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Environmental Conditions in the Namskaket Marsh Area, Orleans, Massachusetts: A Summary of Studies by the U.S. Geological Survey, 1989–2011

Scientific Investigations Report 2016–5122

U.S. Department of the Interior
U.S. Geological Survey

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U.S. Geological Survey
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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	259.0	hectare (ha)
	Flow rate	
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Datum

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Elevation, as used in this report, refers to distance above or below the vertical datum.

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Abbreviations

CCC	Cape Cod Commission
EM	electromagnetic induction
MDEP	Massachusetts Department of Environmental Protection
n	number of samples
N	nitrogen
P	phosphorus
ppt	parts per thousand
PVC	polyvinylchloride
TDN	total dissolved nitrogen
TDP	total dissolved phosphorus
USGS	U.S. Geological Survey
WHOI	Woods Hole Oceanographic Institution

Environmental Conditions in the Namskaket Marsh Area, Orleans, Massachusetts: A Summary of Studies by the U.S. Geological Survey, 1989–2011

By Peter K. Weiskel, Jeffrey R. Barbaro, and Leslie A. DeSimone

Abstract

Namskaket Marsh and its tidal creek system are potential receptors for a treated wastewater plume originating from a septage treatment facility in the northwest part of Orleans, Massachusetts, on Cape Cod. From 1989 to 2011, the U.S. Geological Survey, in cooperation with State and local partners, conducted a series of studies in the Namskaket Marsh area to characterize the potential effects of the plume on the marsh and its tidal creek system. Studies included characterizing the baseline vegetation and salinity distribution in the marsh, monitoring the movement of the wastewater plume downgradient of the septage treatment facility, and sampling nutrient concentrations in the tidal creek system during a baseline period prior to the arrival of the plume at the marsh boundary. The Inner Namskaket Marsh baseline vegetation survey in 1995 found it to be dominated by *Phragmites australis* (common reed, 44 percent of vegetative cover), *Spartina patens* (salt marsh hay, 17 percent), and *Spartina alterniflora* (cordgrass, 9 percent). *Phragmites* occurrence was correlated with shallow pore-water salinity in the marsh peat and was largely confined to areas with salinities less than 4 parts per thousand. Baseline, ebb-tide nutrient concentrations at the tidal creek sampling stations during 1994–96 showed strong seasonal variations for ammonium, likely associated with the seasonal cycle of growth and senescence for the dominant salt marsh grasses (*S. alterniflora* and *S. patens*). The seasonal cycle for nitrate was generally less pronounced.

The movement of the wastewater plume has been monitored from its source at the septage treatment facility to areas immediately adjacent to and beneath the most inland part of the marsh. In late 1994, the plume was first detected by borehole geophysical logging in observation wells along the Cape Cod Rail Trail (rail trail), 600 feet northwest of the infiltration beds, at an elevation of 47 to 53 feet below the National Geodetic Vertical Datum of 1929 (NGVD 29). At the rail trail, the plume was largely confined below a 3- to 8-foot-thick silt/clay layer detected by borehole geophysical logging and confirmed by lithologic samples. By early 1998, a second plume segment was detected above this silt/clay layer at the rail trail, near the plume's southwest boundary. Groundwater sampling in 2003–4 at additional stations southwest of the main plume, as well as beneath Namskaket Marsh, defined the extent of this shallow plume segment in glacial sands underlying the marsh.

The tidal creek sampling stations established in the 1990s were resampled in 2003–4 and 2010–11 to evaluate potential effects of the treated wastewater plume on creek water quality. The annual medians of the 2011 biweekly nitrate and total dissolved nitrogen concentrations were determined for each station and compared to the annual medians of biweekly samples for the baseline years 1994, 1995, and 1996. At all stations, the 2011 median nitrate concentrations were within the range of medians for the 3 baseline years. A similar result was obtained for total dissolved nitrogen. We conclude that the 2011 creek samples, collected approximately 8 years after the shallow plume segment was first detected beneath the marsh, do not show evidence of elevated nitrate or total dissolved nitrogen concentrations attributable to discharge of either the shallow or deep segments of the treated wastewater plume.

Introduction

Land disposal of treated municipal wastewater is a commonly used alternative to the direct discharge of wastewater to surface waters. The Tri-Town Septage Treatment Facility (also referred to as the Tri-Town Facility) in Orleans, Massachusetts, was designed to treat septage, the semisolid residue that is pumped from residential and commercial septic tanks, and then discharge the treated effluent to infiltration beds overlying a predominantly sandy aquifer of glacial origin (DeSimone and others, 1996). The facility, which began operation in 1990, serves the towns of Orleans, Brewster, and Eastham, Mass., on Cape Cod and is located between U.S. Route 6 and the most inland portion of Namskaket Marsh (fig. 1).

Namskaket Marsh occupies a triangular indentation on the northern coast of Cape Cod, near the border of Orleans and Brewster, Mass. The overall marsh system includes a salt marsh, approximately 300 acres in area, typical of those bordering Cape Cod Bay on the northern shore of Cape Cod

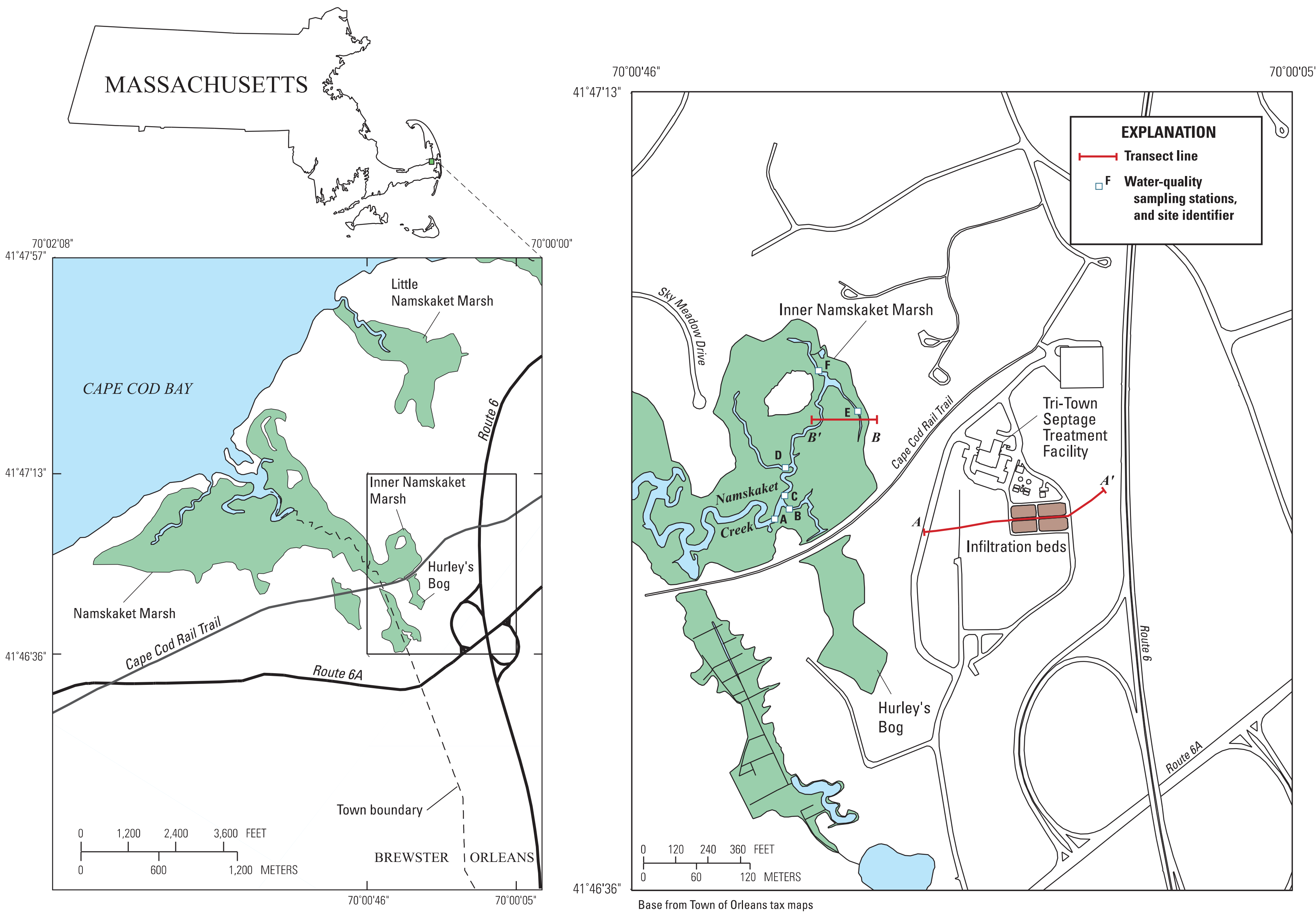


Figure 1. Location of Namskaket Marsh and Creek and the Tri-Town Septage Treatment Facility, Orleans, Cape Cod, Massachusetts (modified from DeSimone and others, 1998a). *A–A′* shows the location of the upland cross section in figure 2. *B–B′* shows the location of the marsh cross section in figure 3. Locations *A–F* are water-quality sampling stations in Namskaket Creek and its tributaries.

(Redfield, 1972). The system also includes Namskaket Creek, a tidal creek (and associated tributaries) that originates in natural groundwater discharge areas located mainly near the boundary of the marsh with adjacent upland areas.

The U.S. Geological Survey (USGS) has conducted several studies at the Tri-Town Facility site, in adjacent upland areas, and in the Namskaket Marsh system, in cooperation with the Massachusetts Department of Environmental Protection (MDEP); the Cape Cod Commission (CCC); and the Orleans, Brewster, and Eastham Groundwater Protection District. These studies began in 1989 and are documented in a series of USGS reports. The reports describe the site geology, aquifer characteristics, groundwater quality prior to wastewater effluent discharge, and initial development and chemistry of the treated effluent plume originating at the Tri-Town Facility (DeSimone and others, 1996). The subsequent movement of the effluent plume, distribution of natural groundwater discharge areas in Namskaket Marsh, and baseline (that is, prior to the potential influence of the effluent plume) water-quality conditions in the Namskaket Creek system have also been described (Weiskel and others, 1996; DeSimone and others, 1998b). Finally, the baseline distribution and abundance of plant species in the most inland part of Namskaket Marsh (Inner Namskaket Marsh, fig. 1) have been assessed and evaluated in relation to pore-water salinity (DeSimone and others, 1998a). The USGS, in cooperation with the Orleans, Brewster, and Eastham Groundwater Protection District, collected more recent water-quality data from the Namskaket Creek system through 2011 and prepared this summary of the previous studies with context provided by the more recent data collection.

Purpose and Scope

The purpose of this report is twofold. First, the report characterizes environmental conditions in the study area in Orleans, Mass., by summarizing the findings of the previous USGS investigations referenced above. Second, the report interprets the results of more recent data collected in the area, in cooperation with the Orleans, Brewster, and Eastham Groundwater Protection District. More recent data collection activities include water-quality sampling of groundwater in the sandy glacial deposits adjacent to and beneath Namskaket Marsh (in 2003–4) and water-quality sampling in Namskaket Creek in 2003–4 and 2010–11 at baseline water-quality stations established in the mid-1990s. The results of 2010–11 water-quality sampling are then interpreted in light of the baseline creek sampling results from the mid-1990s. The types of monitoring stations sampled in the Namskaket Marsh area since 1989 are summarized in table 1.

Baseline Environmental Conditions

In order to understand the movement of the wastewater plume originating at the Tri-Town Facility site, it is useful to review baseline environmental conditions in the Namskaket Marsh study area (fig. 1). Baseline environmental conditions include the geology, aquifer properties, hydrology, and groundwater flow patterns of the upland portions of the study area, as well as the sediments, groundwater discharge areas, and vegetation distribution of Inner Namskaket Marsh. These baseline conditions are summarized in the following sections.

Geology and Aquifer Properties

The Orleans study area is underlain by glacial deposits that date from the retreat of the last Laurentide Ice Sheet from southeastern New England approximately 18,000 years before the present (Oldale and Barlow, 1986). These deposits include sandy glacial outwash plain deposits; fine-grained glacial lake deposits of fine sand, silt, and clay; and sandy moraine (glacier margin) deposits. The Tri-Town Facility is located near a former ice-margin position, at the head of the Harwich outwash

Table 1. Types of monitoring stations where data were collected by the U.S. Geological Survey in studies of the Namskaket Marsh area, Orleans, Massachusetts, 1989–2011, in cooperation with the Massachusetts Department of Environmental Protection, the Cape Cod Commission, and the Orleans, Brewster, and Eastham Groundwater Protection District.

Station type	Location	Data collection type	Monitoring periods	Reference
Groundwater observation wells	Upland areas and Cape Cod Rail Trail	Water levels, aquifer lithology, geophysical logs	1989–96	DeSimone and others, 1996; Weiskel and others, 1996
Creek water-quality stations	Namskaket Creek	Surface-water quality	1993–97; 2003–4; 2010–11	DeSimone and others, 1998b; present study
Marsh pore-water samplers	Inner Namskaket Marsh	Pore-water salinity	1995	DeSimone and others, 1998a
Multilevel samplers	Cape Cod Rail Trail	Groundwater quality	2003–4	Present study
Temporary well-point stations	Aquifer beneath Namskaket Marsh	Groundwater quality	2003–4	Present study

plain (fig. 3 in Walter and Whealan, 2005). Fine-grained lake bottom sediments (silt and clay) interfinger with sandy sediments below and to the northwest of the Tri-Town Facility site toward Cape Cod Bay; the combined thickness of outwash and lake sediments in the area is estimated to be 300 to 400 feet (ft) and extend to an elevation of 250 to 300 ft below National Geodetic Vertical Datum of 1929 (NGVD 29) (Walter and Whealan, 2005). These sediments are likely underlain by a thin layer of compact, low-permeability glacial till, which directly overlies the granitic bedrock of the region (Walter and Whealan, 2005).

In the immediate vicinity of the Tri-Town Facility, three unconsolidated lithologic units of glacial origin (fig. 2) have been identified by DeSimone and others (1996): (1) an upper fine-grained unit consisting of fine to very fine sand, with some silt; (2) an intermediate coarse-grained unit of medium to very coarse sand, with some gravel; and (3) a lower fine-grained unit of fine to very fine or medium to fine sand. The upper and lower fine-grained units each average about 50 ft in thickness, and the intermediate coarse-grained unit varies widely in thickness, from 5 to 60 ft (fig. 2).

The hydraulic conductivities (K values) of the deposits—a measure of the ability of a deposit to transmit water—are discussed in detail by DeSimone and others (1996). Because of variations in hydraulic conductivity, groundwater and associated plumes of dissolved constituents tend to flow preferentially through coarse-grained deposits, as opposed to fine-grained deposits, and horizontally, as opposed to vertically—although local variations in the direction and magnitude of the hydraulic gradient (see, for example, the potentiometric contours of fig. 2) also play an important role in governing groundwater flow patterns in the study area (DeSimone and others, 1996).

Hydrology and Groundwater Flow

The Cape Cod aquifer contains six regional groundwater flow systems, or lenses (Barbaro and others, 2014). The town of Orleans, Mass., overlies the eastern part of the Monomoy lens (see fig. 5 in Walter and Whealan, 2005), and the Tri-Town Facility is located near the northeastern boundary of the lens. Total recharge to the Monomoy lens averages about 27 inches per year over its 86-square-mile area, or 111 million gallons per day. Simulations from calibrated groundwater flow models, under 2003 water-use conditions, indicate that 93 percent of the total recharge is derived from precipitation, 6 percent is derived from septic systems and wastewater treatment facilities, and 1 percent is derived from freshwater streams (Walter and Whealan, 2005).

Groundwater flow through the Monomoy lens has both horizontal and vertical components. Viewed horizontally (figs. 1 and 5 in Walter and Whealan, 2005), regional groundwater flows radially from an area of high water-table elevation near the center of the lens in the towns of Brewster and Harwich, Mass., (southwest of the study area) to areas of natural groundwater discharge, consisting of freshwater streams, coastal marshes and estuaries, embayments, and open coastal waters to the north, east, south, and west of the Monomoy lens. In the vertical dimension, flow begins at the water table across the entire extent of the lens and proceeds through the aquifer toward freshwater streams and coastal discharge areas. Recharge that enters the Monomoy lens near the central mound of the lens will generally reach the greatest depths, follow the longest flow paths, and discharge farthest offshore. Recharge that reaches the water table nearer to the coast generally follows a shallower flow path and discharges to coastal embayments, marshes, or estuaries, such as Namskaket Marsh and Creek. Shallow groundwater from the Monomoy lens may also discharge directly to large bodies of coastal water (for example, Cape Cod Bay) along segments of coast where no marshes, estuaries, or embayments are present. Model simulations indicate that 42 percent of the total inflow to the Monomoy lens discharges to marshes, estuaries, and embayments. An additional 35 percent of the total inflow discharges directly to Cape Cod Bay and Nantucket Sound, 16 percent discharges to freshwater streams, and 7 percent is removed from the lens by public water-supply wells (Walter and Whealan, 2005).

Namskaket Marsh

Namskaket Marsh is an important example of the numerous salt marsh ecosystems found along the northern shore of Cape Cod Bay. In this section, we describe the sediment types found in the marsh and its tidal creek system and consider the effects of the sediments on natural patterns of groundwater discharge and the distribution of marsh vegetation.

Marsh Sediments

Namskaket Marsh occupies an indentation of the shoreline of Cape Cod Bay, near the boundary of the towns of Brewster and Orleans, Mass. (fig. 1). As has been documented in detailed studies of Great Barnstable Marsh, 15 miles to the east of Namskaket Marsh (Redfield, 1972), the large tidal range of Cape Cod Bay (~9 ft) and the abundant supply of sediment (sands and silts) have resulted in the deposition of extensive intertidal sediments along the Cape Cod Bay shoreline and within its indentations. In the protected environments of the indentations, the intertidal flats have been colonized by salt-tolerant grasses—cordgrass (*Spartina alterniflora*) and at higher elevations salt marsh hay (*Spartina patens*)—resulting in the development of salt marshes. Accretion of marsh surfaces on Cape Cod Bay, by accumulation of plant remains and associated inorganic sediment, has generally kept pace with rates of sea-level rise over the past several thousand years (Redfield, 1972). In addition, Redfield notes that original tidal-flat drainage systems in the marshes bordering Cape Cod Bay have largely been preserved because salt marsh creek bottoms also accrete sediment over time.

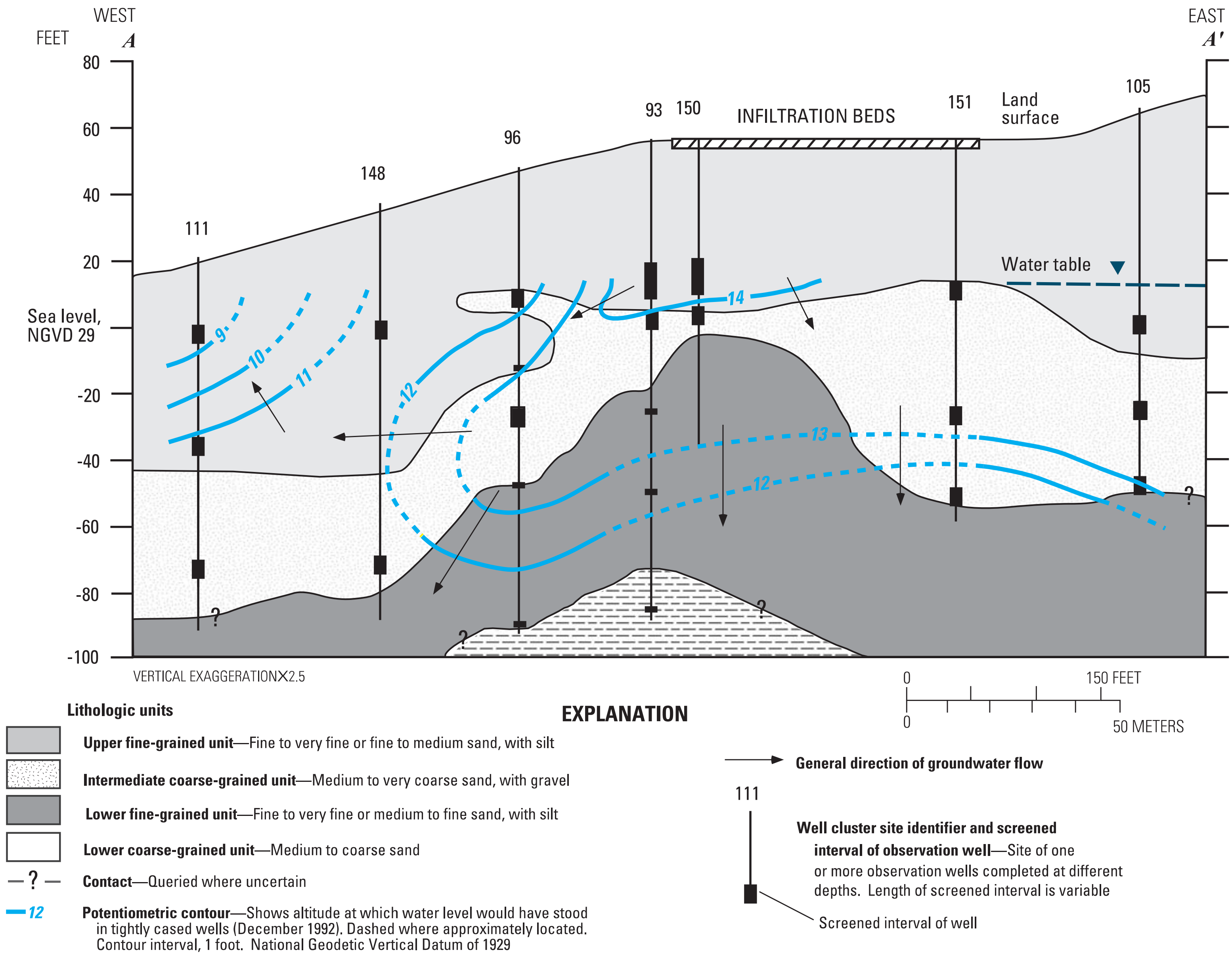


Figure 2. Upland cross section *A–A′* across the Tri-Town Septage Treatment Facility site, Orleans, Cape Cod, Massachusetts, showing major lithologic units, potentiometric contours, and general directions of groundwater flow, December 1992 (from DeSimone and others, 1996). See figure 1 for location of cross section.

The subsurface of Inner Namskaket Marsh was probed with a steel rod, and sediment samples were collected along the east-west transect *B–B′* (fig. 1). The resulting cross section (fig. 3) is consistent with the Redfield model of salt marsh development at Great Barnstable Marsh.

The lowermost sediment consists of undifferentiated sands of glacial origin. A layer of fine mud, likely a tidal-flat mud deposit, overlies the glacial sands. The fine mud grades upward into a muddy peat, which becomes more highly organic in the upward direction. Finally, in the creek bottoms of Inner Namskaket Marsh, we observed a mixture of fine-to-medium sand (tidally derived from Cape Cod Bay) and fragments of peat derived from the slumping of the creek banks. The relatively coarse sand-peat mixture resulting from this depositional process creates a natural groundwater discharge zone (fig. 3) and a potential pathway for plume transport to the creek system (Weiskel and others, 1996).

Groundwater Discharge Areas in Marsh

Two primary areas of groundwater discharge were observed during field studies of Inner Namskaket Marsh (Weiskel and others, 1996). The first area consists of boundary seepage zones adjacent to the upland, where peat directly overlies the glacial sand deposits of the upland, and the basal tidal-flat mud is absent (fig. 3). The second area consists of discharge zones in the tidal creek bottoms described previously in the section “Marsh Sediments.”

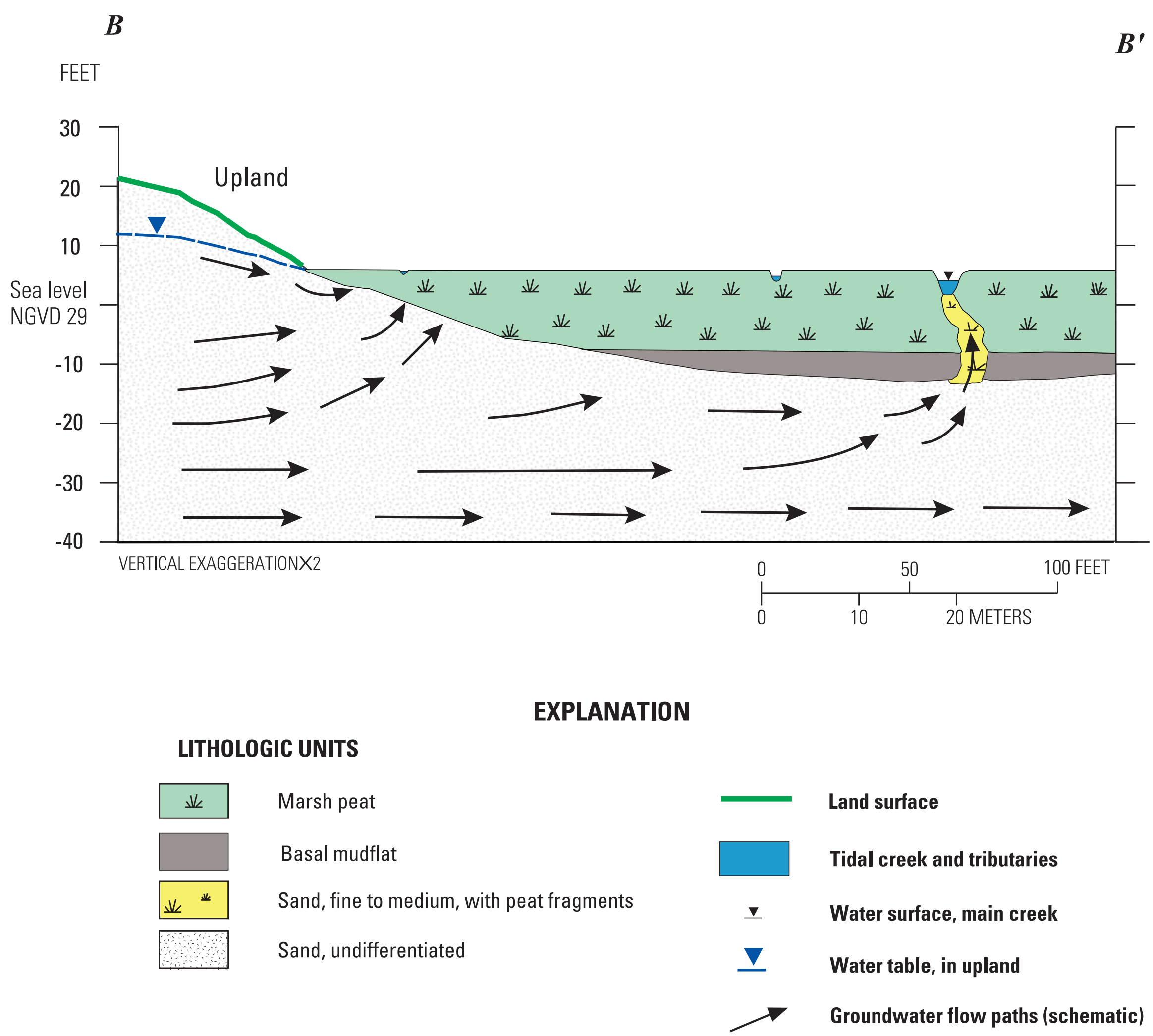


Figure 3. Inner Namskaket Marsh cross section *B–B′*, showing major sediment types inferred from sediment sampling and subsurface probing with a steel rod. Arrows show inferred directions of groundwater flow, and observed zones of groundwater discharge near the marsh-upland boundary and at the main creek bottom. See figure 1 for location of cross section.

Qualitative evidence of boundary seepage is provided by the persistent zone of standing water along the edge of the marsh, under both wet and dry weather conditions, and the persistence of free-standing water during winter cold periods, when the remainder of the Inner Namskaket Marsh surface is frozen. The boundary seepage zone does not readily freeze because ambient groundwater in the study area has a year-round temperature of approximately 10 degrees Celsius (DeSimone and others, 1996). A more quantitative indicator of boundary seepage was provided by the zone of low pore-water salinity (0 to 4 parts per thousand [ppt]) that was observed in July 1995 along most of the Inner Namskaket Marsh boundary (northern, eastern, and southeastern), as well as northeast and southwest of the nearby upland island (fig. 4). DeSimone and others (1998a) provide a detailed description of the pore-water sampling methods and locations.

Several lines of evidence also indicated groundwater discharge through the creek bottoms of Inner Namskaket Marsh. First, extensive baseline water-quality sampling in Namskaket Creek and its tributaries, conducted during the late ebb tide under all weather conditions, found that creek salinities near the end of the ebb tide were persistently less than 2 ppt (DeSimone and others, 1998b). Flood tidal waters, by contrast, typically exceeded 20 ppt. The low salinities during the late ebb period are consistent with dilution of the flood tidal water by groundwater discharge derived from the boundary zone and from upward discharge of groundwater through the creek bottoms in interior areas of Inner Namskaket Marsh. Moreover, upstream-to-downstream sequences of ebb-tide flow measurements in Namskaket Creek showed gains in freshwater-equivalent flow in the downstream direction during the late ebb period in reaches without inflowing tributaries (Weiskel and others, 1996).

Marsh Vegetation

A detailed survey of the vegetation of Inner Namskaket Marsh and Hurley’s Bog was conducted in the summer of 1995 (DeSimone and others, 1998a). The purpose of the survey was to establish the baseline distribution of marsh plant species prior to any potential effects from the treated effluent plume originating from the Tri-Town Septage Treatment Facility. Inner Namskaket Marsh was found to have a typical plant assemblage for a brackish, New England high marsh with a low-salinity transition zone near the marsh-upland boundary (fig. 5). *Phragmites australis* (common reed), *Spartina patens* (salt marsh hay), *Spartina alterniflora* (cordgrass), and a *S. patens*/*Distichlis spicata* (salt marsh hay/spikegrass association) were the most common types of vegetative cover, accounting for 44, 17, 9, and 8 percent, respectively, of the vegetated area of Inner Namskaket Marsh. Seven other species (or species associations) were observed; each of these accounted for 5 percent or less of the vegetated area. In addition, 14 percent of the total area of Inner Namskaket Marsh was covered by dead plant material (wrack).

Hurley’s Bog is located to the south of Inner Namskaket Marsh and is connected to the Namskaket Marsh creek system through a small culvert. The culvert conveys flows beneath a 19th-century former railroad embankment that defines the southern boundary of Inner Namskaket Marsh (fig. 1). Hurley’s Bog is largely covered by a shrub oak/maple wet woodland (73 percent of total area). The lower elevations of the marsh are covered by herbaceous species, dominated by *Phragmites australis* (21 percent of total area). *Iva frutescens*, *Scirpus robustus*, a *Solidago sempervirens*/*S. patens* association, and a *Phragmites australis*/*S. sempervirens* association cover the remaining 6 percent of the total bog area (fig. 5).

Comparison of Inner Namskaket Marsh salinity and vegetation maps (figs. 4 and 5) illustrates the role played by salinity in shaping the vegetation distribution of Inner Namskaket Marsh. The marsh areas dominated by *Phragmites* (fig. 5) generally coincided with the zone of lowest pore-water salinity (0 to 4 ppt) during the summer 1995 study period. The low salinity zones, in turn, coincided with those areas of the marsh (not including the tidal creek bottoms) that experienced high rates of natural groundwater discharge. These discharge areas are found near the marsh-upland boundary, or in other areas where marsh peat deposits are thin or lack a basal unit of tidal-flat mud (for example, to the northeast and southwest of the upland island of Inner Namskaket Marsh; see fig. 4). DeSimone and others (1998a) provide a detailed discussion of these and other factors controlling the vegetation distribution.

Treated Wastewater Plume

Since 1990, the Tri-Town Septage Treatment Facility has discharged treated wastewater effluent to infiltration beds located adjacent to the facility (fig. 1). Infiltration of the treated effluent has resulted in the development of a wastewater plume in the underlying groundwater system, consisting of a mixture of treated wastewater effluent and ambient (or background) groundwater below the infiltration beds. The development and movement of the plume was studied by the USGS in the 1990s (DeSimone and others, 1996; Weiskel and others, 1996) and monitored in the subsurface periodically by the USGS, in cooperation with MDEP and CCC, through 2000. This section of the report summarizes previous USGS work regarding the nutrient composition, physical development, and movement of the treated wastewater plume. More detailed discussion of the effluent and plume chemistry is provided by DeSimone and others (1996).

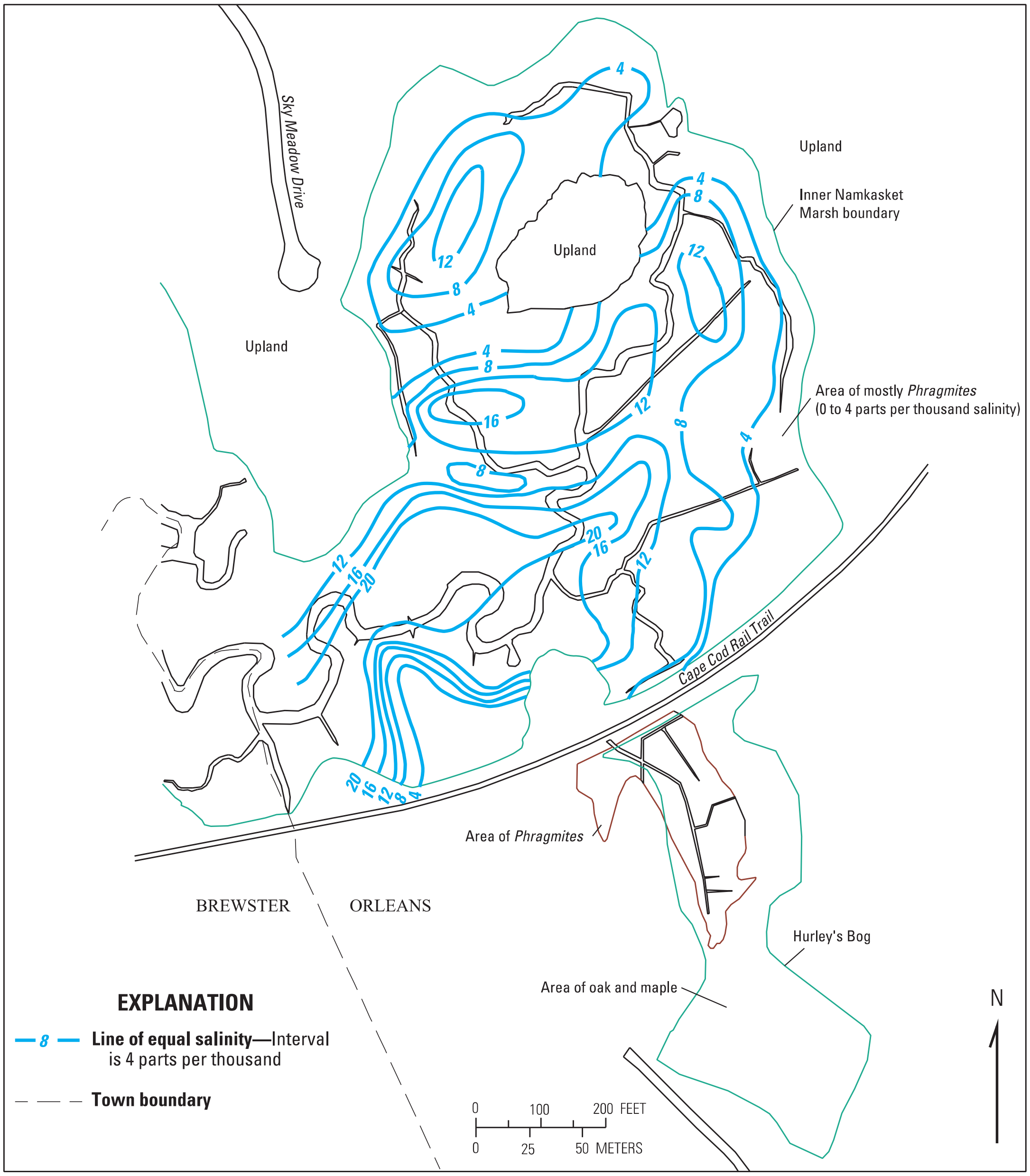


Figure 4. Contour map of pore-water salinity in shallow marsh peat (10–15 centimeters below marsh surface), Inner Namskaket Marsh, Cape Cod, Massachusetts, July 1995 (from DeSimone and others, 1998a). See figure 1 for location. See DeSimone and others (1998a, fig. 2) for locations of pore-water sampling points.

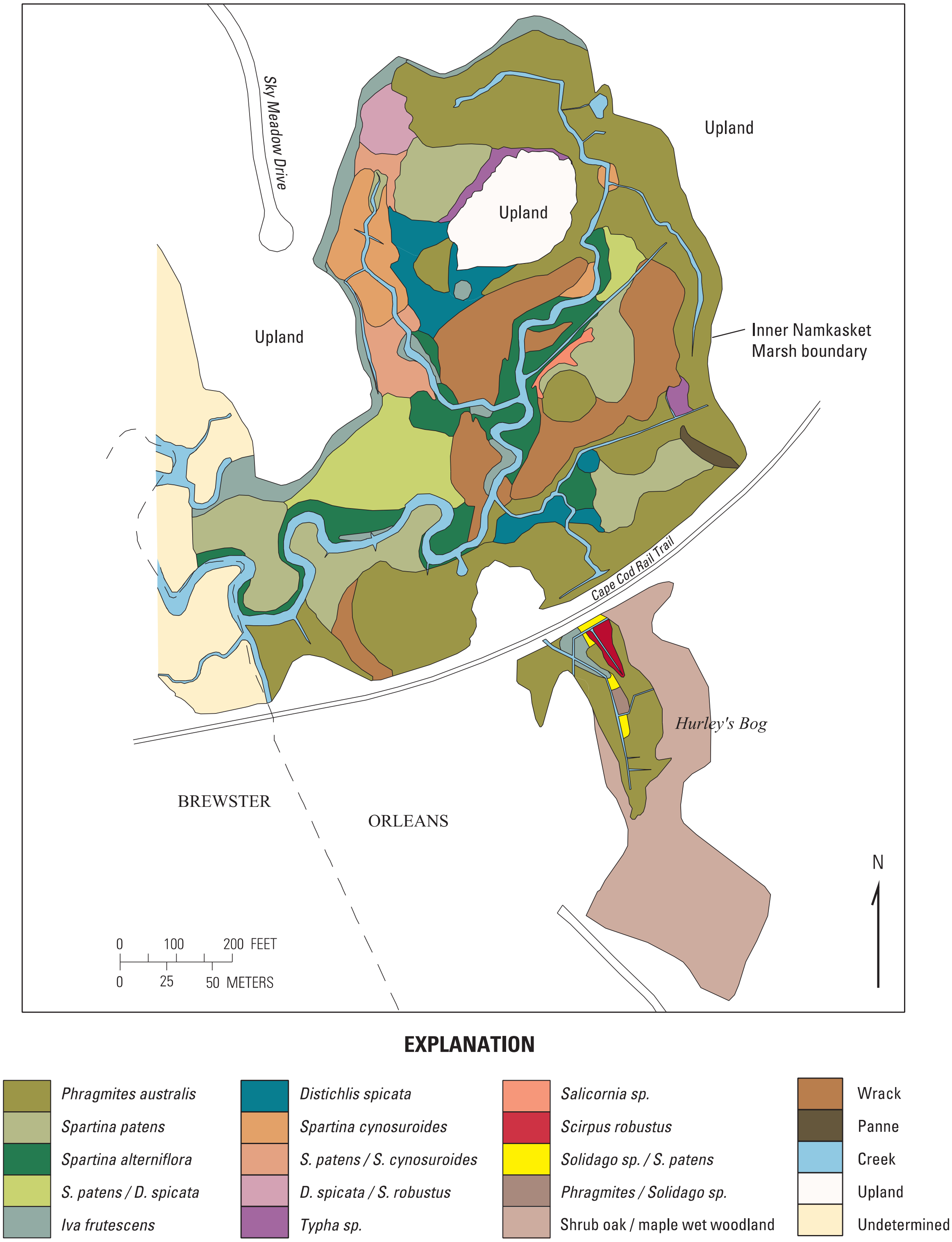


Figure 5. Areal distribution of plant species, Inner Namskaket Marsh, Cape Cod, Massachusetts, July 1995 (from DeSimone and others, 1998a). See figure 1 for location. S., *Spartina*; D., *Distichlis*; sp., species.

Nutrient Concentrations of the Wastewater Effluent and Groundwater Below the Infiltration Beds

A plume began to develop in the aquifer underlying the infiltration beds soon after the Tri-Town Facility began to discharge treated wastewater effluent at the site in early 1990 (DeSimone and others, 1996). The chemical processes below the beds and in the plume that are most relevant to potential downgradient receptors concern the nutrient species of phosphorus and nitrogen; phosphorus (P) is generally the limiting nutrient for eutrophication (excessive algal growth) in freshwater systems (Schlesinger, 1991), whereas nitrogen (N) is generally the limiting nutrient for eutrophication in coastal waters such as Namskaket Creek (Cloern, 2001; Provincetown Center for Coastal Studies, 2009).

During the first 14 years of operation (1990–2003), average-annual total N concentrations in the effluent declined from approximately 50 milligrams per liter (mg/L), as N, to about 35 mg/L, as N (DeSimone and others, 1996; Wright-Pierce, 2005). During this time, average effluent discharge rates from the Tri-Town Facility increased from about 20,000 gallons per day (gal/d) to nearly 30,000 gal/d. As a result, the total N load to the subsurface (discharge rate times effluent concentration) stayed fairly stable, with a slight overall load decrease in the later years of this period. During 2005–14, effluent total N concentrations averaged 30 to 35 mg/L and discharge volumes averaged about 25,000 to 30,000 gal/d (Tri-Town Treatment Facility, written commun., 2016). The resulting average N load value of approximately 2,600 pounds per year (lb/yr) is similar to the value of 2,900 lb/yr determined by Wright-Pierce (2005) for the 2001–3 period, confirming the continued stability of annual N loads during the study period.

At the Tri-Town Facility site, ammonium concentrations declined from 27 mg/L, as N, in the effluent to 1 mg/L, as N, in groundwater at the water table directly beneath the infiltration beds in 1992 (see tables 3, 4, and 5 in DeSimone and others, 1996). However, nitrate concentrations increased from 9.4 mg/L, as N, in the effluent to 35 mg/L, as N, in the groundwater at the water table. The process largely responsible for both of these observations is inferred to be microbial nitrification, a process whereby certain bacteria transform ammonium into nitrate under oxygenated conditions (DeSimone and others, 1996). Phosphorus concentrations, like ammonium, also decline substantially during transport to the water table. These declines during vertical transport reflect the strong chemical affinity between dissolved phosphate and iron-bearing minerals in the sandy glacial deposits underlying the site (DeSimone and others, 1996). Finally, total and dissolved organic carbon in the effluent was found to be almost entirely removed during vertical transport to the water table. This loss of total organic carbon is caused by filtration of particulate carbon by the aquifer and by aerobic respiration of dissolved and particulate carbon fractions by subsurface bacteria. The resulting low levels of dissolved organic carbon in the treated wastewater plume contribute to the low potential for natural removal of nitrate from the plume by bacterial denitrification—a process that requires a source of reactive organic carbon (DeSimone and others, 1996). Median specific conductance in groundwater below the infiltration beds was 3,010 microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25 °C), and median total dissolved nitrogen and phosphorus concentrations were 35 mg/L (as nitrogen) and 0.02 mg/L (as phosphorus), respectively, during 1991–92 (DeSimone and others, 1996).

Development and Movement of the Treated Wastewater Plume

The movement of the treated wastewater plume from the facility infiltration beds to potential downgradient receptors is controlled by several factors, including local (shallow) and regional (deep) groundwater flow directions in the underlying glacial aquifer, the distribution of fine and coarse sediment units in the aquifer, and the spatial configuration of natural groundwater discharge areas downgradient of the facility site. These discharge areas include the marsh-upland boundary zones of Inner Namskaket Marsh, its tidal creek system, its tributary wetlands and creeks such as Hurley's Bog and Creek, downgradient wetlands such as Little Namskaket Marsh, and Cape Cod Bay (fig. 1). This section of the report summarizes the development and movement of the wastewater plume on the facility site and beneath the Cape Cod Rail Trail (rail trail) immediately downgradient of the site.

Plume Development and Movement on the Facility Site

The early development and movement of the plume was mapped by the collection of groundwater samples and by electromagnetic-induction (EM) logging of observation wells. Groundwater samples were collected at observation well clusters located across the facility site, both for chemical analysis of plume constituents and for field determination of specific conductance. Specific conductance is a physical property of water that is highly correlated with total dissolved solids and salinity (Granato and others, 2015). Because ambient groundwater on Cape Cod has relatively low specific conductance (table 3 in DeSimone and others, 1996), this property of a water sample can be used to track the presence and movement of a wastewater plume in cases where the screened interval of the observation well coincides with the vertical position of a plume.

Where the plume position is unknown, EM logging may be used to define the position of a plume. EM logging is a borehole geophysical method that measures the combined electrical conductivity of aquifer material and pore water at a radial distance of approximately 1 foot from a well casing, while the EM probe is lowered down the length of the well (McNeill, 1986). The well casing must be composed of a nonconductive material such as polyvinylchloride (PVC). Changes in EM logs over time, relative to a baseline log, are used to detect the initial appearance and subsequent movement of electrically conductive plumes in groundwater, such as road-salt, municipal-landfill, and treated wastewater plumes. (Sea-water intrusion does not likely affect the conductivity of the shallow aquifer at the Tri-Town Facility site under current sea-level conditions, due to the location of the site about 1 mile inland from Cape Cod Bay [Walter and Whealan, 2005; Walter and others, 2016].) The Tri-Town Facility wastewater plume is more conductive than ambient groundwater beneath the site because it contains elevated concentrations of chloride, calcium, and sodium that have been added to the wastewater during the treatment process (tables 3 and 4, DeSimone and others, 1996). In heterogeneous, unconsolidated glacial deposits like those of Cape Cod, peaks in EM logs that predate the arrival of a plume and remain constant over time typically indicate the presence of fine-grained layers (silt and clay). This is because silt and clay are generally more electrically conductive than the coarse-grained layers (sand) above or below the peak.

The Tri-Town Septage Treatment Facility began discharging treated wastewater to the infiltration beds in February 1990. Within several months, a plume began to develop in the intermediate coarse-grained unit (fig. 2) underlying the infiltration beds. By March 1991, the plume began to split into western and northwestern lobes (fig. 6), caused by the locally high elevation of the water table above a fine-grained sediment unit located beneath the northwestern corner of the infiltration beds. (This water-table mound was observed prior to the initiation of wastewater discharge at the site.)

Subsequent movement of both plume lobes through 1992 was governed by the spatial configuration of the two sediment units (intermediate coarse-grained and lower fine-grained), in combination with the hydraulic gradients driving the movement of each plume lobe. After March 1991, the western lobe began to shift to the northwest (fig. 6), aligning more closely with the flow direction of the northwest lobe through the intermediate coarse-grained unit, at a depth of 15 to 30 ft below the water table (see fig. 12 in DeSimone and others, 1996). Subsequent EM logging indicated that the two lobes began to merge into a single, larger plume prior to plume arrival at the rail trail.

Plume Movement in Upland Areas Near the Cape Cod Rail Trail

In order to monitor the movement of the treated wastewater plume downgradient of the Tri-Town Facility boundary, a set of six observation wells was installed in late 1993, adjacent to the rail trail (wells 180 to 185, fig. 7), which was the nearest accessible location for plume monitoring downgradient of the Tri-Town Facility property. Four additional wells immediately downgradient of the rail trail (wells 192 to 195) were installed after the six observation wells.

Wells were installed by using hollow-stem auger methods to depths ranging from 85 to 120 ft below the land surface. Lithologic samples were collected at 10-ft intervals by using a split-spoon sampler. Wells were constructed from 2-inch inner diameter PVC well casing, and the lowermost 5 feet of each well contained a well screen.

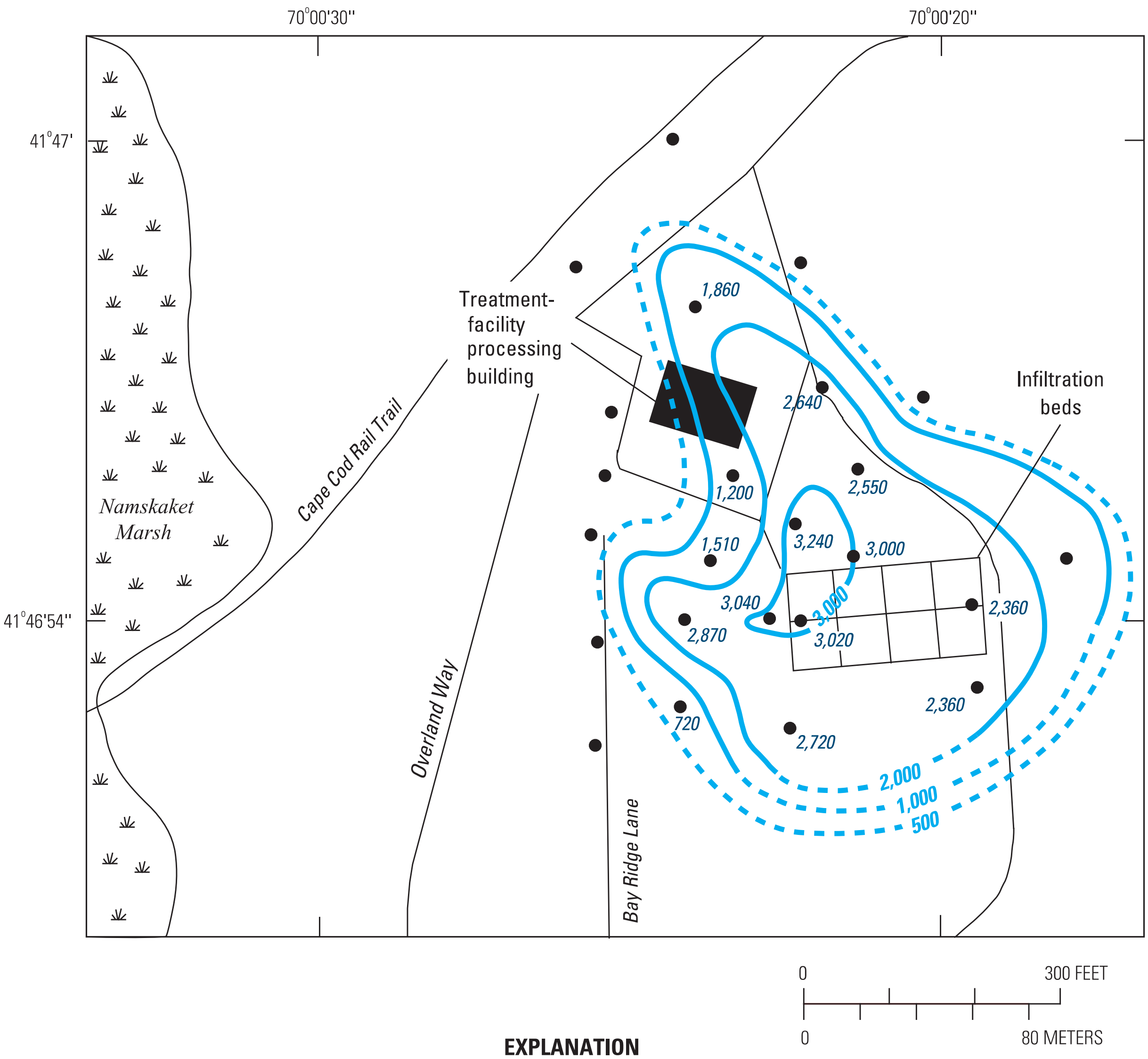
A baseline set of EM logs was collected from wells 180 to 185 in December 1993, and subsequent EM logs were compared to the baseline set. The leading edge of this part (or segment) of the wastewater plume was first detected at the rail trail in November 1994, at wells 182 and 183 (fig. 7), at an elevation of 47 to 53 ft below NGVD 29. Between 1995 and 1999, the plume was also detected at wells 184, 192, and 194 (fig. 7), at depths ranging from 25 to 65 ft below NGVD 29. The logs also indicated a lithologic unit of high electrical conductivity, interpreted to be a silt/clay layer, at elevations ranging from 8 ft above to 40 ft below NGVD 29 along rail trail transect *C–C′* (figs. 7 and 8). This interpretation was confirmed by two observations: (1) the EM peaks in the baseline set of EM logs did not change over time and (2) a silt/clay material was encountered in lithologic samples at all well stations where the EM log peaks and lithologic sampling intervals overlapped.

Using the EM logs and lithologic data, a cross section was constructed parallel to the rail trail to illustrate the subsurface lithology and vertical position of the plume at the rail trail in May 1999 (fig. 8). The sequence of lithologic units along this section was similar to that identified by DeSimone and others (1996) at the Tri-Town Septage Treatment Facility site (fig. 2). A lower fine-grained unit was overlain by an intermediate coarse-grained unit, which in turn was overlain by an upper fine-grained unit. The silt/clay unit was found at the base of the upper fine-grained unit and ranged from 3 to 8 ft in thickness along the section (fig. 8).

The wastewater plume segment at the rail trail in May 1999 was about 450 ft wide and varied in thickness from 10 ft to greater than 40 ft. The plume segment was mainly confined to the intermediate coarse-grained unit below the silt/clay unit, but it likely extended into the lower fine-grained unit where the plume segment reached its greatest thickness, near wells 183 and 184.

Plume Movement Adjacent to Namskaket Marsh

At the southwestern end of the cross section (well 185, figs. 7 and 8), EM logging in early 1998 showed the appearance of a second plume segment above the silt/clay unit. The occurrence of this shallow plume segment above the silt/clay unit at well 185 is consistent with the change in elevation of the silt/clay unit along the rail trail. The top of the unit declines by 48 ft from well 180 to 185 (from 8 ft above to 40 ft below NGDV 29, fig. 8). Because the silt/clay unit is considerably deeper at well 185 than at well 180, it is possible for shallow portions of the wastewater plume originating near the plume’s southwest boundary (for example, near well 111, fig. 7) to remain above the silt/clay layer during downgradient

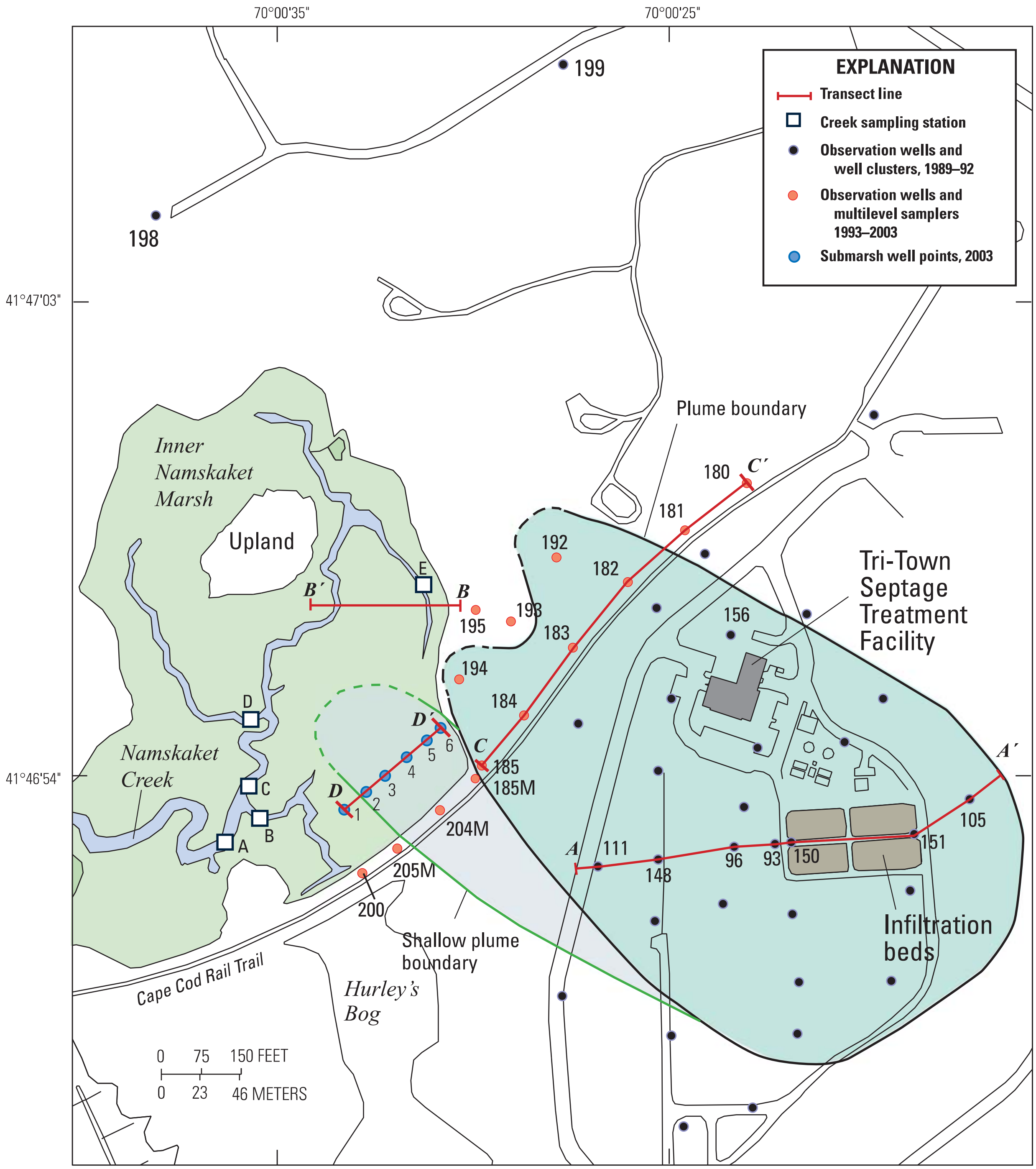


EXPLANATION

500 **Line of equal specific conductance**—Dashed where approximately located. Interval, in microsiemens per centimeter at 25 degrees Celsius, is variable

720 ● **Well cluster site**—Site of one or more observation wells completed at different depths. Blue number is maximum specific conductance, in microsiemens per centimeter at 25 degrees Celsius, at sites where conductance is above the ambient (background) value of 200 microsiemens per centimeter at 25 degrees Celsius

Figure 6. The areal extent of specific conductance in the wastewater plume, December 1992 (modified from DeSimone and others, 1996). At stations with more than one well, maximum value is shown.



Base from Town of Orleans tax maps

Figure 7. Locations of monitoring stations where data were collected by the U.S. Geological Survey at Inner Namskaket Marsh and adjacent upland areas, Cape Cod, Massachusetts. The areal extents of the deep (light green) and shallow (light gray) segments of the septage-effluent plume are shown for May 1999, based on results of electromagnetic-induction logging of observation wells. Boundaries of plume segments are dashed where uncertain.

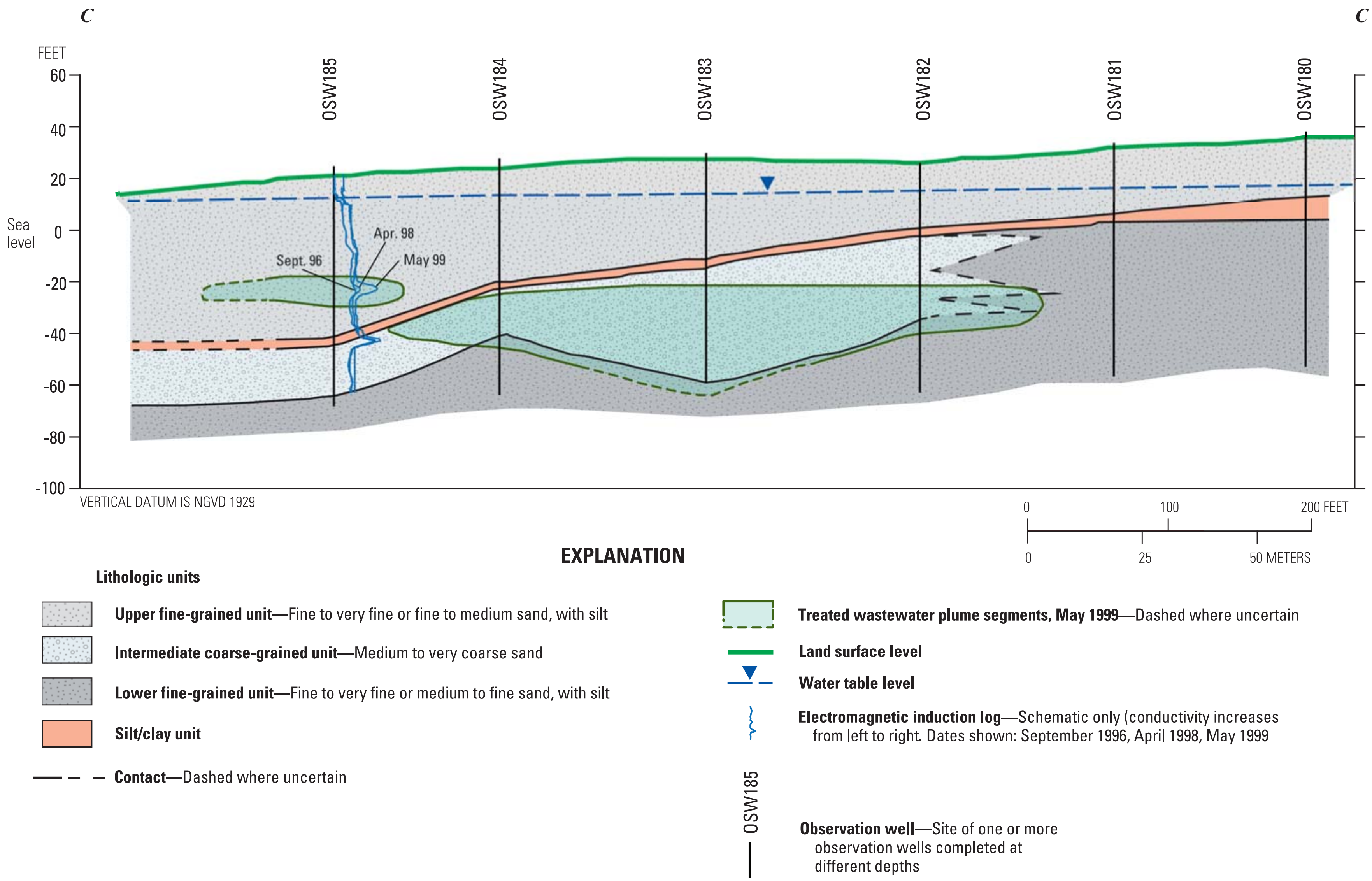


Figure 8. Cross section *C–C′*, showing aquifer lithology and plume position in May 1999, beneath the Cape Cod Rail Trail, Namskaket Marsh, Cape Cod, Massachusetts. Dates (month/year) indicate dates of electromagnetic-induction logs collected at well OSW 185. The logs given are schematic only (conductivity increases from left to right on the profiles). See figure 7 for location of cross section.

transport. By contrast, parts of the plume near the plume's northeast boundary (for example, near well 156, fig. 7) are more likely to move under the silt/clay unit during downgradient transport because of the higher elevation of the unit in this area. It should be noted that the areal extent of the silt/clay unit has only been defined at the rail trail (wells 180 to 185) and in a limited area immediately downgradient (northwest) of the rail trail (wells 192 to 195). (Note that silt and clay were also found in lithologic samples collected farther downgradient, at wells 198 and 199 [fig. 7], but the continuity of the silt/clay unit in the downgradient [northwest] direction is unknown, owing to the limited areal and vertical extent of lithologic data.) If the silt/clay layer has limited areal extent (that is, pinches out) in the upgradient direction between the rail trail and the Tri-Town Facility infiltration beds, the likelihood would increase for shallow plume segments originating from the southwestern part of the plume (fig. 7) to be transported above the slit/clay layer.

The shallow depth to the water table at well 185 made it feasible to confirm the presence of the shallow plume segment by direct groundwater sampling at this location. Subsequently, a multilevel sampler (185M) was installed adjacent to well 185 (fig. 7) by using the methods of LeBlanc and others (1991). Groundwater samples were collected concurrently for field measurement of specific conductance, by using the methods of Radtke and others (2005), and for laboratory analysis of dissolved nitrate by the USGS National Water Quality Laboratory, using the methods of Fishman (1993). Vertical profiles of specific conductance and nitrate were prepared (fig. 9). Maximum values of specific conductance (835 µS/cm at 25 °C) and nitrate (19.1 mg/L, as N) occurred over a depth interval coinciding with the EM-log peak at well 185 (22 to 27 ft below NGVD 29).

After the confirmation of the shallow plume segment at 185M, multilevel samplers were installed and sampled at two additional rail trail stations (204M and 205M, fig. 7) to define the southwestern extent of this plume segment at the rail trail. At sampler 204M, maximum values of specific conductance (461 µS/cm) and nitrate (3.4 mg/L, as N) (fig. 9) were substantially lower than at 185M, although they were above the background levels observed at the Tri-Town Facility site (see table 3 in DeSimone and others, 1996). At sampler 205M, specific conductance was lower than at 204M, and the 205M median (235 µS/cm) was within the range of background values for the study site (75 to 304 µS/cm; table 3 in DeSimone and others, 1996). Nitrate concentrations at 205M were relatively low, and approximately half of the samples had nitrate concentrations below the reporting limit of 0.1 mg/L, as N. Also, it should be noted that nitrate concentrations and specific conductance at 205M did not appear to be correlated, perhaps because either a nonwastewater source raised the conductance, or nitrate concentrations at 205M were lowered by microbial processes. Accordingly, the southwest boundary of the shallow plume segment was likely located between 204M and 205M in early 2004 (fig. 7), at a depth of about 22 to 27 ft below NGVD 29 (fig. 9).

In order to determine the presence of the shallow plume segment downgradient of the rail trail, beneath Namskaket Marsh, a set of temporary well-point stations were sampled in October 2003 in the sandy glacial sediments underlying the marsh sediment. Six stations were installed along a 230-ft transect that was oriented parallel to and 125 ft northwest of the rail trail (fig. 7, *D–D′*). At each station, the well point was first pushed through the soft marsh sediments (peat and basal muds) until the underlying sand was encountered, at elevations ranging from 5 to 12 ft below NGVD 29 (11 to 18 ft below the marsh surface) along the length of the transect. The well points were then driven into the underlying sand, using all-terrain-vehicle-mounted equipment, and sampled at 2.5-ft intervals. At each depth, the well point was purged until the field specific conductance reached a stable value. This value was then recorded, and the procedure was repeated at the next depth. A total of 74 specific conductance values were obtained at elevations ranging from 7 to 42 ft below NGVD 29, across the six well-point stations. The specific conductance meter was calibrated daily prior to sampling, according to USGS procedures (Radtke and others, 2005).

The resulting profiles of specific conductance (fig. 10) indicate the presence of the shallow plume segment in submarsh glacial sand deposits during October 2003. Maximum specific conductance values among the six profiles ranged from 216 µS/cm at well-point station 1 to 905 µS/cm at well-point station 5, and the highest values occurred at the two stations closest to the eastern marsh-upland boundary (stations 5 and 6, transect *D–D′*, fig. 7). Peak conductance values generally occurred over the interval from 24 to 36 ft below NGVD 29 (fig. 10), overlapping with the vertical interval of peak specific conductance observed at the rail trail samplers (22 to 27 ft below NGVD 29). The horizontal extent of the shallow plume segment beneath the marsh is defined by near-background specific conductance values at station 1, which place the southwest plume-segment boundary between stations 1 and 2 during October 2003. This location is opposite the location of the plume boundary at the rail trail, inferred from sampling results at samplers 204M and 205M (figs. 7 and 9). The northeastern limit of the submarsh plume segment was not defined during the October 2003 sampling, but it likely extends at least as far as the marsh-upland boundary opposite well 185.

In order to confirm that specific conductance can be used to accurately represent the position of the shallow plume segment in the submarsh aquifer, samples were collected from a subset of well-point depth intervals for field nitrate analysis, by using the methods of Granato and Smith (1999). A total of 37 samples were collected for nitrate analysis. Among the 17 samples with concentrations greater than or equal to the reporting limit of 0.1 mg/L, concentrations ranged from 0.1 to 19.5 mg/L, as N, and specific conductance ranged from 151 to 876 µS/cm. The Pearson product-moment correlation coefficient (Pearson's *r*) (Helsel and Hirsch, 2002) between specific conductance and the nitrate concentrations for these samples was 0.97. Accordingly, we conclude that the specific

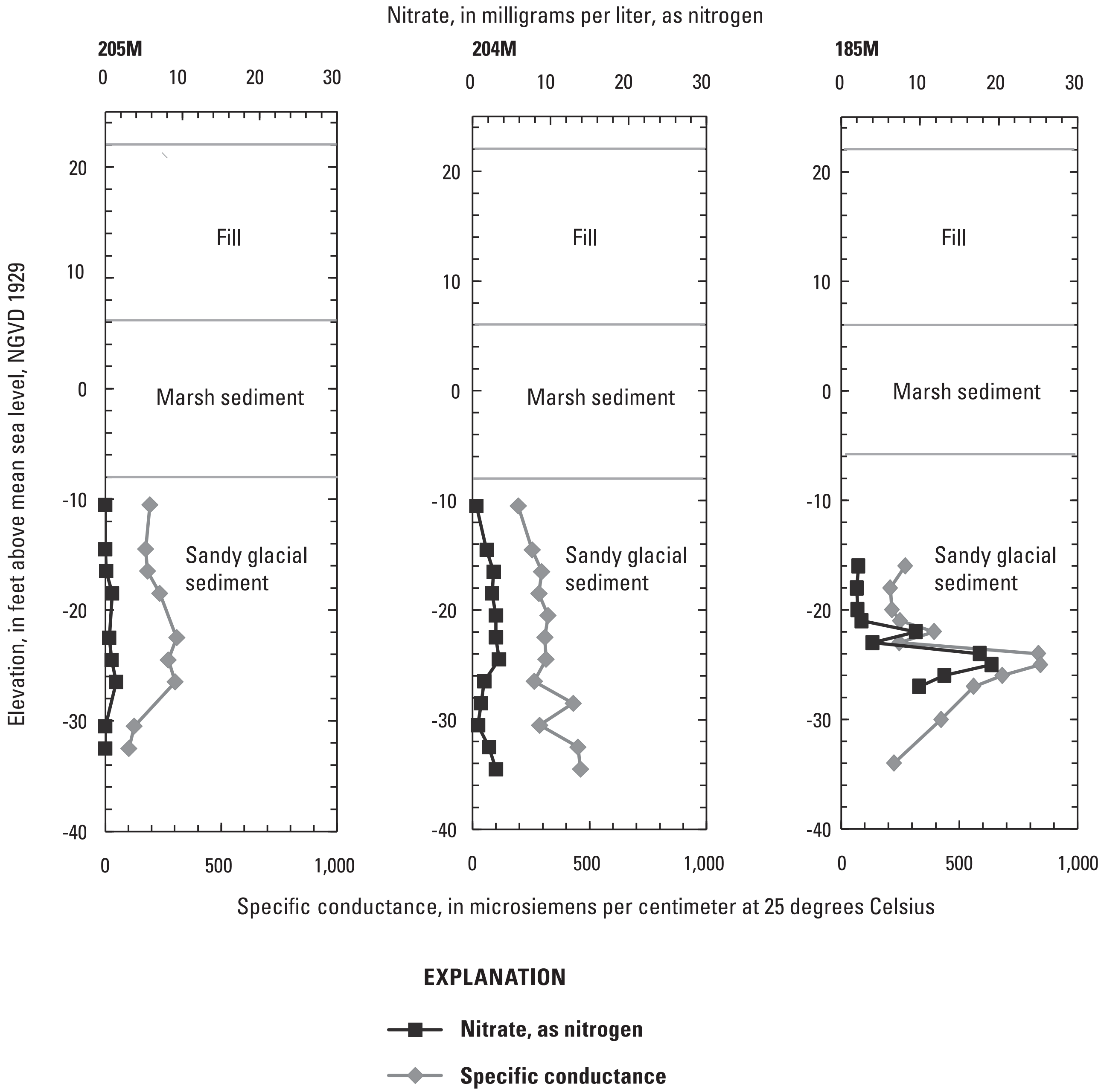


Figure 9. Profiles of specific conductance and nitrate, as nitrogen, at multilevel samplers 205M (January 7, 2004), 204M (January 6, 2004), and 185M (October 16, 2003) at the Cape Cod Rail Trail, Namskaket Marsh, Cape Cod, Massachusetts. See figure 7 for locations of profiles.

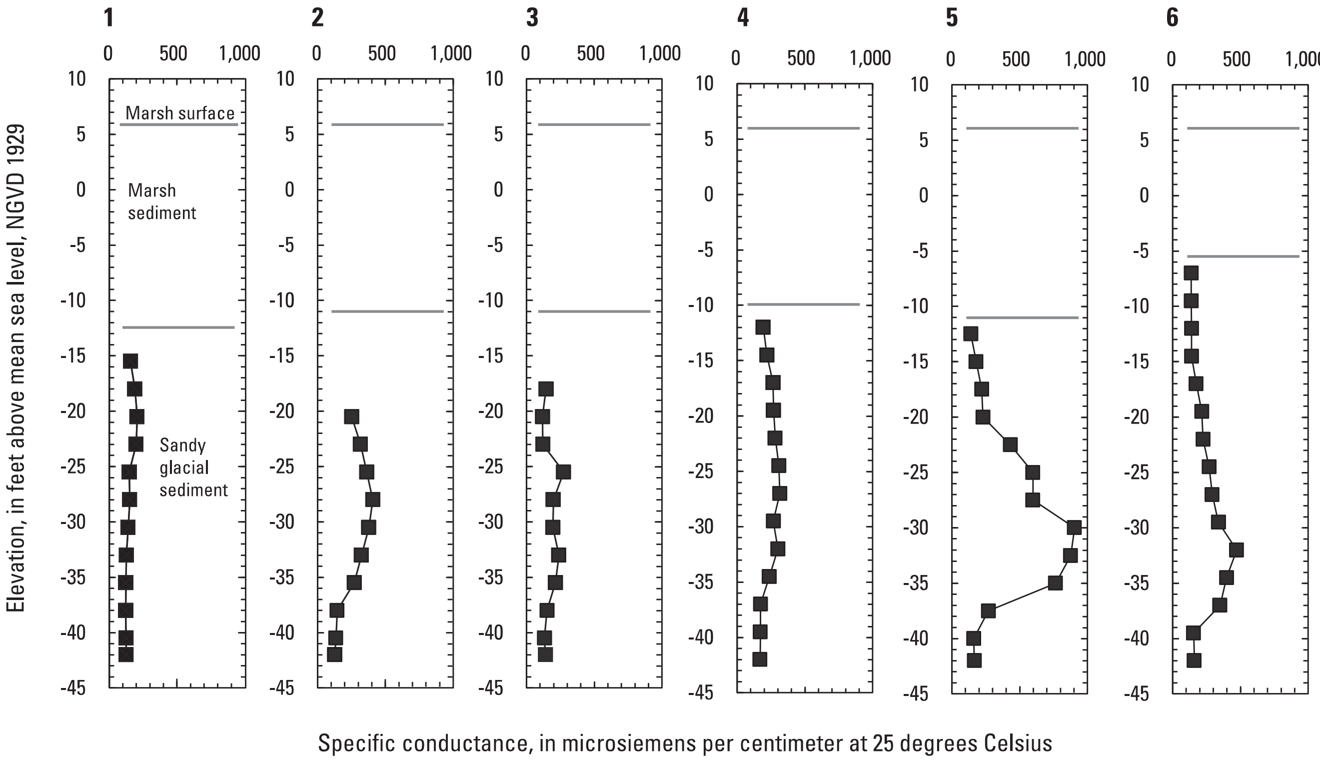


Figure 10. Profiles of specific conductance at submarsh well-point stations 1–6, October 31, 2003, below marsh transect *D–D′*, Namskaket Marsh, Cape Cod, Massachusetts. See figure 7 for locations of profiles.

conductance profiles at the well-point stations (fig. 10) accurately indicate the position of the shallow wastewater plume segment in the sand aquifer below the marsh sediments during the October 2003 sampling period.

Namskaket Creek Water Quality

The most recent field activities in the study area have focused on water-quality sampling in Namskaket Creek and its tributaries—the nearest potential surface-water receptors for discharge from the treated wastewater plume. This approach was adopted for three reasons. First, physical access for continued tracking of the treated wastewater plume in upland areas downgradient of the treatment facility property was limited. Second, continued use of heavy equipment to drive well points and sample groundwater in the aquifer below Inner Namskaket Marsh was deemed to be impractical and potentially harmful to the marsh. Third, Namskaket Creek and its tributaries had been shown by previous work to be locations of natural groundwater discharge from the surrounding upland area (Weiskel and others, 1996). Hence, substantial changes in creek water quality, relative to the 1990s baseline, could serve as indicators of subsurface plume discharge into the marsh-creek system. This section of the report summarizes the results of water-quality sampling in Namskaket Creek and its tributaries during (1) baseline conditions (1993–97) prior to the detection of the shallow plume segment in the aquifer adjacent to Namskaket Marsh and (2) the 2003–4 and 2010–11 periods, after the shallow plume segment had been detected adjacent to and beneath the marsh. Results from the two more recent periods are then compared to the 1990s baseline results.

Baseline Creek Water Quality, 1993–97

Water-quality samples during the baseline period were collected at a total of six sampling stations in the middle to upper reaches of Namskaket Creek and in its tributaries (fig. 1). DeSimone and others (1998b) describe the sampling stations, methods, and water-quality results for the March 1993 to November 1997 baseline period.

Station A (USGS station 0110587900) was the farthest downstream station in the creek system. It was considered to be an integrator station, reflecting water-quality conditions of Inner Namskaket Marsh and Hurley's Bog as a whole (fig. 1). Station B (USGS station 0110587899) was located near the mouth of the tributary that drains Hurley's Bog. Station C (USGS station number 0110587898) was located in the main creek upstream from station A and was sampled only for a short time in 1993. Stations D and E (USGS station numbers 0110587897 and 0110587896, respectively) were located in tributaries to the main creek that drain the western and eastern areas, respectively, of Inner Namskaket Marsh. Station F (USGS station number 0110587895) was located near the upper end of the main creek. Stations E and F were closest to the upland to the east of Inner Namskaket marsh, in the boundary groundwater discharge zone.

To the extent possible, water samples were collected biweekly under neap tide conditions, during late ebb tide, when the groundwater-derived, freshwater fraction of creek discharge is at a maximum. Water samples were collected in 250-milliliter amber polyethylene bottles submerged in the creek by hand. Midchannel water depths during the late-ebb-tide sampling period were generally less than 0.5 ft at all stations, and creek water was well mixed vertically and laterally. Specific conductance was measured with a calibrated digital meter and temperature-compensated electrode during sample collection (Radtke and others, 2005). Samples were analyzed for dissolved concentrations of nitrate plus nitrite, ammonia, total dissolved nitrogen, and orthophosphate; sampling procedures were monitored with the collection of sample splits and field blanks, as reported by DeSimone and others (1998b). Samples collected from March 1993 to March 1997 were analyzed by a laboratory in the Biology Department of the Woods Hole Oceanographic Institution (WHOI). The laboratory's procedures were reviewed and approved by the USGS Office of Water Quality, Branch of Quality Assurance (https://bqs.usgs.gov); the laboratory also participated in the USGS Standard Reference Water Sample Program during the study period (the same program that evaluates the performance of the USGS National Water Quality Laboratory; https://bqs.usgs.gov/srs/). As reported by DeSimone and others (1998b), all reference sample results from the WHOI laboratory were rated as satisfactory by the program (DeSimone and others, 1998b).

Specific conductance during the late ebb tide was lowest in the eastern tributary to the main creek at station E, averaging 2,760 µS/cm over the baseline period (number of samples [n] = 62). Specific conductance was higher in the upper reaches of the main creek at station F (averaging 3,570 µS/cm; n = 65) and in the tributary from Hurley's Bog at station B (averaging 4,450 µS/cm; n = 115). Specific conductance was highest at the mouth of the western tributary to the main creek at station D, where values averaged 11,000 µS/cm (n = 64). The differences in mean, late-ebb-tide specific conductance among these stations likely result from the greater contribution of natural groundwater discharge to late-ebb-tide creek flow at stations E and F relative to stations B and D. Specific conductance at station A (averaging 6,510 µS/cm; n = 127), the farthest downstream station in the main creek, lies within the range of values at the other stations, reflecting the spatial variability in specific conductance in the upstream reaches and tributaries.

Total dissolved nitrogen (TDN) concentrations at station A averaged 0.77 mg/L, as N, and ranged from 0.03 to 1.4 mg/L, as N. With the exception of station F, average TDN concentrations at all stations were similar (0.63 to 0.81 mg/L, as N). Concentrations of TDN at station F averaged 1.4 mg/L, as N. About half of the TDN at most stations was in the form of nitrate, and smaller fractions were present as ammonia and organic nitrogen. (Median nitrite concentrations were very low—averaging about 2 percent of median nitrate concentrations.) The lowest average nitrate concentrations were found at station D (0.048 mg/L, as N), where dissolved nitrogen occurred primarily as ammonia and organic nitrogen. Orthophosphate concentrations at station A averaged 0.095 mg/L as P. This constituent was lower at stations E and F, averaging 0.079 and 0.042 mg/L as P, respectively, than at other stations.

Creek Water Quality, 2003–4 and 2010–11

Creek samples were collected in 2003–4 and again in 2010–11 to evaluate potential effects of the treated wastewater plume on creek water quality. The 2003–4 samples were collected after the shallow plume segment was first detected in the aquifer adjacent to, and beneath, Inner Namskaket Marsh (figs. 9 and 10). A larger number of creek samples were collected in 2010–11 on a biweekly basis to provide information on seasonal changes in nutrient concentrations in relation to the seasonal 1993–97 baseline and to assess the possible effects of the treated wastewater plume on creek water quality. Samples collected during 2003–4 and 2010–11 were analyzed for dissolved nitrate plus nitrite, ammonium, TDN, and orthophosphate concentrations at the USGS National Water Quality Laboratory, using methods of Fishman (1993) and Patton and Kryskalla (2003).

During both the 2003–4 and 2010–11 periods, sampling was conducted at a subset of the six baseline stations: station A (integrator station), station B (mouth of Hurley's Bog tributary), and station E (eastern tributary, boundary groundwater discharge zone) (see fig. 7 for locations). Sampling procedures during both periods were the same as those during the 1990s baseline period.

Creek Water Quality, 2003–4

Samples were collected in November 2003 and in October, November, and December 2004 (table 2). During these 4 months, TDN averaged 1.0, 0.80, and 0.46 mg/L at stations A, B, and E, respectively, and nitrate averaged 0.52, 0.48, and 0.28 mg/L, as N—about half of the TDN concentrations. Total dissolved nitrogen concentration ranges for these 4 months were within the 1990s baseline ranges for the months of October, November, and December. As observed during the 1990s baseline, ammonium concentrations were relatively low during these months, averaging 0.087 mg/L, as nitrogen, across the stations.

Table 2. Late-ebb-tide specific conductance and dissolved nutrient concentrations, Namskaket Creek and tributaries, Orleans, Massachusetts, November 15, 2003; October 29 through December 28, 2004; and June 4, 2010, through August 23, 2011. See figure 7 for locations of sampling stations.

[USGS, U.S. Geological Survey; sampling date, month/day/year; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, nitrogen; P, phosphorus; <, less than; E, estimated (Childress and others, 1999); --, no data]

USGS station number	Local station identifier	Sampling date	Specific conductance (µS/cm at 25 °C)	Ammonia (mg/L as N)	Nitrate plus nitrite (mg/L as N)	Nitrite (mg/L as N)	Orthophosphate (mg/L as P)	Total dissolved phosphorus (mg/L)	Total dissolved nitrogen (mg/L)
110587896	Station E	11/15/2003	890	0.024	0.275	0.002	--	0.06	0.43
110587896	Station E	10/29/2004	--	0.012	0.222	0.002	--	0.03	0.38
110587896	Station E	11/30/2004	--	0.019	0.31	0.002	--	0.04	0.51
110587896	Station E	12/28/2004	--	0.037	0.316	0.002	--	E0.01	0.52
110587896	Station E	6/4/2010	538	E0.02	0.458	E0.001	0.047	0.06	0.64
110587896	Station E	6/18/2010	1,530	0.02	0.315	E0.002	0.044	0.038	0.43
110587896	Station E	7/1/2010	515	E0.01	0.286	E0.001	0.079	0.09	0.46
110587896	Station E	7/16/2010	3,340	0.03	0.29	E0.002	0.051	0.058	0.6
110587896	Station E	7/29/2010	657	0.02	0.165	E0.001	0.126	0.139	0.38
110587896	Station E	8/18/2010	2,890	E0.01	0.101	<0.002	0.075	0.079	0.37
110587896	Station E	8/30/2010	978	E0.01	0.15	<0.002	0.106	0.117	0.29
110587896	Station E	9/15/2010	2,920	<0.02	0.163	<0.002	0.036	0.037	0.3
110587896	Station E	9/30/2010	1,640	<0.02	0.066	E0.001	0.087	0.089	0.16
110587896	Station E	10/14/2010	2,530	0.01	0.156	0.002	0.034	0.034	0.39
110587896	Station E	10/28/2010	2,120	<0.01	0.084	0.002	0.085	0.09	0.2
110587896	Station E	11/15/2010	1,900	<0.01	0.251	0.001	0.03	0.032	0.46
110587896	Station E	11/30/2010	1,480	<0.01	0.303	0.002	0.033	0.032	0.36
110587896	Station E	12/14/2010	2,650	0.01	0.201	0.001	0.021	0.02	0.29
110587896	Station E	12/31/2010	4,770	0.03	0.55	0.003	0.043	0.044	0.67
110587896	Station E	1/14/2011	1,430	0.02	0.676	0.001	0.022	0.025	0.85
110587896	Station E	1/26/2011	2,210	0.02	0.712	0.002	0.017	0.016	0.77
110587896	Station E	2/14/2011	795	0.01	0.711	0.001	0.022	0.022	1.04
110587896	Station E	2/24/2011	3,760	0.02	0.767	0.001	0.015	0.011	0.86
110587896	Station E	3/14/2011	832	0.02	0.7	<0.001	0.016	0.018	0.98
110587896	Station E	3/28/2011	1,440	0.01	0.545	0.001	0.013	0.013	0.61
110587896	Station E	4/11/2011	968	0.02	0.483	0.001	0.018	0.02	0.68
110587896	Station E	4/27/2011	1,200	0.03	0.468	0.001	0.03	0.035	0.6
110587896	Station E	5/10/2011	916	0.05	0.513	0.002	0.019	0.036	0.8
110587896	Station E	5/26/2011	1,270	<0.01	0.387	<0.001	0.026	0.038	0.49
110587896	Station E	6/7/2011	816	0.04	0.485	0.002	0.041	0.053	0.76
110587896	Station E	6/23/2011	1,500	0.03	0.42	0.002	0.057	0.071	0.68
110587896	Station E	7/5/2011	2,110	0.05	0.412	0.002	0.038	0.048	0.82
110587896	Station E	7/25/2011	623	<0.01	0.294	0.001	0.078	0.089	0.46
110587896	Station E	8/8/2011	1,100	0.02	0.262	0.001	0.101	0.114	0.65
110587896	Station E	8/23/2011	508	0.01	0.162	<0.001	0.139	0.16	0.38
110587899	Station B	11/15/2003	270	0.078	0.398	0.003	--	0.14	0.69
110587899	Station B	10/29/2004	--	0.106	0.465	0.005	--	0.12	0.73
110587899	Station B	11/30/2004	--	0.08	0.419	0.004	--	0.12	0.74
110587899	Station B	12/28/2004	--	0.095	0.642	0.003	--	0.09	1.03

Table 2. Late-ebb-tide specific conductance and dissolved nutrient concentrations, Namskaket Creek and tributaries, Orleans, Massachusetts, November 15, 2003; October 29 through December 28, 2004; and June 4, 2010, through August 23, 2011. See figure 7 for locations of sampling stations.—Continued

[USGS, U.S. Geological Survey; sampling date, month/day/year; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, nitrogen; P, phosphorus; <, less than; E, estimated (Childress and others, 1999); --, no data]

USGS station number	Local station identifier	Sampling date	Specific conductance (µS/cm at 25 °C)	Ammonia (mg/L as N)	Nitrate plus nitrite (mg/L as N)	Nitrite (mg/L as N)	Orthophosphate (mg/L as P)	Total dissolved phosphorus (mg/L)	Total dissolved nitrogen (mg/L)
110587899	Station B	6/4/2010	3,500	0.12	0.244	0.009	0.205	0.239	0.62
110587899	Station B	6/18/2010	7,460	0.07	0.387	0.008	0.092	0.11	0.65
110587899	Station B	7/1/2010	4,360	0.11	0.53	0.011	0.181	0.225	0.86
110587899	Station B	7/16/2010	8,810	0.29	0.439	0.019	0.179	0.205	1.1
110587899	Station B	7/29/2010	4,650	0.22	0.613	0.023	0.269	0.303	1.11
110587899	Station B	8/18/2010	5,390	0.16	0.464	0.011	0.155	0.236	1.09
110587899	Station B	8/30/2010	2,930	0.12	0.562	0.01	0.187	0.229	0.96
110587899	Station B	9/15/2010	6,780	0.13	0.591	0.008	0.091	0.147	0.93
110587899	Station B	9/30/2010	3,440	0.13	0.324	0.006	0.124	0.178	0.61
110587899	Station B	10/14/2010	5,670	0.09	0.524	0.005	0.058	0.122	0.89
110587899	Station B	10/28/2010	3,840	0.06	0.125	0.006	0.132	0.212	0.52
110587899	Station B	11/15/2010	3,670	0.1	0.397	0.005	0.103	0.109	0.79
110587899	Station B	11/30/2010	4,630	0.11	0.482	0.005	0.108	0.107	0.7
110587899	Station B	12/14/2010	2,650	0.1	0.358	0.003	0.075	0.087	0.61
110587899	Station B	12/31/2010	9,380	0.13	0.313	0.003	0.034	0.043	0.53
110587899	Station B	1/14/2011	3,630	0.1	0.47	0.002	0.032	0.035	0.81
110587899	Station B	1/26/2011	6,620	0.14	0.438	0.003	0.035	0.033	0.64
110587899	Station B	2/14/2011	2,470	0.13	0.349	0.002	0.049	0.053	0.77
110587899	Station B	2/24/2011	13,200	0.1	0.353	0.002	0.026	0.022	0.53
110587899	Station B	3/14/2011	2,340	0.06	0.485	0.003	0.042	0.045	0.78
110587899	Station B	3/28/2011	4,770	0.05	0.506	0.003	0.039	0.039	0.67
110587899	Station B	4/11/2011	2,800	0.05	0.445	0.004	0.056	0.064	0.83
110587899	Station B	4/27/2011	3,330	0.02	0.214	0.003	0.065	0.071	0.5
110587899	Station B	5/10/2011	4,810	0.05	0.33	0.004	0.054	0.075	0.75
110587899	Station B	5/26/2011	3,680	0.02	0.361	0.005	0.069	0.131	0.68
110587899	Station B	6/7/2011	3,540	0.1	0.366	0.007	0.089	0.154	0.81
110587899	Station B	6/23/2011	3,500	0.12	0.254	0.007	0.141	0.198	0.83
110587899	Station B	7/5/2011	8,480	0.22	0.364	0.011	0.106	0.147	0.97
110587899	Station B	7/25/2011	2,560	0.09	0.58	0.01	0.194	0.221	0.82
110587899	Station B	8/8/2011	4,060	0.16	0.436	0.01	0.215	0.318	1.07
110587899	Station B	8/23/2011	2,550	0.12	0.627	0.01	0.179	0.259	0.99
110587900	Station A	11/15/2003	430	0.161	0.48	0.006	--	0.13	1.41
110587900	Station A	9/8/2004	2,700	0.148	0.675	0.013	--	0.19	1.07
110587900	Station A	10/29/2004	--	0.169	0.426	0.006	--	0.1	0.74
110587900	Station A	11/30/2004	--	0.135	0.513	0.005	--	0.1	0.87
110587900	Station A	6/4/2010	4,630	0.14	0.256	0.011	0.194	0.256	0.96
110587900	Station A	6/18/2010	12,100	0.15	0.289	0.009	0.092	0.102	0.89
110587900	Station A	7/1/2010	6,600	0.26	0.384	0.019	0.302	0.335	1.03
110587900	Station A	7/16/2010	14,600	0.42	0.24	0.021	0.129	0.143	1.03

Table 2. Late-ebb-tide specific conductance and dissolved nutrient concentrations, Namskaket Creek and tributaries, Orleans, Massachusetts, November 15, 2003; October 29 through December 28, 2004; and June 4, 2010, through August 23, 2011. See figure 7 for locations of sampling stations.—Continued

[USGS, U.S. Geological Survey; sampling date, month/day/year; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, nitrogen; P, phosphorus; <, less than; E, estimated (Childress and others, 1999); --, no data]

USGS station number	Local station identifier	Sampling date	Specific conductance (µS/cm at 25 °C)	Ammonia (mg/L as N)	Nitrate plus nitrite (mg/L as N)	Nitrite (mg/L as N)	Orthophosphate (mg/L as P)	Total dissolved phosphorus (mg/L)	Total dissolved nitrogen (mg/L)
110587900	Station A	7/29/2010	7,170	0.38	0.331	0.032	0.313	0.348	1.05
110587900	Station A	8/18/2010	8,390	0.33	0.312	0.023	0.159	0.194	1.08
110587900	Station A	8/30/2010	4,530	0.25	0.402	0.021	0.161	0.254	0.97
110587900	Station A	9/15/2010	9,040	0.27	0.367	0.014	0.102	0.131	0.91
110587900	Station A	9/30/2010	5,340	0.3	0.322	0.022	0.173	0.246	0.91
110587900	Station A	10/14/2010	9,010	0.19	0.38	0.009	0.073	0.119	0.83
110587900	Station A	10/28/2010	6,340	0.17	0.166	0.009	0.125	0.178	0.63
110587900	Station A	11/15/2010	3,960	0.14	0.357	0.007	0.099	0.095	0.76
110587900	Station A	11/30/2010	6,930	0.15	0.434	0.005	0.084	0.082	0.65
110587900	Station A	12/14/2010	4,830	0.13	0.383	0.004	0.073	0.082	0.69
110587900	Station A	12/31/2010	13,000	0.1	0.31	0.003	0.034	0.047	0.54
110587900	Station A	1/14/2011	5,620	0.11	0.537	0.003	0.039	0.043	0.93
110587900	Station A	1/26/2011	11,200	0.13	0.464	0.003	0.031	0.032	0.68
110587900	Station A	2/14/2011	3,180	0.11	0.5	0.004	0.044	0.051	0.93
110587900	Station A	2/24/2011	17,000	0.15	0.347	0.002	0.03	0.027	0.57
110587900	Station A	3/14/2011	3,240	0.08	0.564	0.004	0.058	0.06	1.01
110587900	Station A	3/28/2011	6,010	0.05	0.456	0.003	0.044	0.04	0.64
110587900	Station A	4/11/2011	3,960	0.03	0.275	0.003	0.049	0.059	0.58
110587900	Station A	4/27/2011	4,380	0.01	0.048	0.002	0.055	0.065	0.33
110587900	Station A	5/10/2011	7,680	0.02	0.189	0.003	0.052	0.067	0.49
110587900	Station A	5/26/2011	5,120	<0.01	0.189	0.004	0.085	0.101	0.51
110587900	Station A	6/7/2011	6,880	0.09	0.153	0.004	0.083	0.092	0.63
110587900	Station A	6/23/2011	5,520	0.2	0.245	0.008	0.156	0.171	0.83
110587900	Station A	7/5/2011	7,580	0.52	0.234	0.015	0.122	0.154	1.07
110587900	Station A	7/25/2011	3,580	0.22	0.474	0.044	0.296	0.358	1.08
110587900	Station A	8/8/2011	7,130	0.24	0.347	0.019	0.201	0.303	1.03
110587900	Station A	8/23/2011	3,690	0.17	0.481	0.039	0.28	0.378	1.01

Total dissolved phosphorus (TDP) during 2003–4 averaged 0.13, 0.12, and 0.03 mg/L at stations A, B, and E, respectively. These concentrations were within the October, November, and December ranges for each of the three stations for the 1990s baseline period. Orthophosphate was not determined in the 2003–4 samples; however, based on orthophosphate and TDP concentrations from the 1990s baseline and 2010–11 periods, during which both constituents were determined, we estimate that orthophosphate composed an average of 85, 83, and 99 percent of TDP at stations A, B, and E, respectively, in the 2003–4 samples.

Creek Water Quality, 2010–11

Water-quality samples were collected approximately biweekly at stations A, B, and E (fig. 7) from June 2010 through August 2011 (table 2). As in previous sampling periods, water samples were collected during late ebb tide, when the groundwater-derived, freshwater part of the creek discharge is at a maximum (DeSimone and others, 1998b).

Average specific conductance and dissolved nitrogen and phosphorus concentrations during 2010–11 were comparable to the 1990s baseline values, and the previously observed spatial differences among the three stations persisted. Specific conductance in 2010–11 was lowest in the eastern tributary to the main creek at station E, averaging 1,680 µS/cm, somewhat higher in the tributary from Hurley's Bog at station B (4,870 µS/cm), and highest in the main creek at station A (6,780 µS/cm). Average TDN concentrations at stations A, B, and E during this period were 0.82, 0.79, and 0.56 mg/L, as N, respectively, whereas average concentrations at stations A, B, and E during the 1990s baseline were 0.77, 0.76, and 0.69 mg/L, as N, respectively. As was the case for both the baseline 1990s samples and the 2003–4 samples, about half of the TDN in 2010–11 occurred as nitrate, and smaller fractions occurred as ammonia and organic nitrogen. Nitrite concentrations were negligible, averaging less than 2 percent of nitrate concentrations, as nitrogen, in the 2010–11 samples. Orthophosphate concentrations at stations A and B in 2010–11 averaged 0.12 and 0.11 mg/L as P, respectively. Concentrations were lower at station E, averaging 0.050 mg/L as P. These concentrations were similar to the 1990s baseline values at these stations, which averaged 0.095, 0.10, and 0.079 mg/L as P, respectively.

Seasonal variations in nitrogen and phosphorus concentrations in 2010–11 at stations A, B, and E also were comparable to the 1990s baseline data. To compare seasonal patterns from 2010–11 and the 1990s baseline data, monthly minimum, maximum, and median concentration values were first plotted for the 1990s period (fig. 11, gray lines). We then plotted the 2010–11 biweekly concentrations (June 2010 to August 2011) on the same graphs (fig. 11). The November 1993 to September 1996 period was chosen as the baseline for comparison because it was the period of highest frequency of sampling at stations A, B, and E during the 1990s.

Among the nutrient species, orthophosphate and ammonium exhibited the strongest seasonal variations in concentration at most stations. Orthophosphate concentrations showed peaks in July and August, declined through March, followed by increases through August (figs. 11*A*, *C*, *E*). Ammonium concentrations also show peaks in July–August but showed a longer period of decline, through May, before increasing again until August. Station E showed weaker seasonal trends in ammonium and lower overall concentrations than stations A and B. The seasonal trends, where observed, occurred in both the 1990s baseline and 2010–11 data. They likely reflect the dynamics of nutrient uptake and release by marsh plants in Inner Namskaket Marsh, as has been documented elsewhere on Cape Cod (Valiela and Teal, 1979; Howes and Goehringer, 1994). Both orthophosphate and ammonium appear to be released to the creek system as the salt marsh plants *S. patens* and *S. alterniflora* senesce in the late summer. The largest seasonal variation in orthophosphate and ammonium concentrations occurred at station A (figs. 11*A*, *B*), which has the largest area of *S. alterniflora* in upstream areas immediately adjacent to the creek banks. The smallest seasonal variation in these nutrient species occurred at station E (figs. 11*E*, *F*), which has little salt marsh vegetation in its upstream contributing area. This is especially true for ammonium at station E, where ammonium concentrations were low and showed the smallest seasonal variation of any nutrient species at any of the stations.

Nitrate and TDN (figs. 11*G*–*L*) concentrations showed less seasonal variation than orthophosphate and ammonium at the creek sampling stations. The weaker seasonal nitrate signal in the creek samples may partly reflect the fact that orthophosphate and ammonium nitrogen are taken up by marsh plants (and subsequently released) in preference to nitrate during the annual growth and senescence cycle. However, station E provides a counterexample—a strong nitrate signal that is out of phase with the orthophosphate and ammonium signals evident at the other stations. From late fall to late winter, median monthly baseline nitrate concentrations increase substantially at this station, during both the 1990s baseline period and 2010–11 (fig. 11*K*).

One possible explanation for this seasonal nitrate pattern is that nitrate uptake and release at station E is largely governed by the *Phragmites* stand in this portion of the marsh, rather than by the *S. patens* and *S. alterniflora* grasses near the main creek (fig. 5). The decline in nitrate from May through October at station E (fig. 11*K*) may reflect the uptake of nitrate by *Phragmites* during the growing season. The subsequent rise in nitrate concentration from October through April may result from the release and oxidation of dissolved nitrogen species by the *Phragmites* stand during its annual senescence period. More detailed study of the *Phragmites* stand and its biogeochemistry would be required to test this hypothesis.

Potential Effects of the Treated Wastewater Plume on Creek Water Quality

Namskaket Creek and its tributaries are the nearest potential surface-water receptors for the treated wastewater plume originating at the Tri-Town Septage Treatment Facility (fig. 1). For this reason, late-ebb-tide water-quality sampling was conducted from 1993 to 1997 to establish baseline nutrient concentrations and their seasonal variation in the creek system, prior to any potential influence from segments of the treated wastewater plume. As previously described, three of the baseline sampling stations (A, B, and E; fig. 7) were subsequently resampled in 2003–4 and 2010–11 to evaluate whether creek nutrient concentrations in the boundary seepage zone (station E), the Hurley's Bog outlet creek (station B), and the downstream integrator station (station A) may have changed as a result of the possible effects of either the deep or shallow plume segments. Monthly and seasonal variations during the baseline and subsequent sampling periods were addressed in previous sections; in this section, we consider whether there has been a shift in the overall baseline concentrations, by evaluating water-quality change at the annual time scale.

Dissolved nitrate is the primary water-quality constituent used to indicate potential plume discharge to the creek system, for several reasons. First, nitrate is present at relatively high concentrations in both the shallow (figs. 9 and 10) and deep (DeSimone and Smith, 2000) segments of the plume in the vicinity of the marsh. Second, it is generally transported conservatively through the well-oxygenated sands of the study area (DeSimone and Smith, 2000) and in the Cape Cod aquifer as a whole (Barbaro and others, 2014), in contrast to other nutrient species that reach the groundwater immediately beneath the facility infiltration beds (DeSimone and others, 1996). Third, excess nitrate-nitrogen loads may contribute to eutrophication of estuarine and coastal ecosystems. In addition, we evaluated changes in TDN as a secondary indicator of plume discharge. In order to assess possible changes at each of the three stations, the median of the biweekly, late-ebb-tide concentrations was first determined for each of the 3 years of high-intensity sampling—1994, 1995, and 1996. The median of biweekly concentrations for the 2011 sampling period was then determined, and this median was compared to the range of medians associated with the 3 baseline years.

At station A, the medians of biweekly nitrate concentrations for the 3 baseline years in the 1990s ranged from a low of 0.23 to a high of 0.46 mg/L, as nitrogen (fig. 12). The station A nitrate median for 2011 was 0.36 mg/L—within the range of annual values for the 1990s baseline years. At station B, baseline nitrate medians ranged from 0.25 to 0.43 mg/L, as nitrogen. The 2011 median was 0.42 mg/L, as nitrogen, also within the range of the 1990s values. At station E, baseline nitrate medians ranged from 0.30 to 0.56 mg/L, as nitrogen, and the 2011 median was 0.40 mg/L, as nitrogen—within the range of 1990s annual values. TDN concentrations showed an overall pattern of median concentrations similar to that for nitrate (fig. 12); that is, all median TDN concentrations for 2011 were within the respective ranges of the 1990s baseline concentrations. Although the stations differed in the fraction of TDN as nitrate (ranging from about 46 percent nitrate at stations A and B to 64 percent at station E), these differences did not affect the overall relation between the 2011 TDN concentrations and the 1990s baseline concentrations.

The long-term water-quality sampling in the creek system leads to two conclusions. First, substantial seasonal variation in dissolved nutrient concentrations was found at the creek sampling stations, associated with the seasonal cycle of plant growth and senescence in Inner Namskaket Marsh, the hydrologic position of each station in the creek system (for example, headwater station E versus downstream station A), and the dominant plant species present upstream of each station (for example, *Phragmites* versus *Spartina* species). Second, the annualized nitrate and TDN concentrations for 2011 were found to be within the range of annualized concentrations during the baseline years 1994, 1995, and 1996. We conclude that the 2011 samples, collected approximately 8 years after the first appearance of a shallow segment of the wastewater plume in the sandy sediments beneath the marsh, do not show evidence of increased nitrogen concentrations in the creek or its tributaries from the treated wastewater plume.

Because both segments of the plume were detected adjacent to, or beneath, the marsh as early as 2003, the second result above indicates two possible fates for the plume (or some combination of the two). First, the plume segments may be moving with the regional groundwater flow system below the marsh, toward downgradient discharge areas such as Little Namskaket Marsh or Cape Cod Bay. Second, the plume segments may be fully or partially discharging to creek reaches within Inner Namskaket Marsh, but the nitrate and other dissolved nitrogen species in the plume segments are being removed by chemical and microbial processes during vertical transport through the creek-bottom and marsh-boundary sediments or are being diluted to such an extent in the creeks that changes in the concentration of nitrogen species cannot be detected.

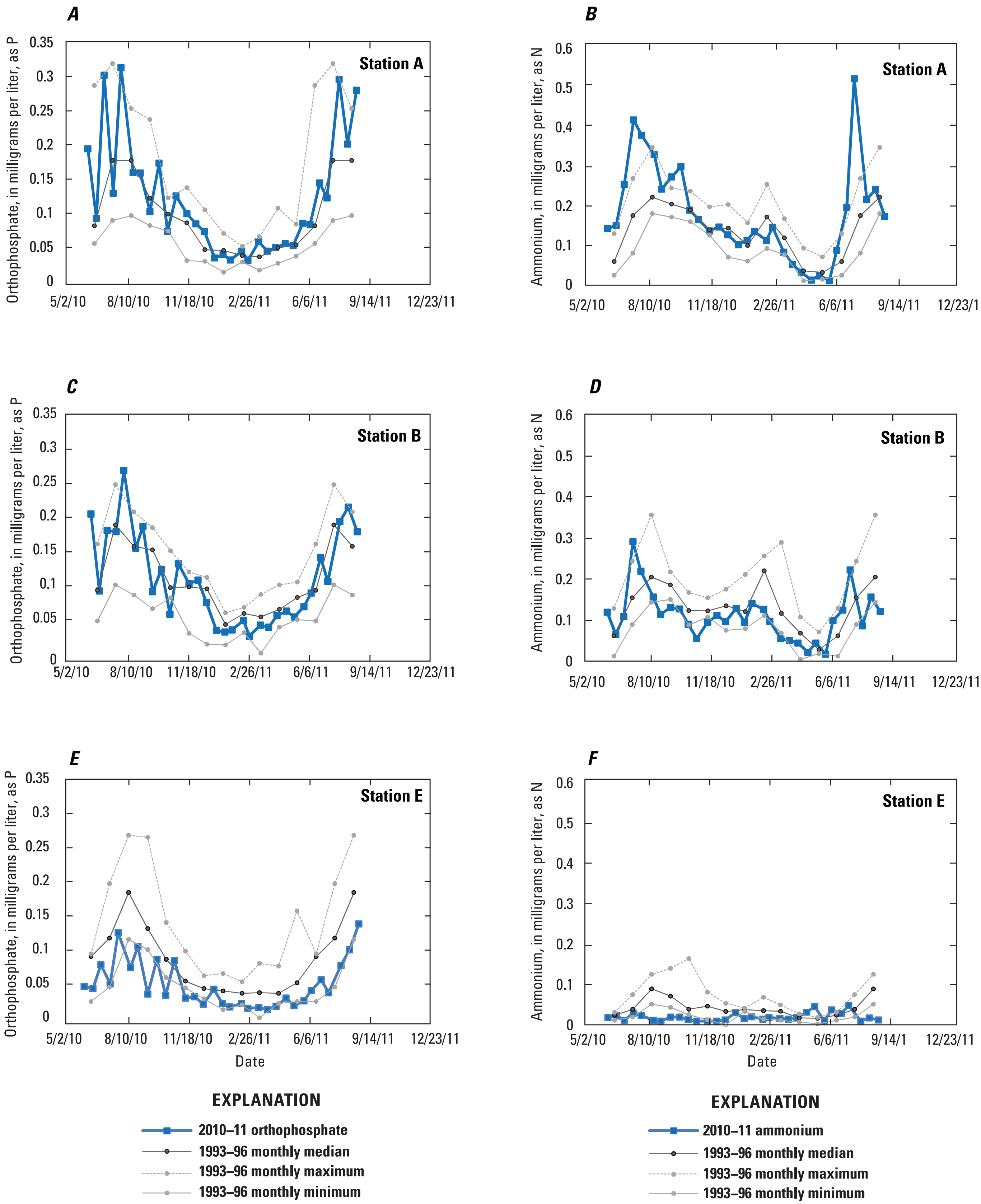


Figure 11. Temporal variation in nutrient concentrations at long-term sampling stations A, B, and E, Namskaket Creek and tributaries, Orleans, Massachusetts. See figure 7 for locations. Panels *A–F*, concentrations of orthophosphate, as phosphorus (P), and ammonium, as nitrogen (N). Panels *G–L*, concentrations of nitrate, as N, and total dissolved nitrogen, as N.

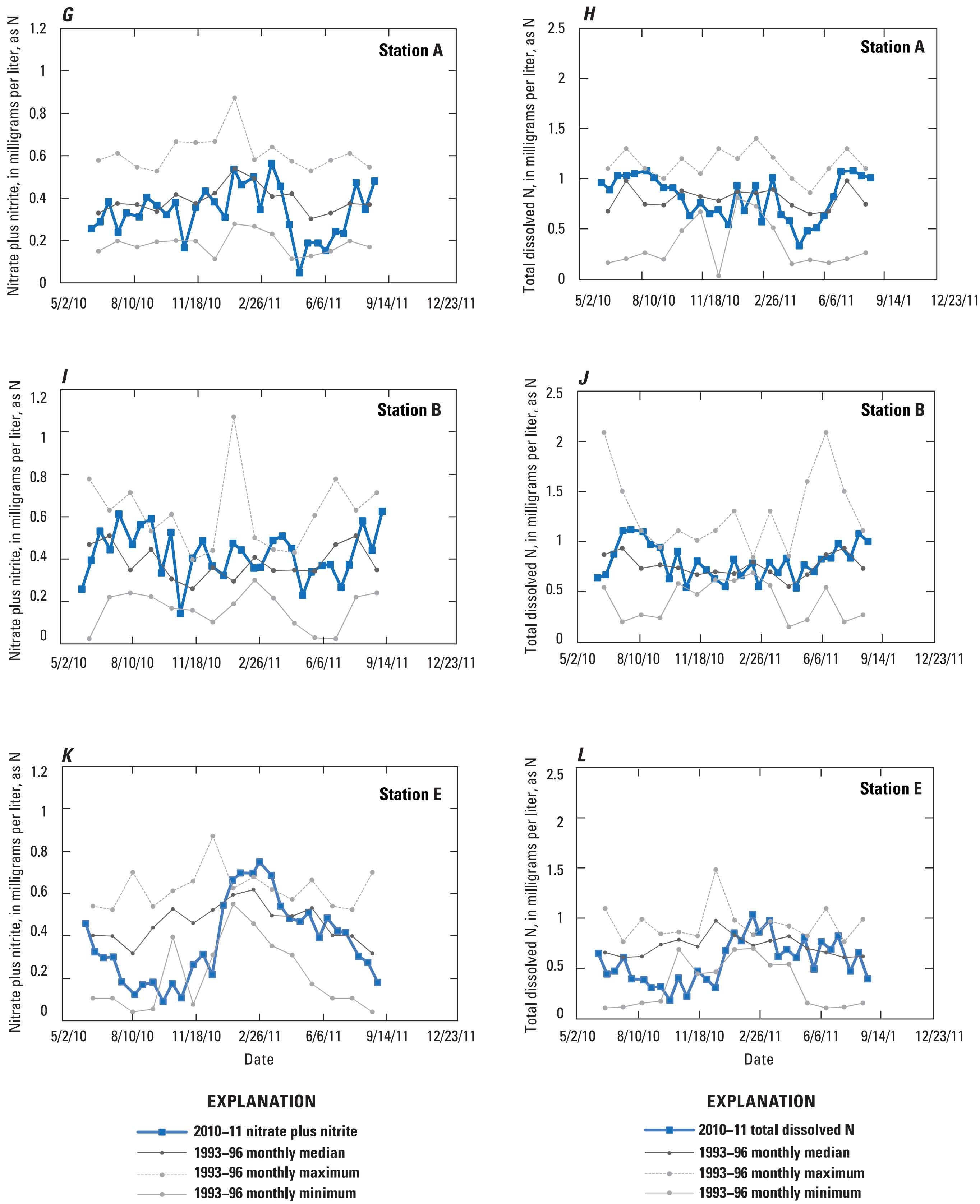


Figure 11. Temporal variation in nutrient concentrations at long-term sampling stations A, B, and E, Namskaket Creek and tributaries, Orleans, Massachusetts. See figure 7 for locations. Panels *A–F*, concentrations of orthophosphate, as phosphorus (P), and ammonium, as nitrogen (N). Panels *G–L*, concentrations of nitrate, as N, and total dissolved nitrogen, as N.—Continued

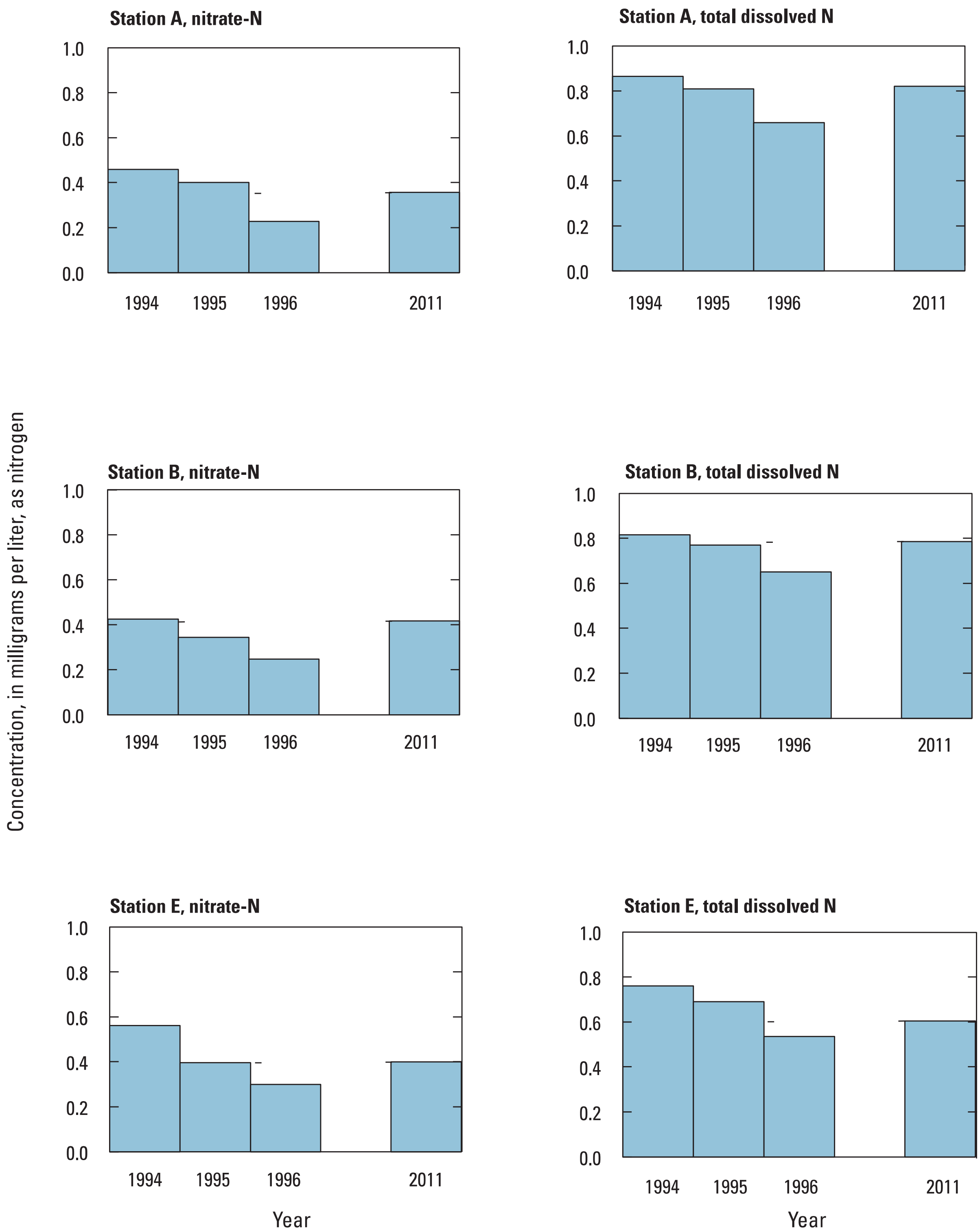


Figure 12. Annual medians of biweekly nitrate, as nitrogen (N), and total dissolved nitrogen concentrations, as N, in late-ebb-tide samples from stations A, B, and E, Namskaket Creek and tributaries, Orleans, Massachusetts. Biweekly samples were collected under baseline conditions in 1994 (number of samples [n] = 26), 1995 (n = 22), and 1996 (n = 18) sampling periods. Samples were also collected in the 2011 (n = 26) sampling period, after segments of the treated wastewater plume had been detected both adjacent to and beneath Namskaket Marsh. Dashed lines show the 2011 annual medians of biweekly nitrate, as N, and total dissolved nitrogen concentrations, as N, in relation to the 1990s concentrations for the same sampling stations. See figure 7 for locations of stations.

Summary and Conclusions

Namskaket Marsh and its tidal creek system are potential receptors for a treated wastewater plume originating from a septage treatment facility in the northwest part of Orleans, Cape Cod, Massachusetts. In order to characterize potential effects of the plume on the marsh and its tidal creek system, the U.S. Geological Survey, in cooperation with state and local partners, characterized baseline environmental conditions in the marsh and creek system and monitored the movement of the plume from its source to areas immediately adjacent to and beneath the marsh. The creek system was systematically sampled to assess (1) baseline seasonal variations in nutrient concentrations prior to plume arrival at the marsh boundary and (2) potential long-term changes in creek nutrient concentrations resulting from possible discharge of the plume to the creek system.

The upland part of the study area is underlain by a complex sequence of glacial deposits, consisting of sandy, outwash plain sediments and fine-grained, glacial-lake sediments, totaling 300 to 400 feet (ft) in thickness. At Namskaket Marsh, this glacial sequence is directly overlain by tidal-flat muds, which grade upward into salt marsh peat. The tidal creeks of Inner Namskaket Marsh originate in groundwater discharge zones near the marsh-upland boundary, where tidal-flat muds are thin or absent. In more interior parts of the marsh, groundwater discharges to the creeks through sandy creek-bottom sediments. Inner Namskaket Marsh was dominated by three plant species during the 1995 baseline sampling: *Phragmites australis* (common reed, 44 percent of vegetative cover), *Spartina patens* (salt marsh hay, 17 percent), and *Spartina alterniflora* (cordgrass, 9 percent). The distribution of plant species across Inner Namskaket Marsh was correlated with shallow pore-water salinity in the peat. *Phragmites* was most abundant in the marsh-upland boundary zone where pore-water salinities were generally less than 4 parts per thousand.

The facility began discharging treated wastewater effluent to infiltration beds in 1990, and a plume began to develop by 1991. Median specific conductance in groundwater below the infiltration beds was 3,010 microsiemens per centimeter at 25 degrees Celsius, and median total dissolved nitrogen and phosphorus concentrations were 35 milligrams per liter (as nitrogen) and 0.02 milligrams per liter (as phosphorus), respectively, during 1991–92. In late 1994, the plume was first detected by borehole geophysical logging in observation wells along the Cape Cod Rail Trail (rail trail), 600 feet northwest of the infiltration beds, at an elevation of 47 to 53 feet below the National Geodetic Vertical Datum of 1929 (NGVD 29). Borehole logging at the rail trail, and in the area immediately to the northwest, also indicated the presence of a 3- to 8-ft-thick silt/clay unit, located above the zone occupied by the wastewater plume. Lithologic samples of clayey silt confirmed the presence of this layer. Borehole logging in early 1998 near the plume's southwest boundary at the rail trail detected the appearance of a second plume segment above the silt/clay unit. The second plume segment was found at 22 to 27 ft below NGVD 29 at this location, where the top of the silt/clay unit reached its lowest observed elevation along the rail trail (40 ft below NGVD 29). The presence of an upper plume segment at this location was confirmed by groundwater sampling in October 2003. Well-point sampling was also conducted in October 2003 in the glacial sands beneath Namskaket Marsh, along a transect of stations parallel to and 125 ft northwest of the rail trail. Profiles of specific conductance, supplemented by field nitrate analyses, confirmed the presence of the shallow plume segment at an elevation of 24 to 36 ft below NGVD 29 (30 to 42 ft below the marsh surface).

The water quality of Namskaket Creek and its tributaries was sampled during a baseline period (1993–97), and again in 2003–4 and 2010–11, to evaluate potential effects of the treated wastewater plume on creek water quality. Creek samples for specific conductance and dissolved nutrients were collected biweekly at three principal sampling stations during late ebb tide, when the groundwater-derived, freshwater fraction of creek flow is at a maximum. The 1990s baseline concentrations showed a strong seasonal cycle for orthophosphate and ammonium, likely associated with the seasonal cycle of growth and senescence of the dominant salt marsh grasses (*S. alterniflora* and *S. patens*). The seasonal cycle for nitrate was generally less pronounced. However, because nitrate is present at higher concentrations in the wastewater plume segments than the other nutrient species, and because it was shown to be readily transported through the aquifer, we evaluated whether the annualized baseline concentrations of nitrate at the sampling stations had changed from the 1990s baseline, owing to possible effects of plume discharge on creek water quality. The annual median of the 2011 biweekly nitrate concentrations was determined for each station and compared to the annual medians for 1994, 1995, and 1996. At all three stations, the 2011 median nitrate concentration was within the range of medians for the 3 baseline years of the 1990s. A similar result was obtained for total dissolved nitrogen.

We conclude that the 2011 creek samples, collected approximately 8 years after the shallow plume segment was first detected beneath the marsh, do not show evidence of elevated nitrate or total dissolved nitrogen concentrations attributable to discharge of the plume segments. The plume segments may be moving with the regional groundwater flow system below the marsh, toward downgradient discharge areas such as Little Namskaket Marsh or Cape Cod Bay. Alternatively, the plume segments may be fully or partially discharging to creek reaches within Inner Namskaket Marsh, and the nitrate and other dissolved nitrogen species in the plume segments are (1) being removed by chemical and microbial processes during vertical transport through the creek-bottom and marsh-boundary sediments or (2) diluted to such an extent in the creeks that changes in the concentration of nitrogen species cannot be detected.

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