentrations at the most downstream sampling site ranged from 0.03 to 0.40 mg/L as nitrogen, and orthophosphate concentrations ranged from 0.03 to 0.30 mg/L as phosphorus. Nitrate concentrations ranged from 0.11 to 0.87 mg/L as nitrogen, and showed no seasonal pattern. The marsh vegetation is dominated by *Phragmites australis* (common reed) in areas of low pore-water salinity near the marsh boundary, and by *Spartina patens* (salt-meadow grass) in the interior areas of the marsh. Because the septage-effluent plume has not reached the marsh to date (1995), further study is needed to (1) map the path of the plume toward its expected marsh discharge area, (2) measure rates of nitrogen transformation and removal in the marsh before and after plume discharge, and (3) monitor the possible effects of the plume on the water quality and vegetation of the marsh ecosystem.

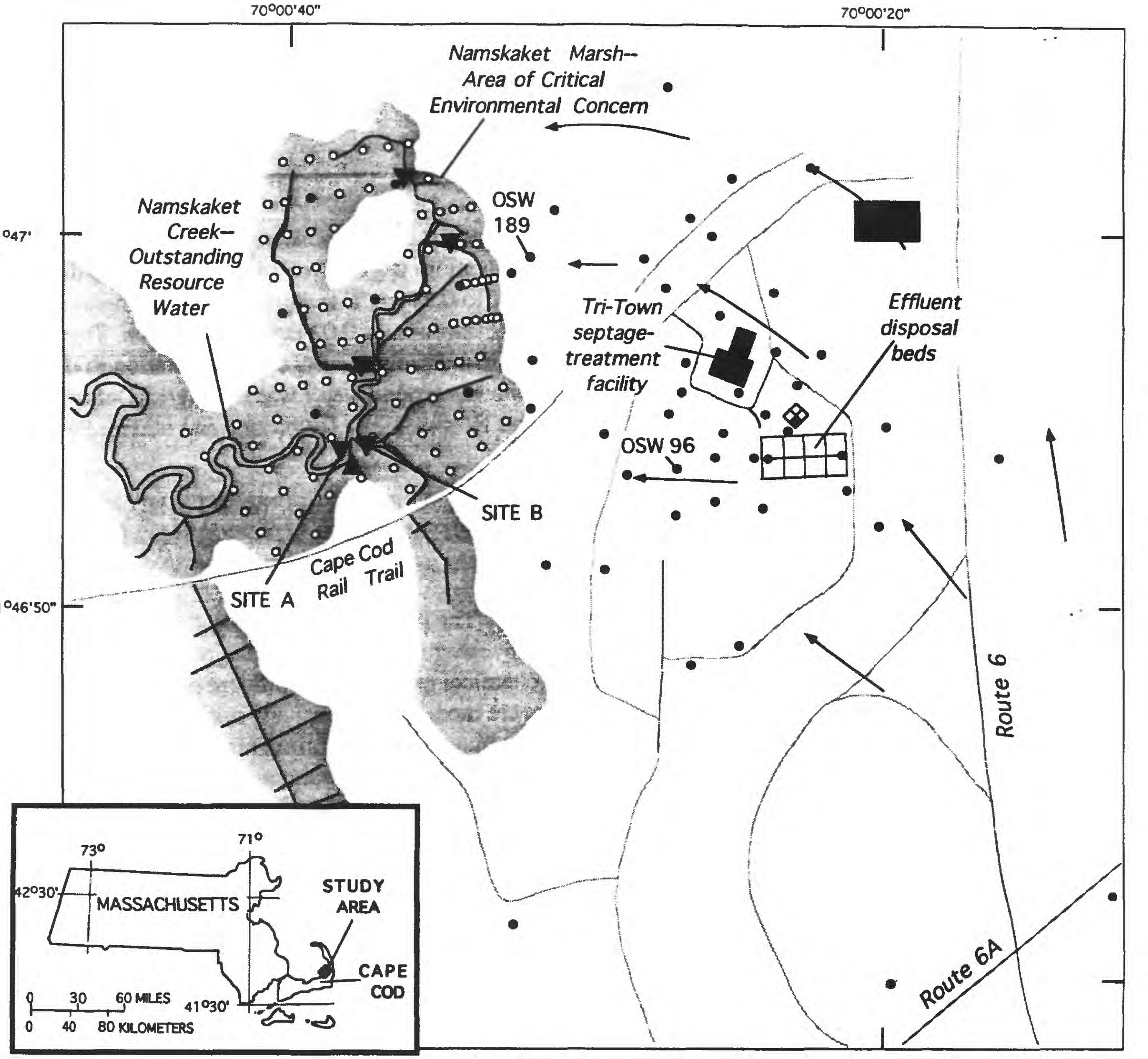
INTRODUCTION

Disposal of nitrogen-rich effluent from point and nonpoint sources is a major environmental concern in the United States. In Massachusetts, where coastal aquifers provide the sole source of public and private water supply for a large part of the population, land disposal of effluent by wastewater-treatment facilities and septic systems can pose health and environmental problems. Ground water containing high concentrations of nitrate as nitrogen can be toxic to small children. Thus, the USEPA has set a Maximum Contaminant Level of 10 mg/L as N for drinking water (Frimpter and others, 1990). Furthermore, discharge of nitrogen-rich effluent to coastal embayments, either directly through outfalls or indirectly through ground-water discharge, can promote eutrophication—excessive growth of phytoplankton, macro-algae, and other aquatic vegetation. Subsequent decay of this vegetation consumes oxygen, often leading to fish kills and general habitat degradation (Nixon, 1993). Because plant growth in coastal waters generally is limited by the availability of dissolved nitrogen rather than phosphorus or other nutrients, discharge of nitrogen-rich effluent has a particularly high potential to promote coastal eutrophication (Weiskel and Howes, 1992).

An alternative to directing effluent to coastal waters is to direct effluent to land-disposal areas just inland of the coastline. In Massachusetts, siting treatment facilities in this manner has the potential to minimize water-quality degradation of aquifers used for water supply, while complying with provisions in the Massachusetts Ocean Sanctuaries Act that prohibit direct outfalls along much of the coastline (see Mass. General Laws 132A, sections 13-16). Such an approach also would take advantage of chemical and microbial processes that remove nitrogen and other contaminants during subsurface transport.

The U.S. Geological Survey (USGS), in cooperation with the Massachusetts Department of Environmental Protection, Office of Watershed Management, and the Cape Cod Commission, is presently (1995) investigating the development of a septage-effluent plume at a study site in Orleans, Massachusetts, on Cape Cod (fig. 1). The Tri-Town Septage Treatment Facility treats septage, the semisolid residue pumped from residential and commercial septic tanks, and produces a secondary-level effluent (DeSimone and others, 1995). Nitrogen-rich effluent has been discharged to the underlying sandy aquifer since February 1990. Namskaket Marsh and Creek are about 1,000 ft downgradient of the treatment facility, and are the probable discharge areas for the resulting effluent plume (fig. 1). Namskaket Marsh has been recognized by the Commonwealth of Massachusetts as an Area of Critical Environmental Concern, and Namskaket Creek that drains the marsh has been designated as an Outstanding Resource Water.

The purpose of this report is to summarize (1) the characteristics of the aquifer and ground water underlying the site prior to effluent discharge, (2) the physical development and chemical characteristics of the effluent plume in the aquifer, (3) the distribution of ground-water discharge in Namskaket Marsh, (4) the processes governing nitrogen transformation in the aquifer, marsh, and tidal-creek system, and (5) the initial results of water-quality and vegetation monitoring in Namskaket Creek and Marsh.



EXPLANATION

← GENERAL DIRECTION OF GROUND-WATER FLOW

- • OBSERVATION WELL--Shows location of single well or multiple-well cluster used to measure ground-water levels and monitor water quality
- ○ PORE-WATER SAMPLING SITE--Shows location of shallow well used to measure salinity of marsh pore water
- ▼ CREEK SAMPLING SITE--Shows site where surface water is sampled for water-quality analysis
- ▲ AUTOMATED STAGE AND WATER-QUALITY MONITORING STATION--Shows site where creek stage and salinity are continuously monitored
- ◈ PRECIPITATION STATION

Figure 1. Location and instrumentation of the Namskaket Marsh Research Site, Cape Cod, Massachusetts.

AQUIFER CHARACTERISTICS, GROUND-WATER FLOW, AND GROUND-WATER QUALITY PRIOR TO EFFLUENT DISCHARGE

Characterization of the glacial aquifer, ground-water-flow system, and background water quality at the Orleans site began in October 1988, during construction of the treatment facility (DeSimone and others, 1995). By the end of 1995, 94 observation wells had been installed at 50 locations across the upland portion of the site (fig. 1). The lithology and hydraulic properties of the sediments at each well location were determined by the analysis of sediment samples and the use of geophysical logs. The sediments composing the aquifer consist of heterogeneous layers of fine, medium, and coarse sands of glacial origin that contain variable amounts of silt and gravel.

Ground-water levels, measured monthly from August 1989 through 1995, were 40 to 60 ft below land surface and fluctuated 2 to 3 ft annually at the upgradient end of the site near Route 6 (DeSimone and others, 1995). Ground-water levels were less than 5 ft below land surface and fluctuated less than 1 ft annually near the boundary with Namskaket Marsh. Water levels in observation wells also were used to define the directions and rates of ground-water flow under natural, pre-effluent-discharge conditions. Ground water was determined to flow westward and northwestward across the site from the interior of Cape Cod toward Namskaket Marsh and Cape Cod Bay at an average rate of about 0.40 ft/d. Initiation of effluent discharge in February 1990 has not significantly affected the direction of ground-water flow across the site (DeSimone and others, 1995). Effluent disposal at the site also is unlikely to affect existing public-water supplies on Cape Cod, which are situated farther inland.

Ground-water samples were collected in March and September 1989 to characterize ambient (background) ground-water quality. The median dissolved-solids concentration in the ambient samples was 70 mg/L. Sodium and chloride were the dominant ions, with median concentrations of 15 and 21 mg/L, respectively. Dissolved nitrate concentrations ranged from less than 0.10 to 3.4 mg/L as nitrogen, with an estimated median concentration of 0.07 mg/L as nitrogen. Ambient concentrations of dissolved ammonium were lower, ranging from less than 0.01 to 0.37 mg/L as nitrogen, with a median concentration of 0.02 mg/L as nitrogen. The median dissolved-oxygen concentration in the ambient ground water was 6.8 mg/L (DeSimone and Howes, 1995; DeSimone and others, 1995).

PHYSICAL DEVELOPMENT AND CHEMICAL CHARACTERISTICS OF THE SEPTAGE-EFFLUENT PLUME, 1990-95

The physical and chemical development of the septage-effluent plume in ground water and the chemical quality of the effluent prior to disposal were monitored intensively during the first 3 years of effluent disposal from February 1990 to December 1992 (DeSimone and others, 1995). Effluent and ground-water samples were analyzed to determine the concentrations of dissolved nitrogen and other major chemical constituents discharged to the aquifer and transported in the plume. Borehole electromagnetic-induction (EM) logs, which measure the electrical conductivity of the aquifer sediments and pore water adjacent to an observation well, also were used during 1990-92 to monitor plume movement. During 1992-95, plume movement was monitored using EM logging only. Septage-effluent-contaminated ground water was readily detected by use of EM logs (fig. 2).

In December 1992, the effluent plume (as defined by the specific conductance of ground water) extended 200 to 450 ft from the effluent disposal area, with the areas of highest concentrations extending west and northwestward in the directions of ground-water flow (fig. 3A). By September 1995, the leading edge of the plume extended 700 to 900 ft from the disposal area to within about 200 ft of the marsh. The plume moved at an average velocity of 0.4 ft/d through a

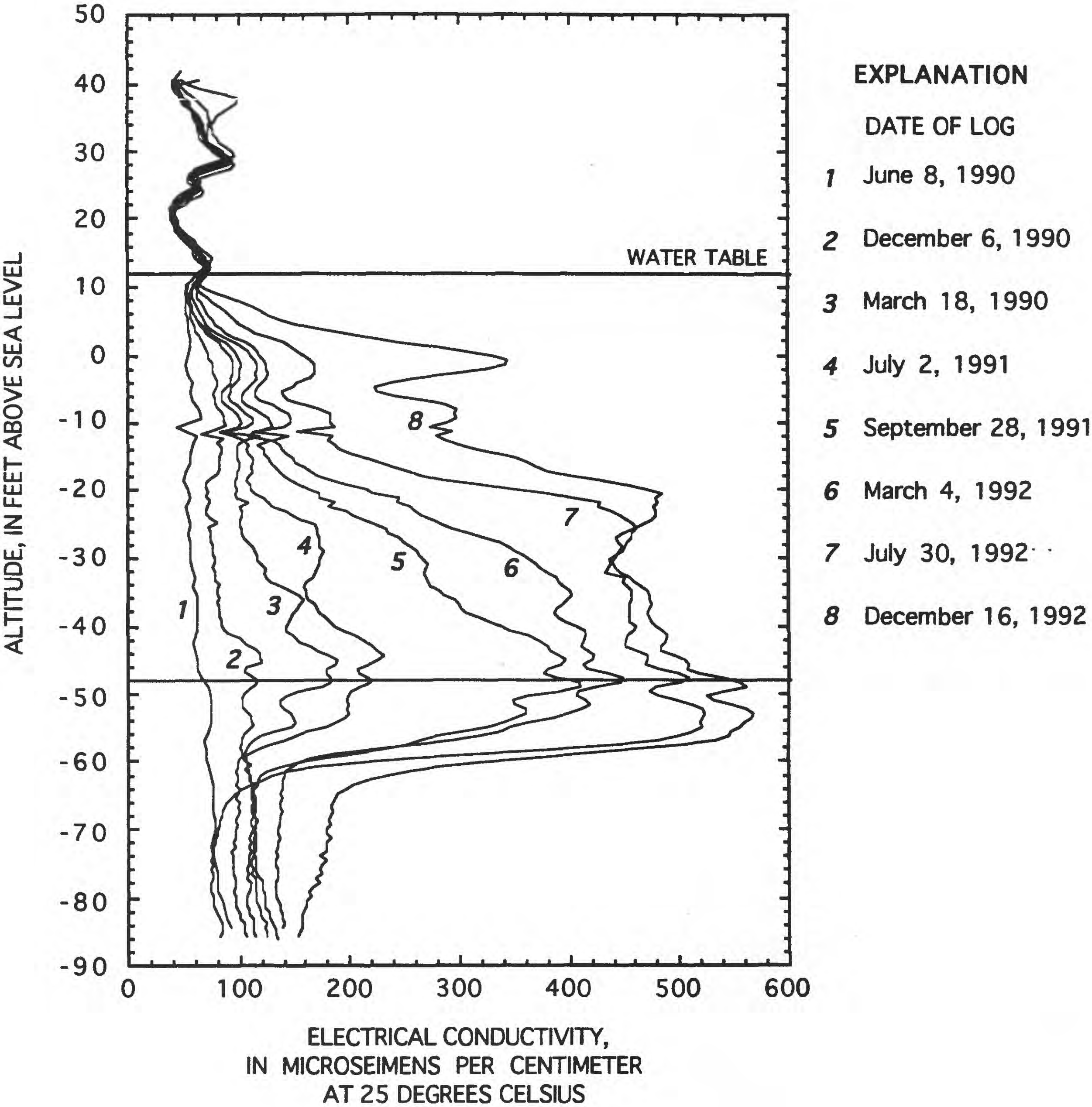


Figure 2. Electrical conductivity of the aquifer sediments and pore water over time in well OSW 96, 125 feet downgradient from the effluent-disposal area. Log 1 shows the electrical conductivity prior to arrival of the septage-effluent plume at the well. The increase in electrical conductivity over time shown by logs 2 through 8 is caused by an increase in the specific conductance of the ground water as effluent-contaminated ground water reaches the site. The electrical conductivity (specific conductance) of the effluent (3,330 µS/cm) is much higher than that of ambient ground water (120 µS/cm). (Modified from DeSimone and others, 1995, fig. 13*B*.)

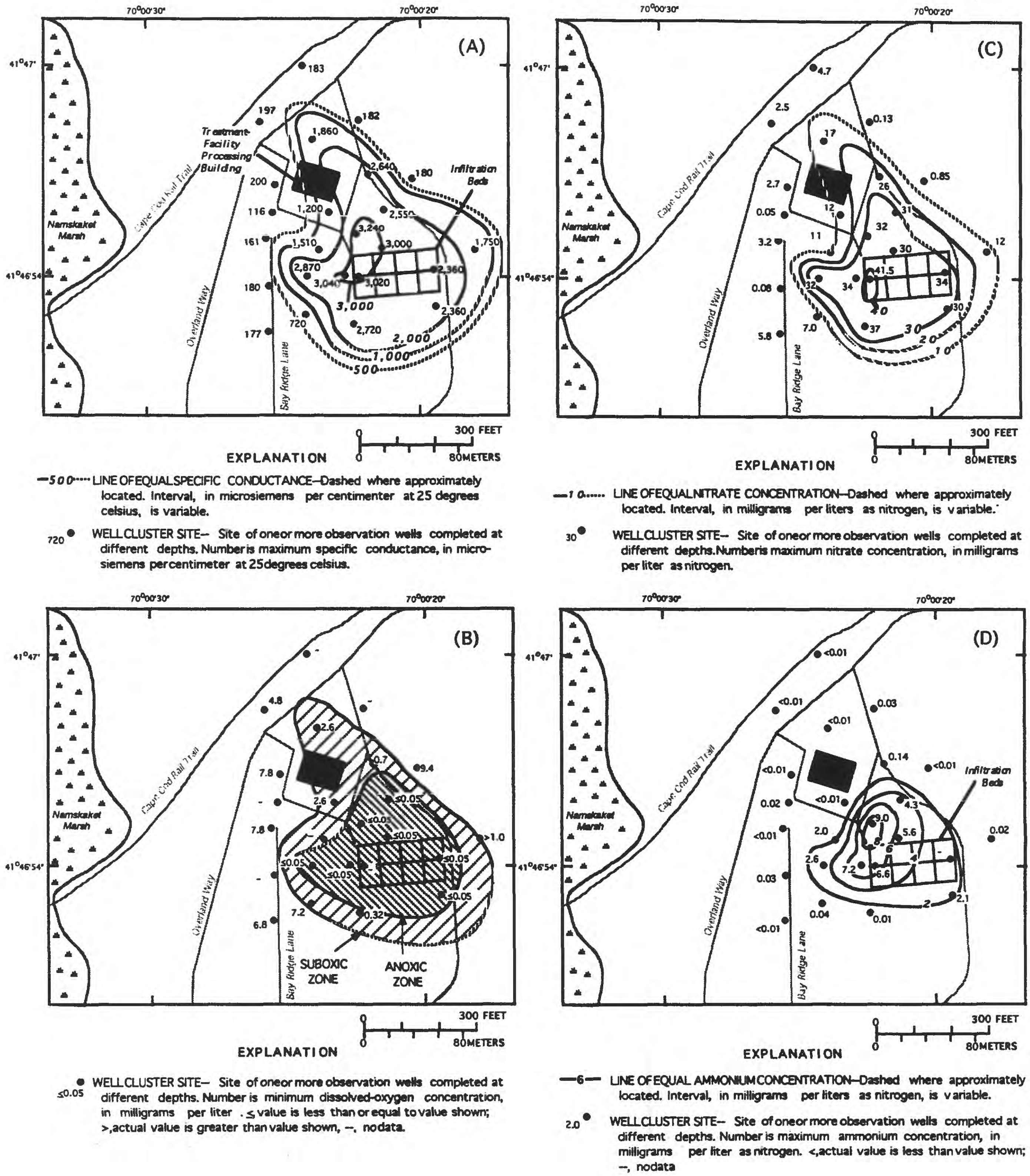


Figure 3. Areal distribution of (*A*) specific conductance, (*B*) dissolved oxygen, (*C*) nitrate, and (*D*) ammonium in upland ground water, December 1992. (Modified from DeSimone and others, 1995, figs. 9, 15, 18, and 19.)

layer of medium to very coarse sand (figs. 4 and 5). Vertically, the plume extends from the water table to about 35 ft below sea level near the disposal area; farther downgradient, the plume is at variable depths (for example, 5 ft above to 15 ft below sea level and 46 to 56 ft below sea level along section *A-A'*, fig. 5). Effluent-contaminated ground water moved downward in the aquifer near the disposal area because vertical gradients in hydraulic head induce downward flow because the medium- to coarse-grained sand unit dips downward, and possibly because the effluent-contaminated ground water was more dense than the ambient ground water (DeSimone and others, 1995). At its present velocities (0.40 ft/d), the leading edge of the plume is expected to reach the marsh boundary by early 1997.

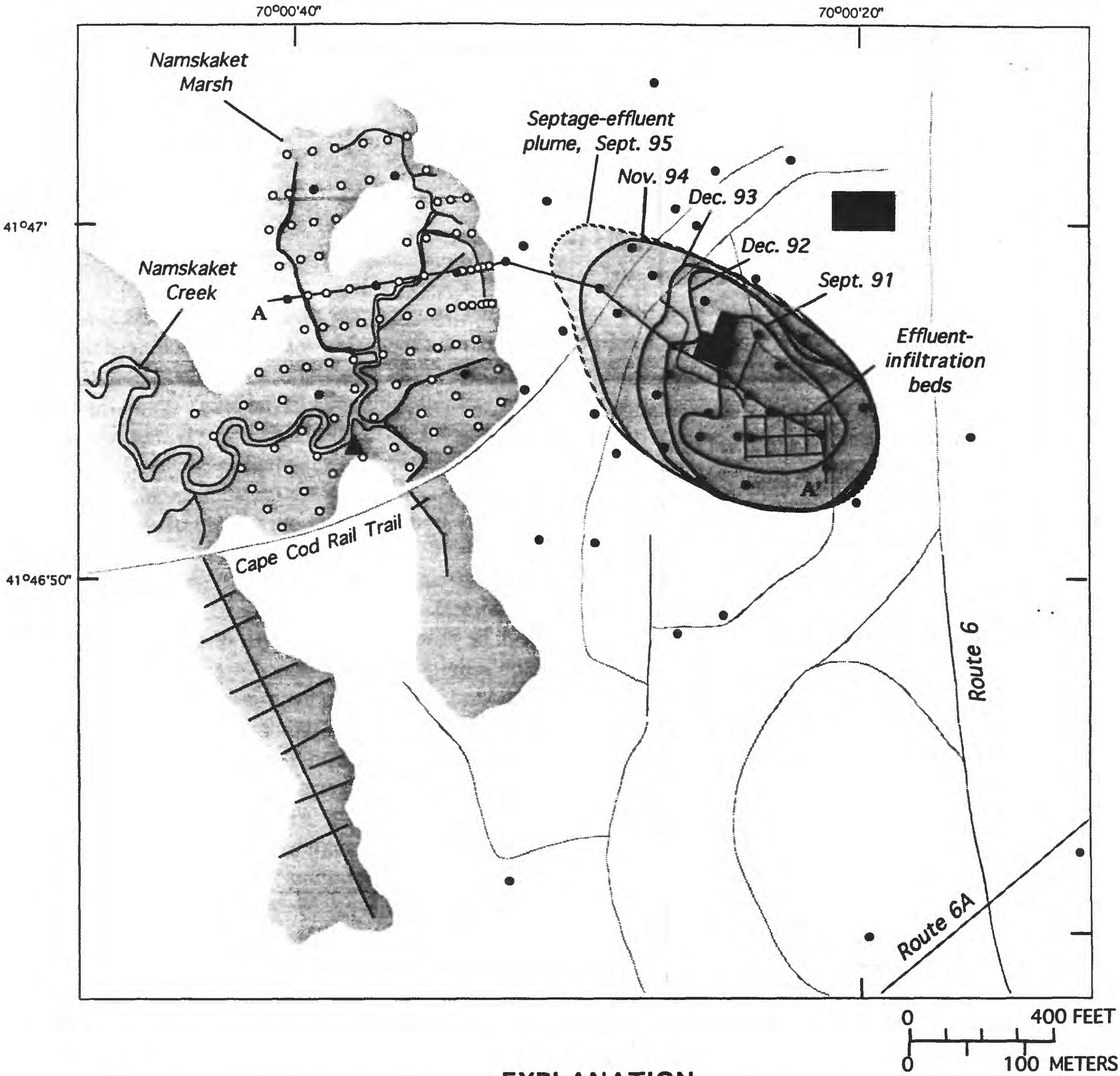
Effluent nitrogen occurs as ammonium, nitrate, and organic nitrogen when discharged from the facility (fig. 6). During transport through the 40-foot-thick unsaturated zone, the organic nitrogen and ammonium were largely transformed through microbial processes to nitrate during the initial 3 years of discharge (fig. 6). Concentrations of nitrate ranged from less than 10 mg/L as nitrogen near the vertical and horizontal boundaries of the plume to as much as 40 mg/L as nitrogen in the center of the plume in December 1992 (fig. 3*C*). The low nitrate concentrations at the edges of the plume were caused by dilution with ambient ground water. Oxygen consumption by ammonium- and organic-carbon-oxidizing bacteria in the unsaturated zone and just below the water table caused anoxic conditions in the vertical and horizontal center of the plume (fig. 3*B*), where ammonium concentrations also were high (ranging from 2 to more than 8 mg/L as nitrogen, fig. 3*D*).

FACTORS AFFECTING POTENTIAL TRANSPORT OF THE EFFLUENT PLUME TO NAMSKAKET MARSH

Ground-Water Discharge to Namskaket Marsh, 1994-95

Ground-water discharge to Namskaket Marsh during 1994-95 primarily occurred in seepage zones near the marsh/upland boundary, in the bottom sediments of the creek system, and in other areas where the marsh peat is thin or lacking a basal clay unit. The boundary seepage zones are clearly illustrated by the areal distribution of salinity in the shallow pore water of the marsh (fig. 7). Marsh areas where the pore-water salinity is less than 4 ppt correspond to zones where persistent standing water or ground-water seepage can be observed at the marsh surface. Areas where the salinity is greater than 4 ppt generally show no evidence of seepage. Pore-water salinities in the bottom sediments of the creek system also generally are less than 4 ppt, which is indicative of ground-water discharge.

Areally averaged rates of ground-water discharge to the marsh were inferred from ebb-tide discharge measurements in Namskaket Creek (figs. 8 and 9). From March 1994 to September 1995, freshwater discharge during the late-ebb-tide period ranged from 0.14 to 0.53 ft^3/s at creek site A (fig. 1), and was well correlated with ground-water levels in the adjacent aquifer (fig. 8). This range in streamflows corresponds to a ground-water discharge range of 0.12 to 0.44 $(gal/ft^2)/d$ averaged across the entire marsh and creek-bottom surface upstream of site A. Discharge rates in the boundary seepage areas and creek bottoms were about 7.0 $(gal/ft^2)/d$ or about 25 times higher than these areally averaged rates. Discharge rates in the marsh interior where the marsh peat was thick and commonly underlain by a basal clay unit, were much lower than the areally averaged rates.



EXPLANATION

AREAL EXTENT OF THE SEPTAGE-EFFLUENT PLUME IN GROUND WATER, BASED ON ELECTROMAGNETIC-INDUCTION LOGS OF DEEP WELLS AT THE SITE

A——A' LINE OF HYDROGEOLOGIC SECTION--Section shown in figure 5.

• OBSERVATION WELL--Shows location of single well or multiple-well cluster used to measure ground-water levels and monitor water quality

○ PORE-WATER SAMPLING SITE--Shows location of shallow well used to measure salinity of marsh pore water

▲ AUTOMATED STAGE AND WATER-QUALITY MONITORING STATION--Shows site where creek stage and salinity are continuously monitored

Figure 4. Areal extent of the septage-effluent plume, as defined by electromagnetic-induction logs, September 1991 to September 1995.

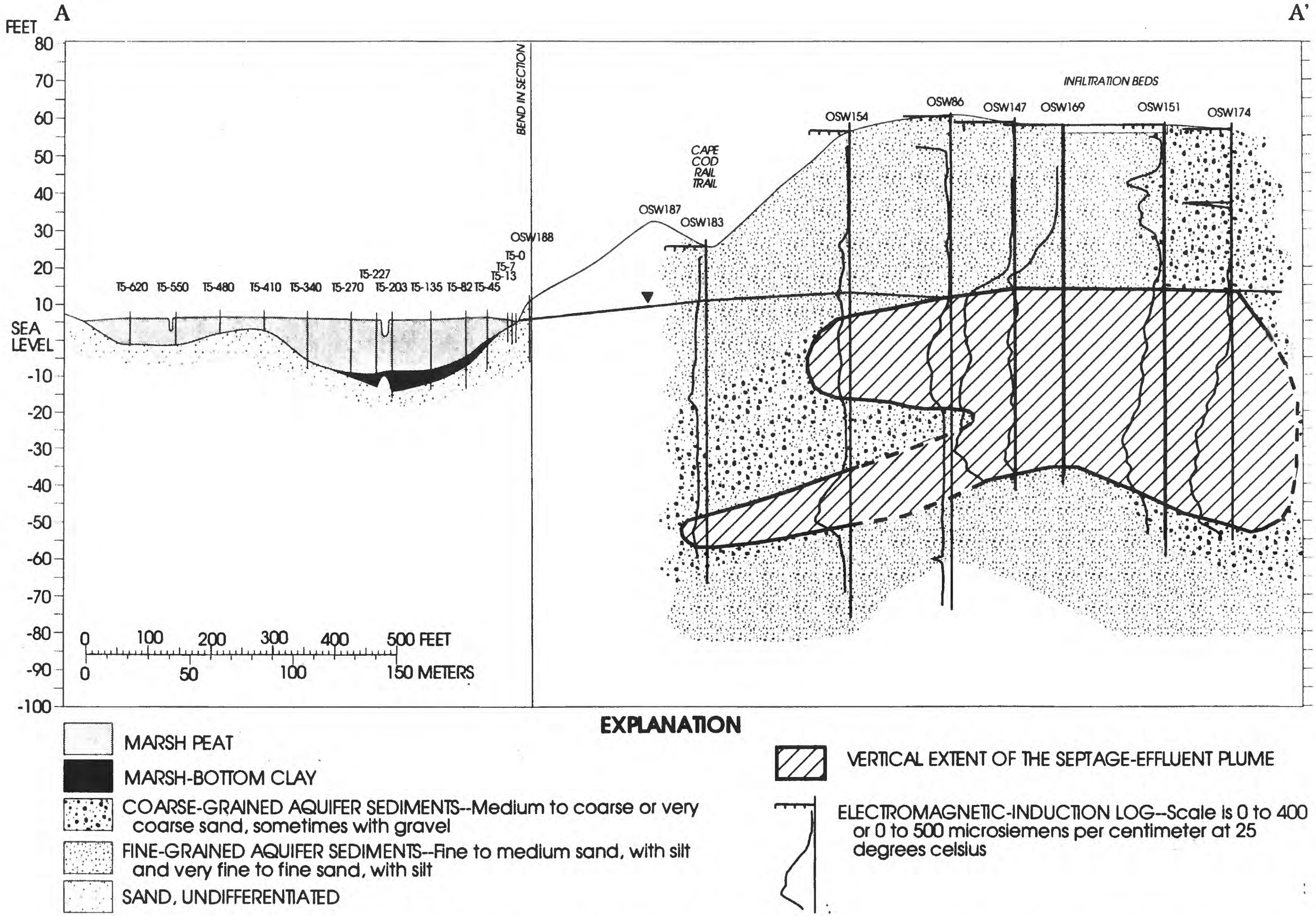


Figure 5. Aquifer and marsh lithology, the vertical and lateral extent of the septage-effluent plume, and electromagnetic induction logs along section *A-A'* through the upland aquifer and Namskaket Marsh, Orleans, Massachusetts, November 1994. Line of section shown in figure 4.

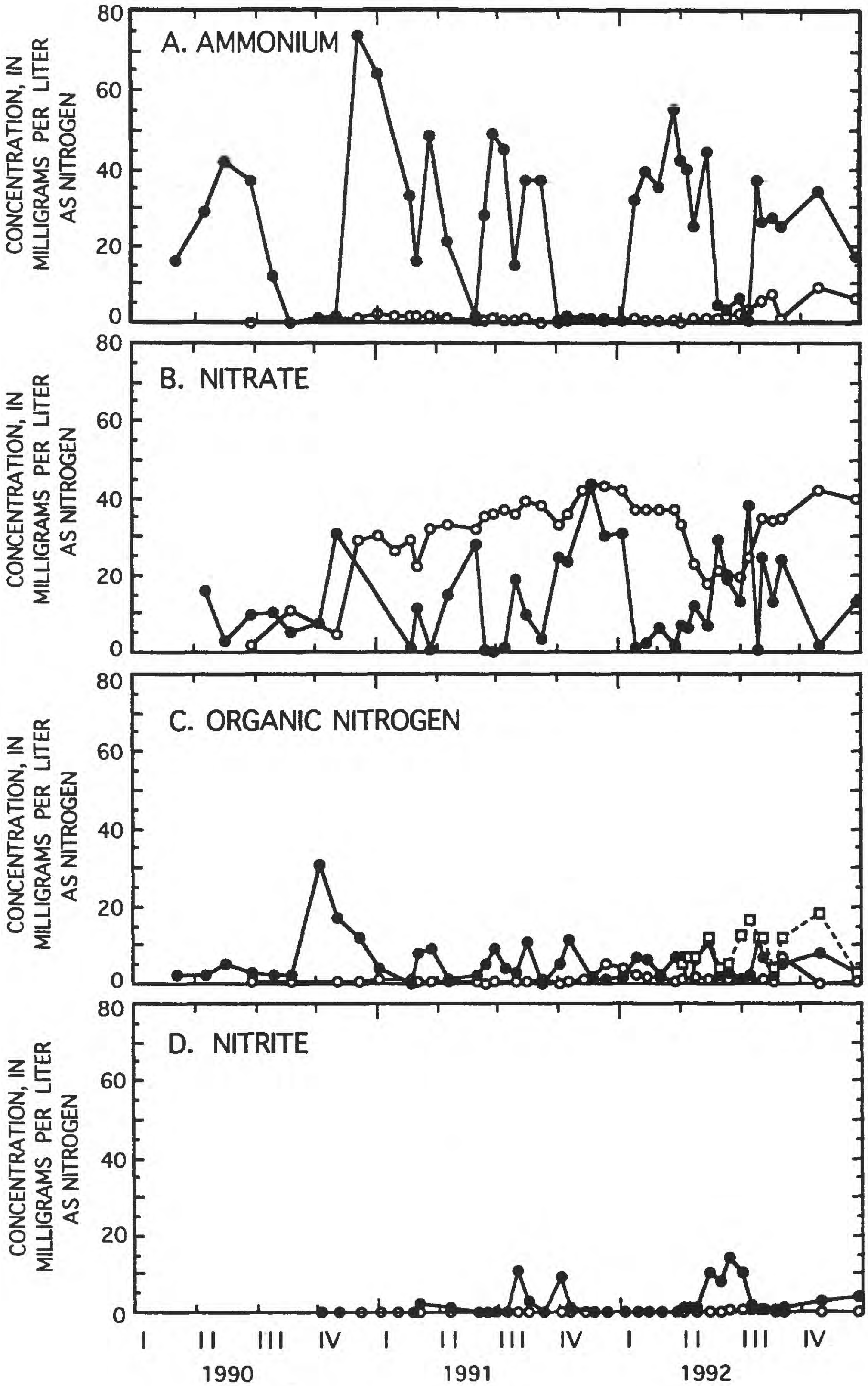


Figure 6. Concentrations of nitrogen species in effluent (solid circles, dissolved; open squares, dissolved and particulate) and ground water at the water table beneath the infiltration beds (open circles), Tri-Town Septage-Treatment Facility, Orleans, Massachusetts, March 1990 through December 1992. Higher concentrations of nitrate and lower concentrations of ammonium and organic nitrogen in ground water than in effluent indicate that ammonium and organic nitrogen in effluent are transformed to nitrate in the unsaturated zone. (Modified from DeSimone and others, 1995, fig. 7.)

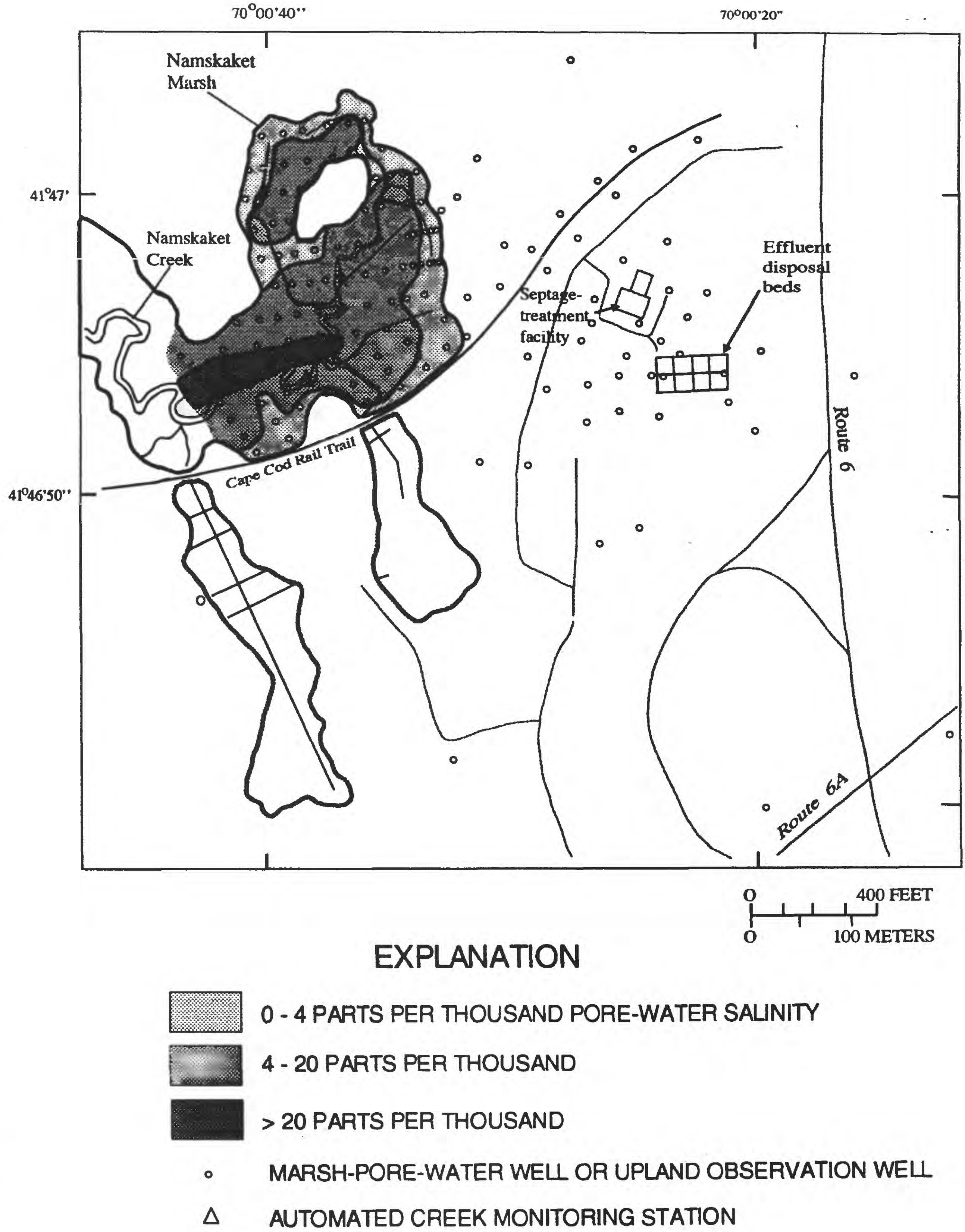


Figure 7. Areal distribution of pore-water salinity, 30 centimeters below marsh surface, Namskaket Marsh, Orleans, Massachusetts, August 1994.

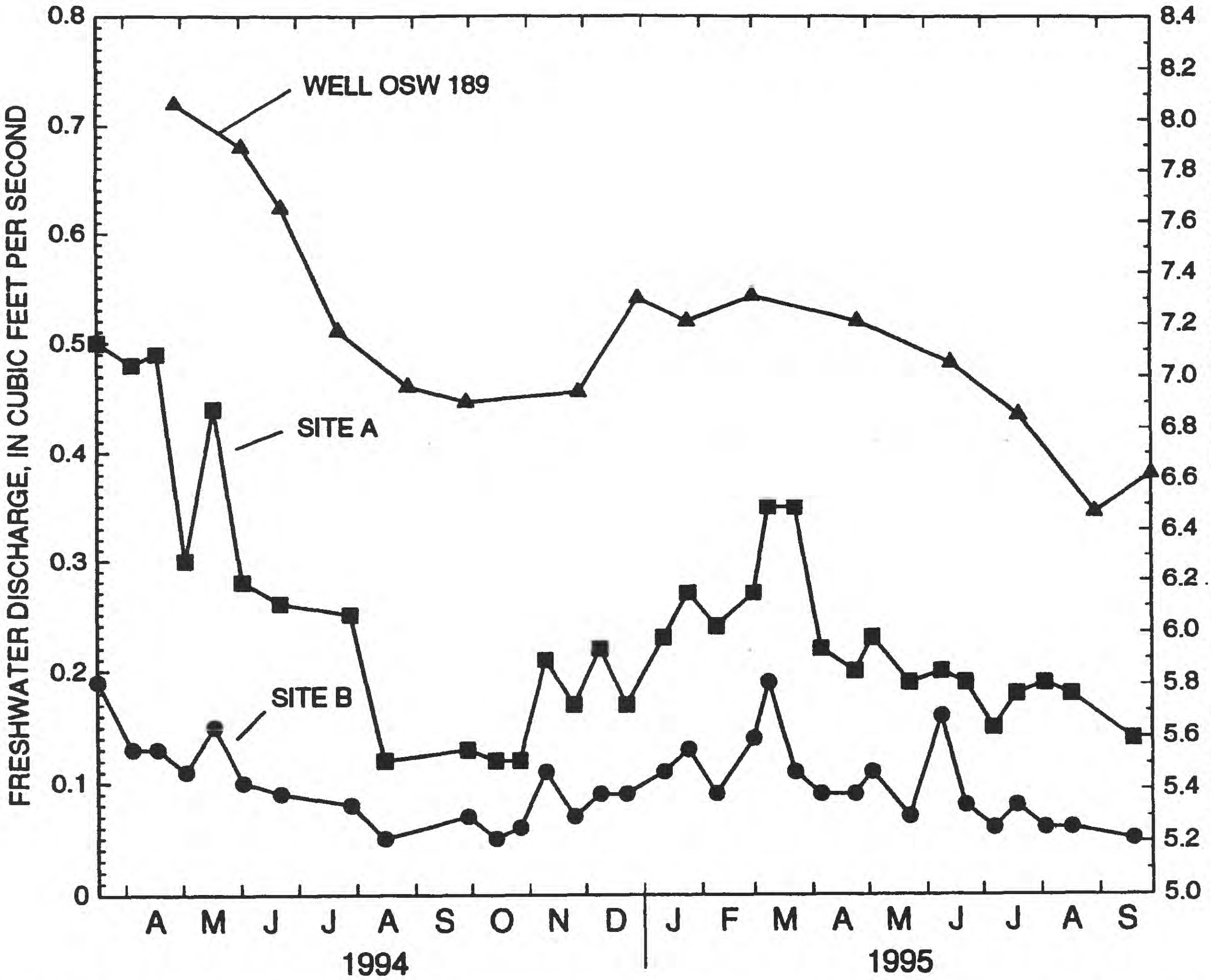


Figure 8. Ebb-tide discharge measured biweekly during period of constant stage, sites A and B, Namskaket Creek, and water-table altitude at upland well site OSW 189 near Namskaket Marsh, Orleans, Massachusetts, March 1994 through September 1995. (Locations shown in figure 1.)

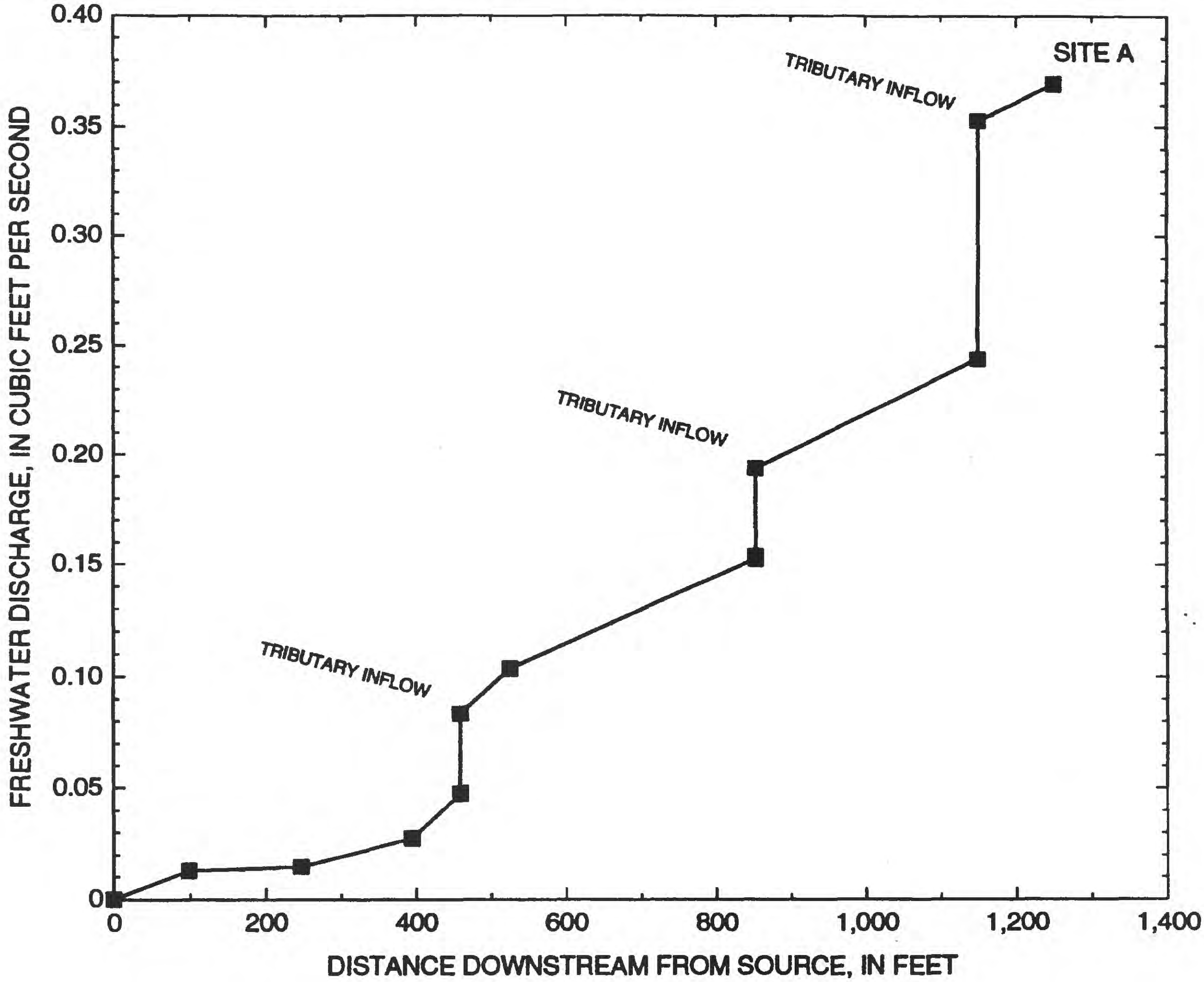


Figure 9. Ebb-tide discharge measured at selected sites downstream of source and upstream of site A, Namskaket Creek, during period of constant stage, March 23, 1995. Sharp increases in discharge at 460, 850, and 1,150 feet downstream of source are due to tributary inflows. (Locations shown in figure 1.)

Nitrogen Transformations in the Coastal Aquifer, Namskaket Marsh, and Namskaket Creek System, 1990-95

Study of nitrogen transformations at the site to date (1995) has focused on two natural processes—ammonium sorption and denitrification—that are most likely to decrease nitrogen concentrations in ground water and minimize potential effects of effluent nitrogen on Namskaket Marsh. Ammonium sorption is the process whereby ammonium as nitrogen is naturally removed by aquifer sediments, thereby decreasing concentrations of dissolved nitrogen in ground water. Denitrification is the process by which subsurface bacteria oxidize organic carbon and transform dissolved nitrate to nitrogen gas (N_2) in the absence of oxygen. Nitrogen gas is a harmless form of nitrogen that is naturally present in ground water and the atmosphere and does not cause eutrophication.

Nitrogen transformations in the upland aquifer were studied from 1990 through 1992. Findings during this period showed that denitrification and ammonium sorption occurred in the anoxic zone in the center of the effluent plume where nitrogen was present as nitrate and ammonium. Denitrification was measured in sediment cores and by N_2 production along discrete flowpaths in the aquifer. Denitrification, as measured by these two methods, averaged 25±19 and 7.7±3.6 µg/L as N per day, respectively (DeSimone and others, 1995). Based on these rates and a plume-wide N_2 survey, denitrification transformed about 2 percent of the total mass of nitrogen discharged to the aquifer through December 1992 (fig. 10). Denitrifying activity was limited by the low concentrations of organic carbon in the plume and thus did not greatly attenuate dissolved-nitrogen concentrations. In contrast, about 16 percent of the total mass of nitrogen in the plume in December 1992 was held by aquifer sediments through ammonium sorption (fig. 10). Other processes potentially attenuating dissolved-nitrogen concentrations had little effect; thus, most of the nitrogen discharged to the aquifer in effluent was transported with the ground water as nitrate.

Transformation of ambient (background) nitrogen in the marsh and creek-bottom sediments was studied in 1994-95, prior to the discharge of the effluent plume to the marsh. Preliminary measurements indicate that denitrification is primarily nitrate-limited in the boundary-seepage zone of the marsh, and secondarily limited by the availability of degradable organic carbon. This finding indicates a potential for significant nitrogen removal during plume discharge through the boundary seepage zone. Uptake of in-stream nitrate by bottom sediments in Namskaket Creek was measured with benthic chambers on six dates at five creek sites ranging from the creek headwaters to 800 ft downstream. Mean rates of sediment nitrate uptake ranged from 3.9 to 7.6 mg of nitrogen per square meter per hour. Rates of creek-bottom-nitrate uptake also were highly limited by nitrate availability, and only secondarily limited by organic-carbon concentrations. Denitrification appears to be the primary uptake process, though photosynthetic uptake by benthic autotrophs also occurs in the creek.

WATER-QUALITY, TIDAL, AND VEGETATION MONITORING PRIOR TO PLUME ARRIVAL IN THE NAMSKAKET MARSH AND NAMSKAKET CREEK SYSTEM, 1993-95

Water-Quality and Tidal Monitoring

Nutrient concentrations in Namskaket Creek have been monitored biweekly since March 1993. Surface-water samples are collected during the late ebb tide, when the freshwater part of the creek discharge is at a maximum. Samples are analyzed for ammonium, orthophosphate, and nitrate. These data have been collected to document the baseline variation in nutrient concentrations characteristic of the creek prior to plume arrival (fig. 11). During 1993-95, ammonium concentrations showed a strong seasonal pattern, with concentrations at the primary sampling site (site A, fig. 1) ranging from about 0.03 mg/L as nitrogen in the early spring to more than 0.40 mg/L as nitrogen in the late

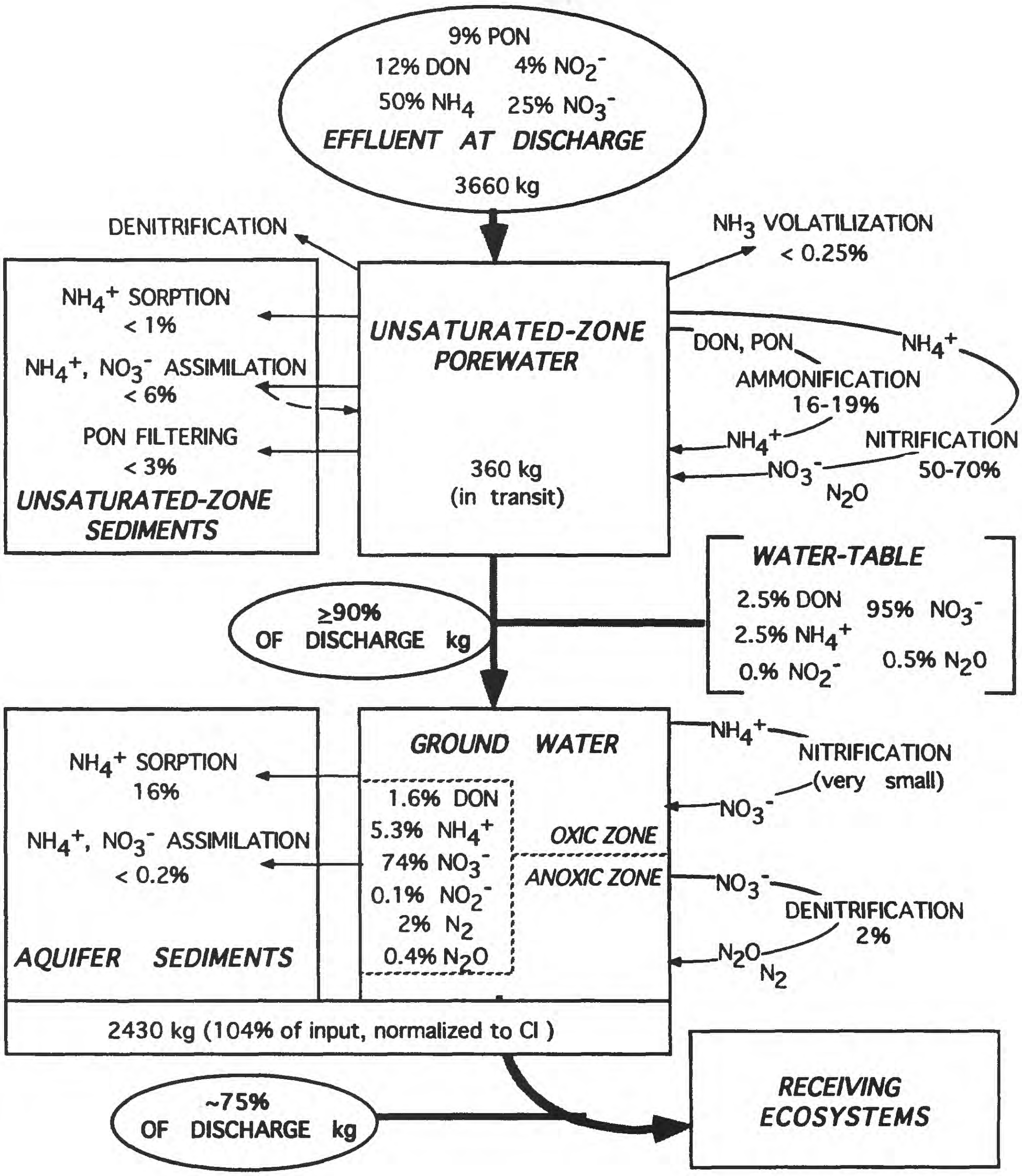


Figure 10. Mass balance of nitrogen species and reactions in the effluent, unsaturated zone, and saturated zone of the upland aquifer, Namskaket Research Site, Orleans, Massachusetts, February 1990 through December 1992. PON, particulate organic nitrogen; DON, dissolved organic nitrogen; NH_4^+, ammonium; NH_3, ammonia; NO_2^-, nitrite; NO_3^-, nitrate; N_2O), nitrous oxide; N_2, dinitrogen from denitrification. (Modified from DeSimone and others, 1995, fig. 35.)

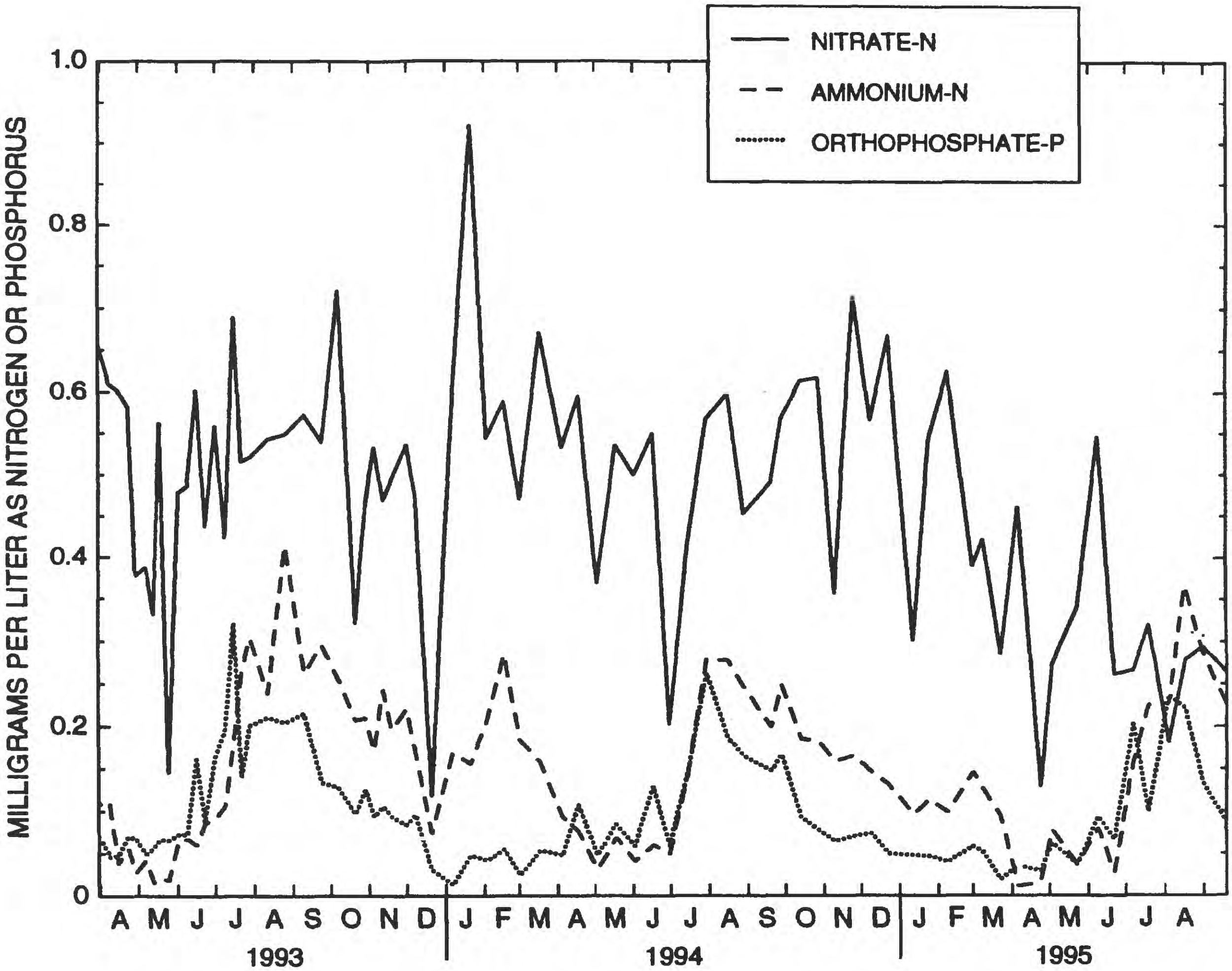


Figure 11. Ebb-tide concentrations of dissolved nutrients measured biweekly during period of constant stage, site A, Namskaket Creek, March 31, 1993 through September 1995.

summer. Orthophosphate concentrations followed a similar seasonal pattern, with overall concentrations ranging from about 0.03 to 0.30 mg/L as phosphorus. Nitrate concentrations, which ranged from 0.11 to 0.87 mg/L as nitrogen, did not follow a clear seasonal pattern during 1993-95.

Stage and specific conductance data have been collected since May 1993 with a USGS mini-monitor (site A, fig. 1) to characterize the tidal regime of the marsh and creek. The tidal regime is an important factor controlling the vegetation distribution of the marsh, both before and after the expected arrival of the effluent plume. As expected, the marsh is ebb dominated in the area under study, because of its location about 1 mi inland from Cape Cod Bay. The median stage for high tide at site A is 5.4 ft above sea level. The average altitude of the marsh surface is about 6.0 ft above sea level. About 20 percent of the high tides flood the marsh surface. These tides generally occur at the time of the new and full moons and are known as spring tides. Median specific conductance at high tide at site A is 26,000 μS/cm, which is equivalent to a salinity of 17 ppt. Specific conductance generally exceeds 42,000 μS/cm (27 ppt) during spring tides at site A.

Vegetation Monitoring

The distribution and biomass of salt-marsh vegetation and creek-bottom algae are being mapped to document the baseline vegetation community of Namskaket Marsh and Creek. Vegetation distributions in the summer of 1995 were estimated from aerial photography and verified with the observed distribution of major plant types (fig. 12). The two dominant plant associations in the high marsh are *Spartina patens* (salt meadow grass) and *Phragmites australis* (common reed). The *Phragmites* are concentrated in areas of low pore-water salinity (0-4 ppt) (fig. 12). In addition to pore-water salinity, plant distribution is greatly affected by deposition of thick mats of dead plant material (wrack) by storms and spring tides. Such deposits can kill the underlying vegetation (by preventing light penetration), create large areas of bare soil, and initiate processes of plant succession (Bertness and Ellison, 1987).

The creek-bottom macro-algal community was mapped throughout the creek system in the summer of 1994. Major genera were mapped by field observation, with laboratory confirmation on harvested samples. *Rhizoclonium* was the dominant macro-algal genus present in the creek bottom areas. *Bangia* also was observed in some areas. Microphytes, such as diatoms, are known to have high rates of primary production in bottom sediments year round, and are therefore expected to be a sensitive indicator of changed nutrient conditions caused by discharge of the effluent plume to the creek system. Microphyte density was surveyed in the creek bottoms in the summers of 1994 and 1995, by measuring the chlorophyll-*a* concentration of the top several millimeters of creek sediment. Chlorophyll-*a* concentrations ranged from 0.2 to 35 $\mu g/cm^2$. The highest values represent dense microphyte populations. This variability is common in marsh creeks and can be attributed to heterogeneity in light exposure, flow regime, and grazing by invertebrates.

In May 1995, a small-scale marsh fertilization experiment was initiated at two sets of test plots, one located in a *Spartina patens* zone, and the other in a *Phragmites australis* zone (fig. 12). The purpose of the experiment is to measure the effect of nitrogen fertilization on plant biomass and tissue-nitrogen concentration at the peak of the growing season and to compare these data with data from adjacent unfertilized control plots. The nitrogen loading rate used [0.94 $(g/ft^2)/wk$ of nitrogen] approximates the loading rate expected from plume discharge to the boundary seepage zone of the marsh. Preliminary data from the first growing season indicate no significant difference in biomass between fertilized and unfertilized plots in the *S. patens* zone, and a somewhat higher (20 percent) biomass in the fertilized plots in the *Phragmites* zone as compared to the unfertilized control plots. Base biomass values in the unfertilized control plots were 70.2 ± 12.4 g/ft^2 and 81.2 ± 12.4 g/ft^2 (dry weight) in the *S. patens* and *Phragmites* zones, respectively.

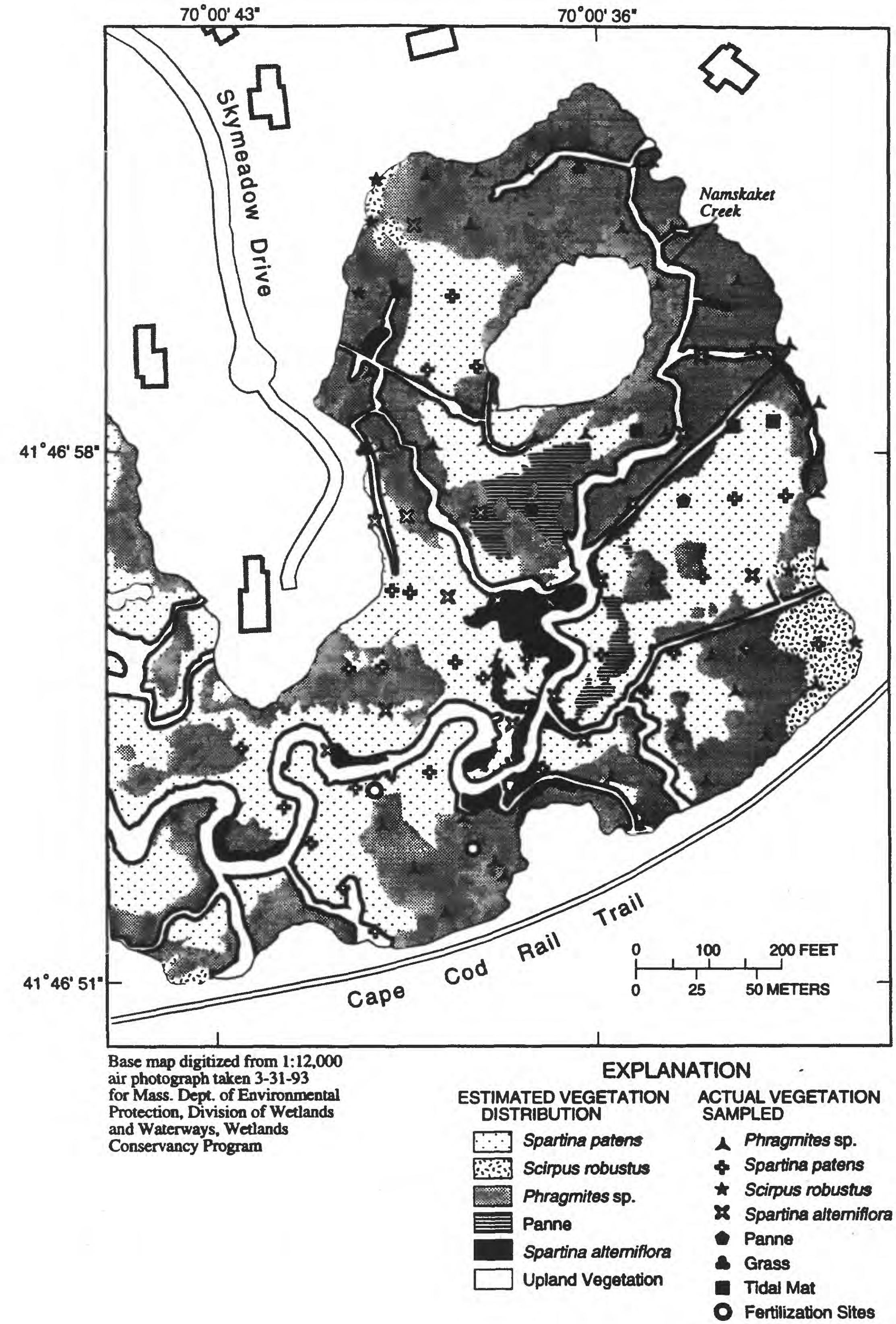


Figure 12. Distribution of dominant plant species in Namskaket Marsh estimated from aerial photography and ground sampling.

SUGGESTIONS FOR FURTHER STUDY

Further work at the Namskaket Marsh site is needed to (1) continue monitoring the movement of the effluent plume toward the marsh, (2) quantify rates of nitrogen transformation and removal occurring in the upland-marsh-creek system before and after plume arrival, and (3) monitor the possible effects of the plume on the water quality and vegetation of the marsh system.

Continued plume tracking will require installation of one or two more transverse sets of observation wells between the Cape Cod Rail Trail and the marsh for quarterly EM logging (fig. 4). Additional clusters of wells also should be installed in the aquifer underlying the marsh prior to plume arrival at the marsh to allow prediction of future plume transport directions. After the expected arrival of the plume at the marsh, wells should be driven in the marsh and underlying aquifer sediments orthogonal to the longitudinal axis of the plume, and sampled monthly for specific conductance. At least once after the plume arrives at the marsh, the entire upland and marsh well network should be sampled synoptically for concentrations of nitrogen constituents and dissolved oxygen, specific conductance, and other field parameters.

Studies of nitrogen behavior at the site (DeSimone and others, 1995) suggest that the unsaturated zone underlying the treatment facility disposal beds (fig. 1) plays a major role in transforming effluent nitrogen. Further work is needed to establish the chemical conditions and the distribution of microbial transformation processes in the unsaturated zone beneath the beds. These conditions and processes can be best determined through aquifer and pore-water sampling over an annual cycle. The potential for enhancement of nitrogen removal in the unsaturated zone through denitrification also should be investigated, preferably with a small-scale carbon addition experiment.

Preliminary results also suggest that denitrification in the marsh and creek-bottom sediments may remove substantial amounts of dissolved nitrate during ground-water discharge. Measurements of actual and potential denitrification rates should continue, and the quantitative significance of these rates for the overall fate of the plume nitrogen should be predicted. These predictions should then be compared with measured nitrogen fluxes resulting from discharge of the plume to the marsh and creek system.

Results to date (1995) indicate considerable natural variability in creek nutrient concentrations, sediment microalgae density, and marsh vegetation types. Because the factors controlling these characteristics of the marsh vary from year to year as well as seasonally, it is necessary to continue monitoring the marsh so that the potential long-term effects of the plume on the marsh ecosystem can be determined with confidence.

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