

**Hydrologic Evaluation of Groundwater Discharge
Nauset Marsh, Cape Cod National Seashore,
Massachusetts**

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EXECUTIVE SUMMARY

The principal objective of this study, which was conducted during the period 1992 - 1994, was to evaluate the quantity and quality characteristics of coastal groundwater discharge into the Nauset Marsh System. This was done during a two year period in order to determine variations of groundwater discharge over time.

The Nauset Marsh area of Cape Cod is a system of marshes and small bays and coves which connect with the Atlantic Ocean to the east. Tidal ranges within the main embayments average 1.34 m., but may range up to 1.68 m. during spring tides. The tidal flux in the shallow waters of the Nauset Marsh System is an important factor in the flushing of terrestrial groundwater discharge with its pollutants from the System.

The average annual precipitation is 111.6 cm. During the period of this study, the area had total annual precipitation values of 105.0 cm. in 1992, 122.2 in 1993 and 151.0 in 1994, with monthly values ranging from 1.06 cm in August, 1993 to 25.0 cm in December, 1994. The area is covered with unconsolidated glacial sediments of high permeability. Hence, there is little surface drainage with an estimated 40% of the annual precipitation infiltrating the ground's surface to become groundwater recharge, and subsequently, coastal discharge.

Much of the 1927 hectare watershed area of the Nauset Marsh System is developed for residential or commercial purposes. As of 1993 there are an estimated 1460 residences and other buildings in the watershed, including the Cape Cod National Seashore Visitors Center which is visited by approximately 670,000 persons each year. All of the area is serviced by on-site individual sewage disposal systems. Of particular concern from this situation is the potential impact from nutrients which enter the groundwater system and discharge at the coastline into the shallow receiving water of the Nauset Marsh System. In the confined, poorly flushed components of the Nauset Marsh System there is a potential for eutrophication.

To accomplish this study, five locations were selected for detailed field measurements of groundwater discharge characteristics and water quality. These locations represent a variety of regional conditions, namely variations in residential population, geologic characteristics and shoreline vegetation. Each of these sites was subjected to groundwater piezometric measurements and water quality sampling to determine patterns of flow and water quality variations. The water quality measurements were accomplished to determine concentration levels of salinity and nitrogen. It was found that the discharge of groundwater occurs during low tide periods in a highly irregular pattern along the shoreline. Permeability tests and grain size analysis show that greater flow occurs in zones of more permeable clean sands, with relatively little water passing through sediments with abundant vegetation which tends to trap less permeable silt. The field work was supplemented on a regional scale by thermal infrared aerial photography accomplished under a contract by the National Park Service. The photography was done during a low tide event on 7 August, 1994 when temperature contrast between discharging groundwater and the warmer receiving water was about 7 degrees centigrade. The temperature contrast was sufficient to delineate zones of coastal groundwater discharge. The discharge varies greatly along the shore margin, in much the same pattern as that

identified in the smaller scale site studies.

At each site monitor wells were placed for water level measurements and water quality sampling. In addition, both vertical and horizontal water quality profiles were made to ascertain patterns in the variation of salinity and nitrogen content. In some cases the vertical profiles penetrated the fresh water layer which typically overlies salt water in coastal areas. The usual pattern of beach groundwater quality in the inter tidal beach zone is that of an upper salty layer caused by salt water infiltration at high tide, a fresh water layer of inland origin moving to discharge at the coast, and an underlying salt water layer connected to the bay through permeable sediments.

Additionally, short term intensive measurements were conducted at two of the sites to examine the temporal and spacial distribution of groundwater discharge. At these two sites pressure transducers with data loggers for continuous water level measurements were installed in the intertidal zone. This data also enabled the determination to be made of groundwater discharge quantity and location variation during the tidal cycle. In more prolific spring areas the maximum groundwater discharge rate at low tide was calculated to be 3.0 cubic meters/day/square meter of beach face. The water discharge is at a maximum velocity of 9.0 meters/day. This velocity is sufficient to remove fine grained sediment, thus both maintaining, as well as enhancing spring flow.

Direct field measurements were made to determine the nitrogen concentrations in groundwater discharging at each of the five study sites. The nitrogen content was plotted versus the salinity content for all water samples at each site. As a very general observation, field measurements at the sites show a trend of increasing nitrogen with decreasing salinity indicating a primary fresh water source for the nitrogen. Two regression lines for nitrogen versus salinity were determined: one for the least squares mean fit of all data and the second for the maximum nitrogen concentration envelope. A maximum nitrogen data envelope plot shows the maximum nitrogen concentration at varying degrees of salinity, assuming all samples contain fresh water from the same source and are fully mixed. It was found that the average groundwater nitrogen content for all sites was 1.92 mg/l, but varied from 0.1 mg/l for Salt Pond Bay to 3.9 mg/l for Weeset. The maximum average nitrogen content for fresh water, based on the envelope analysis, was 3.7 mg/l, with a range from 0.1 mg/l for Salt Pond Bay to 8.0 mg/l for Weeset.

The watershed area was divided into ten sectors for purposes of calculating a hydrologic budget and estimating the nitrogen input from on-site sewage disposal. The budget calculations assume an estimate of 40.6 cm/year average groundwater recharge over the Nauset watershed, and household wastewater release of 520 liters/day/residence with a nitrogen content of 35.0 mg/l. It was further assumed that all nitrogen remained in the groundwater until discharge at the beach. The total estimated annual nitrogen contribution to Nauset Marsh from groundwater is 10,146 kg /year at an average concentration of 1.65 mg/l in the discharging groundwater, without allowance for denitrification. This value compares favorably with the average measured value of 1.92 mg/l. The estimated nitrogen concentration at individual sectors ranged from 0.64 mg/l at Nauset Bay to 3.52 mg/l at Nauset Heights. It is important to note that this estimate does not include other nitrogen sources of potential importance, notably lawn fertilizer input.

Overall conclusions are as follows:

1. The distribution of fresh groundwater outflow varies greatly along the shoreline depending on the heterogeneous nature of beach sand hydraulic conductivity. Further, the groundwater outflow occurs in a relatively narrow seepage zone only during low tide episodes.
2. The vertical movement of the bay water due to the tidal fluctuation causes major groundwater flow direction changes in the beach during the tidal cycle, effectively creating a hydraulic dam during high tide periods which blocks groundwater discharge.
3. The horizontal shoreward movement of the salty bay water during a flood tide causes a layer of salt water to infiltrate in the beach and overlay the outward flowing fresh water.
4. The concentration of anthropogenic nitrogen in the flowing groundwater tends to vary directly as the freshness of the groundwater, provided there is no denitrification.
5. The timing, location and magnitudes of the groundwater outflow during the tidal cycle can be determined by analysis of the piezometric heads along the beach face during the tidal cycle.
6. The location and magnitudes of the groundwater discharge during the tidal cycle are largely determined by the topography and geology of the beach face.

Recommendations for additional study are:

1. Conduct further water quality sampling at major groundwater discharge areas identified in the low tide shoreline surveys. This would include more and different discharge zones than that included at the five sites.
2. Accomplish detailed vertical and horizontal water quality surveys at the Salt Pond Site beach to locate and define the on-site sewage disposal leachate discharge from the National Park Service Visitors' Center.
3. Relate the groundwater discharge and surface water runoff quality at Salt Pond to the Salt Pond water quality and flushing characteristics to evaluate the potential for eutrophication.
4. Accomplish additional comprehensive tide related piezometric and water quality measurements in the beach zone, similar to those done at the Salt Pond and Eldredge Sites, to obtain a better understanding of the dynamics of the groundwater discharge phenomena.

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1 INTRODUCTION

1.1 Problem Statement and Justification of the Study

As groundwater approaches a coastal area, it carries with it various anthropogenic contaminants from inland sources. Consequently, the coastal groundwater discharging through the tidal area has a potential adverse effect on the environment. Nitrogen is a contaminant which occurs commonly in coastal groundwater, and is frequently the limiting nutrient for vigorous aquatic growth in salt water embayments (Weiskel and Howes, 1991; Kennish, 1992). Of particular concern is the potential for eutrophication (Nixon, et al, 1986; Howarth, 1988). The increase of nutrients encourages dense growth of certain rooted aquatic plants and algal mats. The subsequent biodegradation of the vegetation results in deoxygenation which creates an adverse effect for aquatic life (Fuhs, 1974; Valiela, et al, 1992).

Groundwater discharge along the shoreline has been found to be a primary source of the nitrate-nitrogen entering coastal embayments (Capone and Slater, 1990; Giblin and Gaines, 1990). The extent to which nitrate-nitrogen persists through the coastal discharge process will depend in large degree on the physical and hydrogeologic characteristics of its pathway. If it passes through clean coarse grained sediments the nitrate will tend to remain as a stable conservative constituent. If, however, the groundwater flow path carries it through organic-rich sediments significant denitrification and loss of nitrogen can occur (Capone and Slater, 1990). A key problem in evaluating the extent of denitrification is the need to determine and describe the groundwater flow path through the beach zone, especially as it relates to passage through organic rich coastal sediments. The problem, however, is not trivial since the nature of groundwater discharge through a tide affected beach zone is both complex and dynamic (Urish and Ozbilgin, 1989; Nielsen, 1990; Turner, 1993; and Millham and Howes, 1994).

A large increase in the residential population and in tourism in the Nauset Marsh area of Cape Cod, coupled with a dependence on individual sewage disposal systems in the area has caused a rise in the concentration of nitrate-nitrogen in the groundwater system. Giblin and Gaines (1990), as well as Jones et al (1990), found evidence of high nitrogen content in groundwater flowing into the Nauset Marsh System. An average of 3.0 mg/l was determined for the groundwater around Town Cove at the southern end of the Nauset Marsh system. Frimpter and Gay (1979) found Cape Cod groundwater concentrations to be as high as 6.3 mg/l in some areas. Giblin and Gaines also found nitrate concentration to be proportionate to the density of the residential, service and/or recreational buildings, and other facilities existing in groundwater flow paths. Therefore, the concentration of nitrates can vary greatly from location to location, being dependent upon the number of residences with on-site sewage disposal systems and other operations contributing nitrogen within the flow path, as well as hydrologic factors.

1.2 Study Objectives

The objective of this study is an assessment of the characteristics and a quantification of the groundwater outflow and seepage through coastal areas at Nauset Marsh, Cape Cod, Massachusetts.

To attain this objective, the following tasks were addressed:

1. The delineation of the groundwater flow system at the discharge locations. This will define the physical groundwater characteristics within the beach including beach hydrologic parameters, flow paths, flow velocity, salt water-fresh water interactions, and variations in the groundwater system.
2. Investigation of the composition and dynamics of the freshwater outflow through the beach face. This includes the determination of the tidal fluctuation influence on the groundwater discharge.
3. Characterization of the quality of the groundwater at the points of discharge at the coastal zone, in terms of the degree of salinity and nitrogen concentrations.

1.3. Location and Description of the Study Area

Nauset Marsh is located on the Atlantic Ocean shore of Cape Cod, Massachusetts, a peninsula of approximately 173 km in area, lying offshore of the New England coast. It is bounded on the east side by the Atlantic Ocean and on the west side by Cape Cod Bay (Figure 1.1). It is about 72 km long and ranges from 2 km to 22 km wide. At the Nauset Marsh area the peninsula is about 5 km wide.

1.3.1 Geography

The Nauset Marsh area, which includes the towns of Eastham and Orleans, is a system of marshes, small bays and coves which connect with the Atlantic Ocean. The region is well developed and contains significant recreational areas, notably those belonging to the National Park Service. The estimated area of the Nauset Marsh watershed is 1927 hectare (4762 acres), with approximately 1460 houses and other buildings. In 1993, the National Park Service Visitors' Center located at Salt Pond was visited by approximately 670,000 visitors in 1993. The Visitors' Center, as well as local residences and businesses depend on on-site sewage disposal systems.

1.3.2 Climate

Cape Cod has a maritime humid climate characterized by a moderate range of temperatures with well-developed summer and winter seasons. The seasonal extremes are moderated by the surrounding ocean waters. In July, high temperatures average 25.3° C and lows average 16.5° C. February is the coldest month with average temperatures ranging from 3.4° C to -4.4° C. According to Strahler (1972) the average annual precipitation at the Upper Cape is 102 cm with monthly distribution ranging from an average of 5.85 cm in July to 11.45 cm in September. Millham and Howes (1994) cite average annual precipitation at the Lower Cape to be about 112 cm/year. It is expected that the precipitation in the Nauset Marsh area averages about 110 cm/year. During the study years of 1992, 1993 and 1994, the region had annual precipitations of 105.03 cm, 122.20 cm and 150.96 cm, respectively (Portnoy, 1996). It is noted that 1994 was an extremely wet year. Figure 1.2 shows a plot of the monthly precipitation during the study period.

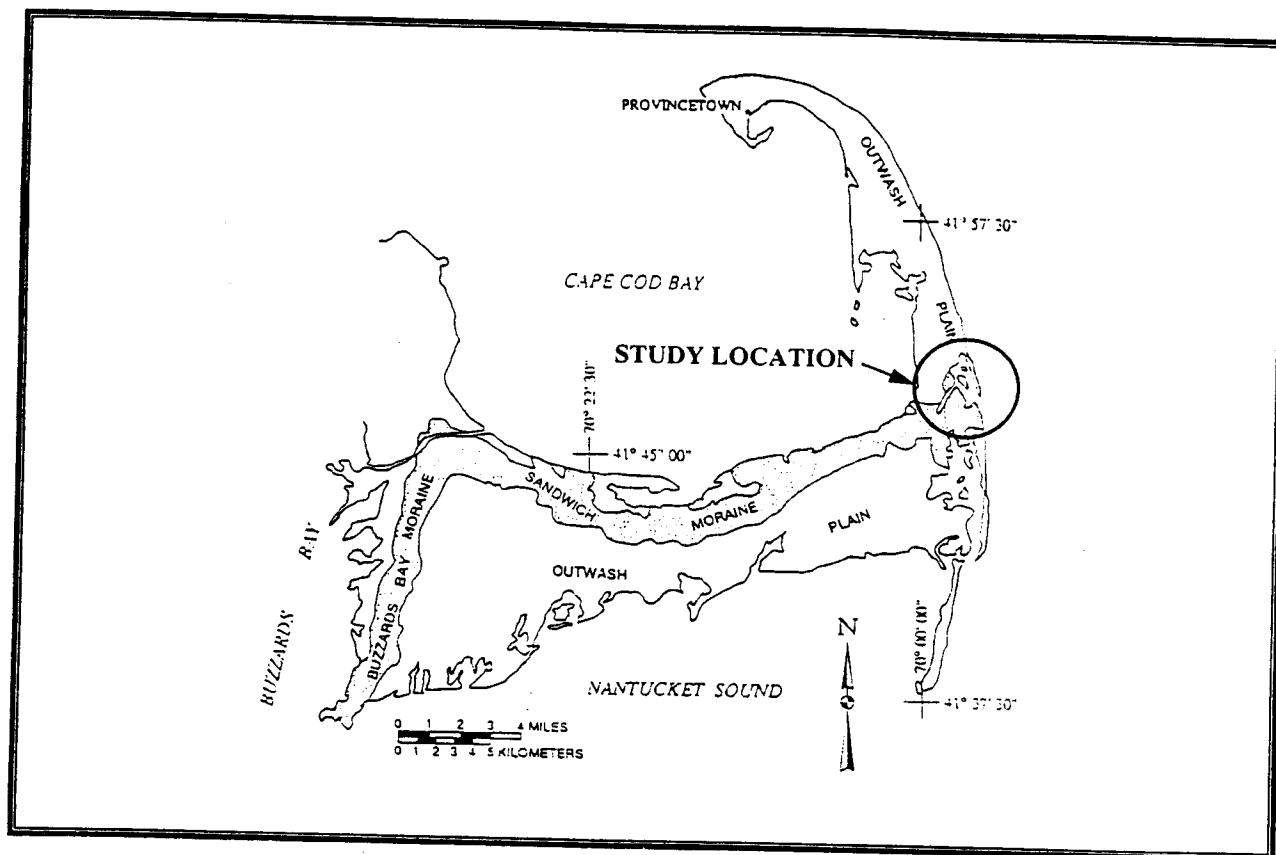


Fig. 1.1 General location map of the study area

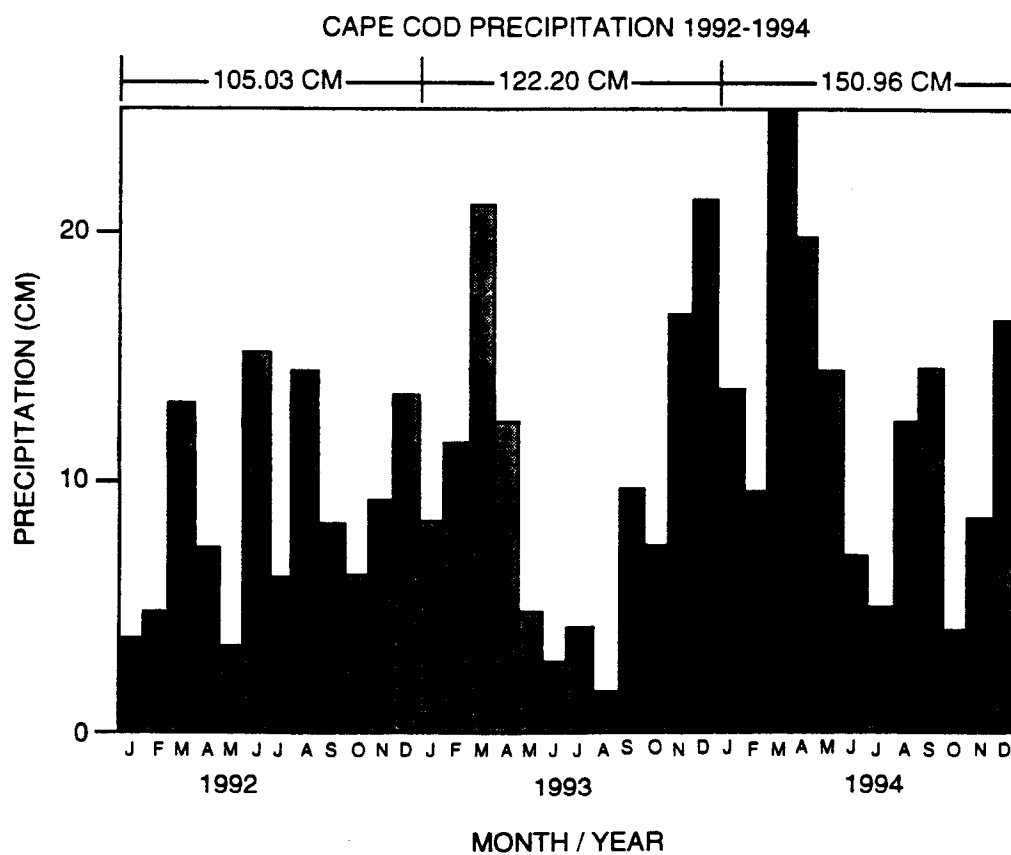


Fig. 1.2 Plot of Cape Cod precipitation: 1992-1994

1.3.3 Watershed Topography

The topography of the study area is undulating with elevations ranging from sea level to 4.25 m. There are numerous embayments and coastal wetlands. The ground cover is mostly low vegetation consisting of grass, shrubs and pitch pine trees. One of the most significant features on the Cape is the large number of different sizes of fresh water ponds. More than ten fresh water ponds are scattered over the study area. These ponds resulted from deposition of ice blocks and subsequent melting causing depressions, or "kettles", in the outwash plains and moraines (Strahler, 1966). Where these ice block depressions extend below the water table ponds develop. Hydrologically these ponds are of considerable importance, functioning both as focused recharge areas in winter and as hydraulic sinks in summer due to the evaporation effect.

In the study area the most significant pond is Minister Pond, which lies about 0.5 km to the northwest of Salt Pond. Water elevation in Minister Pond is 4.25 m above mean sea level (USGS, 1974), while the Salt Pond mean elevation is approximately 0.8 m above mean sea level. This is a large hydraulic head difference and suggests substantial groundwater flow may occur from Minister Pond to Salt Pond.

1.3.4 Geology

Cape Cod is composed almost entirely of unconsolidated sediments deposited by glacial ice and by meltwater streams issuing from that ice (Strahler, 1972). Most of the glacial material is sand, gravel and boulders, but there are layers of clay and silt, also of glacial origin, enclosed within or beneath the coarser deposits. These deposits belong to the last four major glaciations affecting North America during the Pleistocene Epoch, or "Ice Age", began 75,000 years and ended about 12,000 years ago. Beneath the glacial deposits of the entire area lies basement rock of a very old granite similar to that exposed in mainland Massachusetts. Between the hard basement rock and the deposits there are some soft rock layers (Strahler, 1972). The overlying deposits at the study sites consist of both glacial outwash sand and gravel and ice contact deposits (Oldale, 1980).

The eastern Outer Cape, including Nauset Marsh, is located is composed of outwash plains which were formed in an interlobate area between two ice lobes, the Cape Cod Bay lobe on the west and the south channel lobe on the east which lay offshore from the present coast. The outwash plain sediments were deposited primarily from this later lobe (Fisher, 1972). The Nauset Marsh area is comprised of coarse unconsolidated sands of marine origin and in some parts a thin top layer of silty organic deposits covers the sand.

1.3.5 Fresh-salt Groundwater Relationships

Groundwater in the region occurs largely in a classical Ghyben-Herzberg fresh water lens (Ghyben, 1894; Herzberg, 1901; Hubbert, 1940; Fetter, 1988) poised on higher density sea water which completely underlies the Cape Cod Peninsula (Strahler, 1972). In this system, precipitation percolates downward through unsaturated soil, collects in a layer atop sea water, and slowly flows as groundwater toward the coast to discharge through intertidal or subtidal sediments. At the coastline the groundwater discharges in a narrow zone at low tide (Glover, 1964). This discharge

phenomenon has been examined and generally verified by field measurements in essentially tideless conditions by Bokuniewicz (1980) at Great South Bay, New York. However, in tide affected coastlines the discharge is greatly time and tide dependent. (Urish, 1987; Turner, 1993).

1.3.6 Groundwater Fluctuations

A number of studies have been conducted which investigate tide induced groundwater hydraulic head fluctuations in the coastal area (Todd, 1980; Emery and Foster, 1948 and others). Plots of coastal groundwater elevations recorded with time typically show a sinusoidal fluctuation, which increases in lag time and decreases in amplitude as the distance increases from the coastal water boundary (Todd, 1980). This fluctuation causes, at certain times of the tidal cycle, a complete reversal of the groundwater flow in the beach zone. Additionally, water levels and groundwater discharge in the beach zone are particularly affected by the nature of the beach boundary. Urish and Ozbilgin (1989) have made a comparison of the effect of the sinusoidal tidal movement into the groundwater at a vertical shore face as compared with movement into a sloping shore face. They have found that on sloping beaches, because of the tidal fluctuation, significant mounding of groundwater occurs due to the slow drainage of the beach groundwater as the tide goes out. As a result of these effects, in many instances, hydraulic damming of groundwater occurs during high tides and discharge takes place only during low tide periods.

The tidal regime in Nauset Marsh consists of a semi-diurnal tidal cycle with the principal variations following the changes in the moon's phase. The tidal range is about 1.34 m. There is a tidal lag time of about 1 to 2 hours between the marsh and the open ocean. Additionally, the tidal fluctuation translates into the coastal groundwater system, creating a highly dynamic aquifer boundary condition.

1.3.7 Beach Groundwater Flow Pattern

As groundwater approaches a coastal discharge boundary it moves upward along a saltwater-freshwater interface and discharges in a narrow zone along the intertidal zone. This is both because of the difference in hydraulic head and because of the upward density gradient created as the lighter density fresh water meets salt water at the shoreline. The interface between fresh and salt water is actually a transition zone which varies in width depending on the tidal fluctuation and the strength of the groundwater discharge. The generalized nature of the discharge pattern as a static concept is illustrated by Glover (1964) in Figure 1.3. However, in a beach zone subjected to tides, the tidal dynamics are extremely important, greatly modifying this steady state picture to a dynamic condition as will be described in this study.

1.4 Site Characteristics

Five sites of varying characteristics were selected for this study in conjunction with representatives of the National Park Service. The Nauset Marsh shoreline is a combination of sand areas and vegetated areas which contain organic rich sediments. The five sites selected are distributed in locations which will cover different hydrogeologic conditions, as well as areas of expected variations in concentrations of nitrogen. The five sites are located as shown in Figure 1.4. Table 1.1 summarizes the characteristics of the five sites:

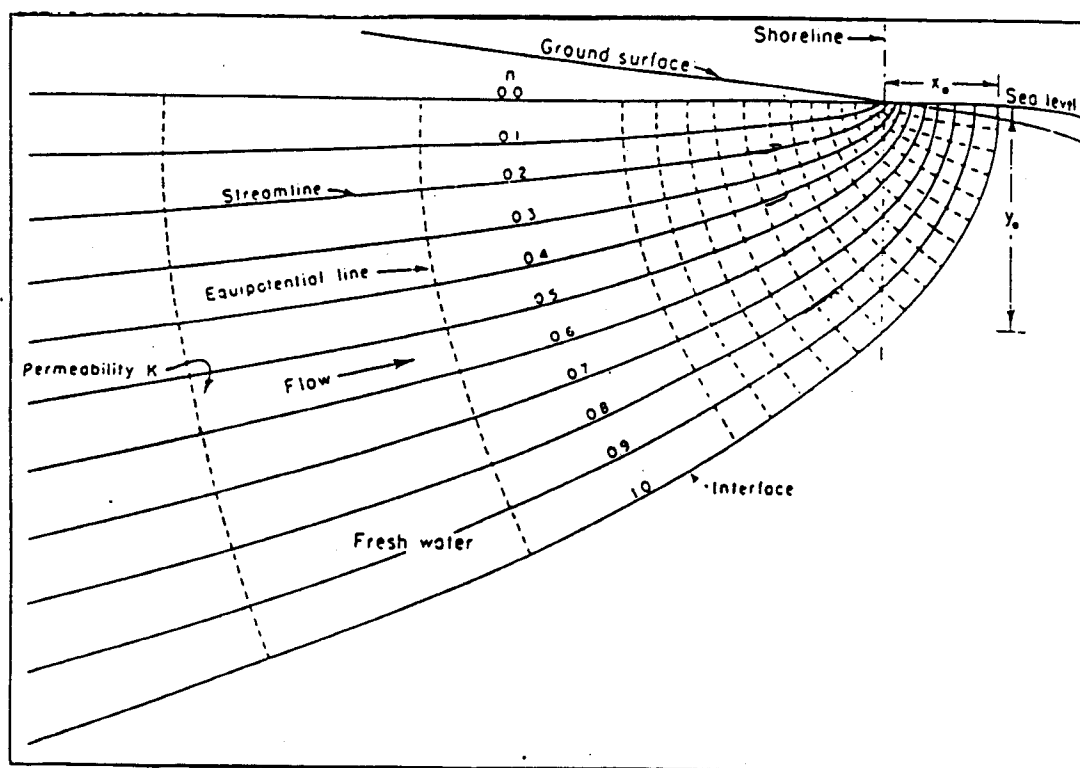


Fig. 1.3 Groundwater flow pattern at a beach

Table 1.1 Nauset Marsh Study Site Characteristics.

SITE (LOCATION)	GEOLOGIC TYPE (Oldale, 1981)	SHORE TYPE	BEACH SLOPE (upper-mid-lower)
A (Salt Pond)	glacial outwash	vegetated/with sandy breaks	0.170-0.115-0.045
B (Salt Pond Bay)	glacial outwash	well vegetated	0.067-0.050-0.030
C (Shore Garden)	glacial outwash	sandy/with marginal vegetation	0.085-0.065-0.040
D (Eldredge) Section A-A Section B-B	glacial ice contact	mostly vegetated	0.050-0.100-0.065 0.080-0.080-0.040
E (Weeset)	glacial ice contact	vegetated/with sandy breaks	0.065-0.65-0.015

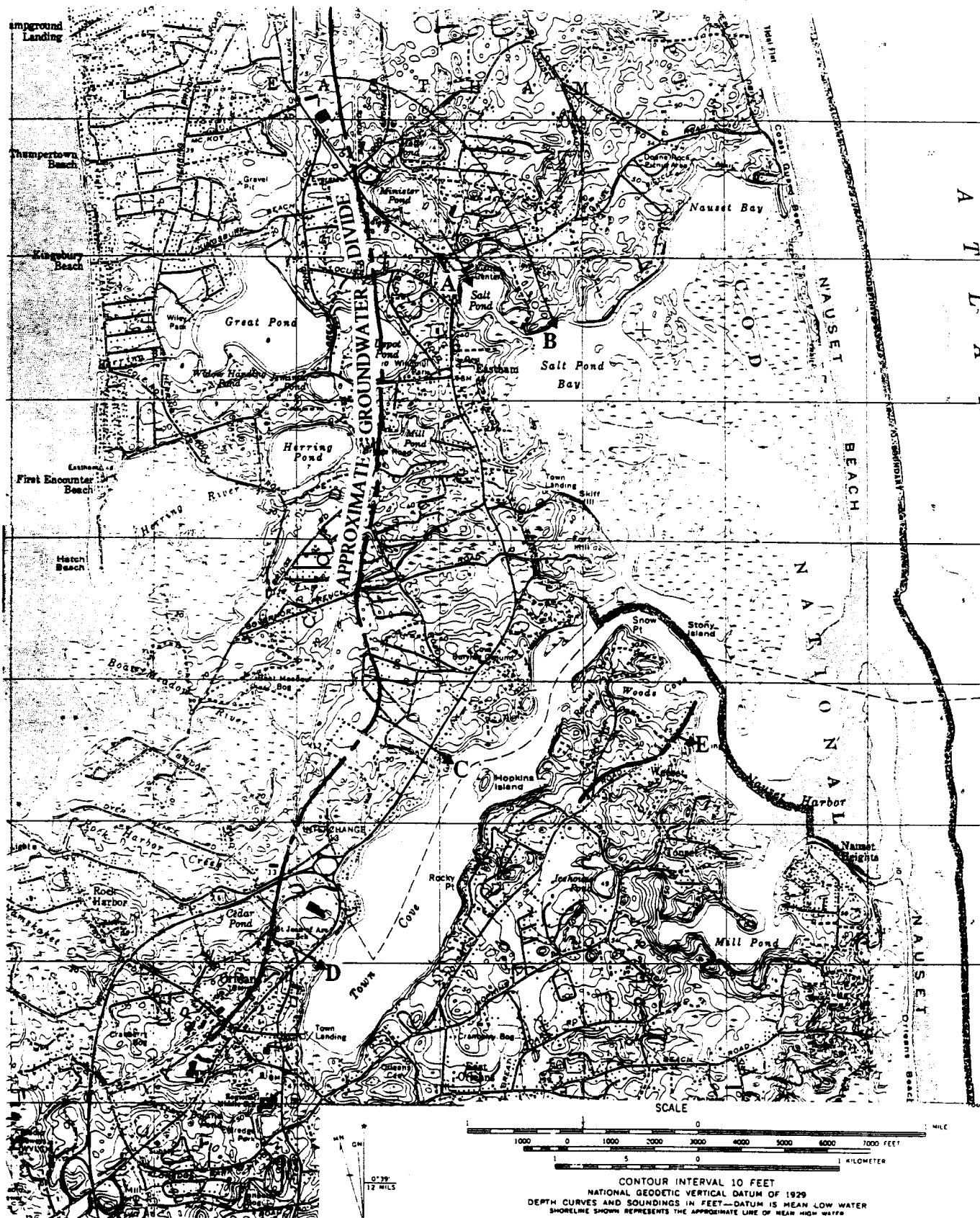


Fig. 1.4 Site location map: Nauset Marsh Study

Descriptions of the five sites are as follows:

1.4.1 Salt Pond Site (A)

This site is located on Salt Pond by the Visitors' Center, east of Route 6 (Figure 1.4). This site contains two types of sloping beaches, one of which is clean and sandy and the other covered with coastal vegetation e.g. *Spartina*. A plan view and a cross section of the Salt Pond beach are shown in Figure 1.5. Photographs looking along the beach line and perpendicular to the beach are presented as Figure 1.6. The Salt Pond site has a specific significance in that high levels of anthropogenic nitrogen are expected to reach the beach as a result of a large wastewater contribution from the nearby National Park Service Salt Pond Visitors' Center. There are approximately 700,000 visitors per year at this location, primarily during a three month summer period of June through August.

1.4.2 Salt Pond Bay Site (B)

This site is located on Salt Pond Bay, north of the entrance of the water channel that connects Salt Pond Bay with Salt Pond, about 0.9 km from Site A (Figure 1.4). This site is a sandy beach with a small 0.5 m high scarp near the low tide, and it is covered with scattered strips of coastal vegetation, mainly *Spartina*, near the water. Eroded peat layers dominate the intertidal zone. A plan view and a cross section of the Salt Pond Bay beach are shown in Figure 1.7. Photographs looking along the beach line and perpendicular to the beach are presented as Figure 1.8.

1.4.3 Shore Garden Site (C)

Shore Garden is located on the west side of Town Cove, about 4 km south of Site A, opposite Hopkins Island (Figure 1.4). This site is a combination of sloping sandy beach, with parts covered with coastal vegetation. A plan view and a cross section of the Shore Garden beach are shown in Figure 1.9. Photographs looking along the beach line and perpendicular to the beach are presented as Figure 1.10.

1.4.4 Eldredge Site (D)

The Eldredge Site is located on the west side of Town Cove, 0.9 km south of the Shore Garden Site (Figure 1.4). This site is mostly a sloping sandy beach, with some other parts covered with coastal vegetation, namely *Spartina*. Strong seepage areas are visible at this site at low tide. A plan view and a cross section of the Eldredge beach are shown in Figure 1.11. Photographs looking along the beach line and perpendicular to the beach are presented as Figure 1.12.

1.4.5 Weeset Site (E)

This site is located on Nauset Harbor, at Town Landing near Weeset (Figure 1.4). The location has a sloping beach, with some parts covered with coastal vegetation, mostly *Spartina*. A plan view and a cross section of the Weeset beach are shown in Figure 1.13. Photographs looking along the beach line and perpendicular to the beach are presented as Figure 1.14.

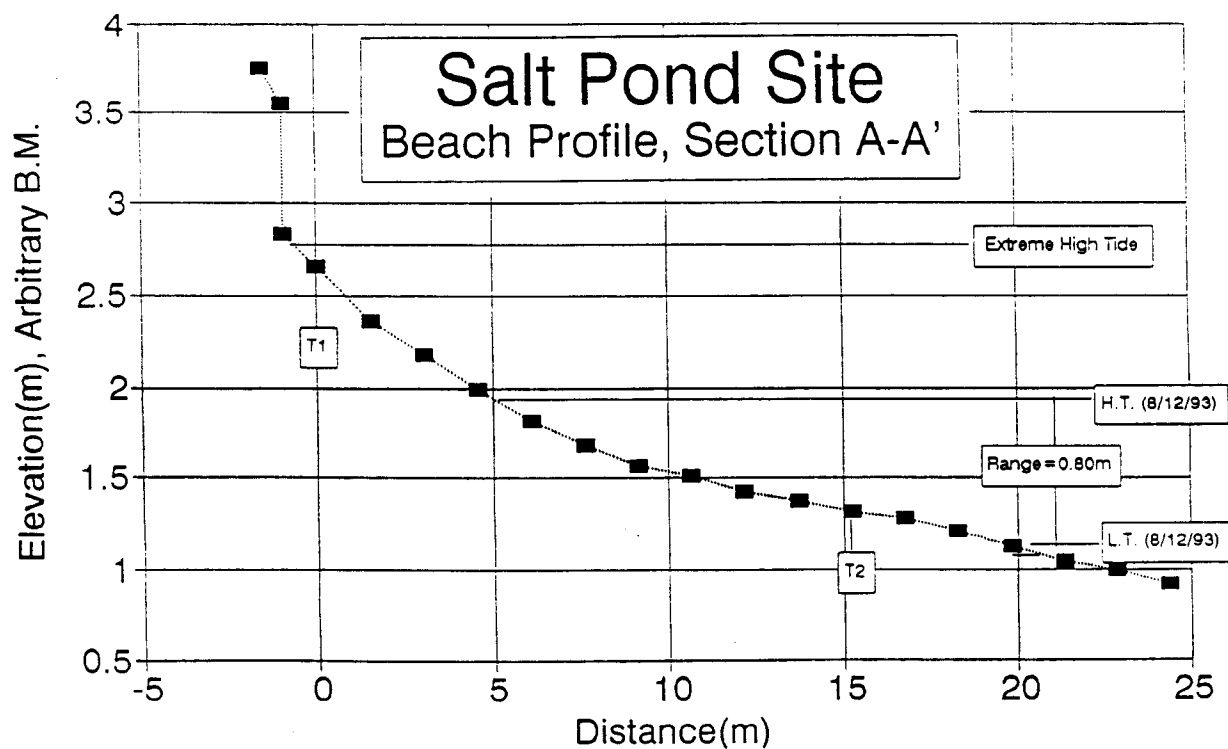
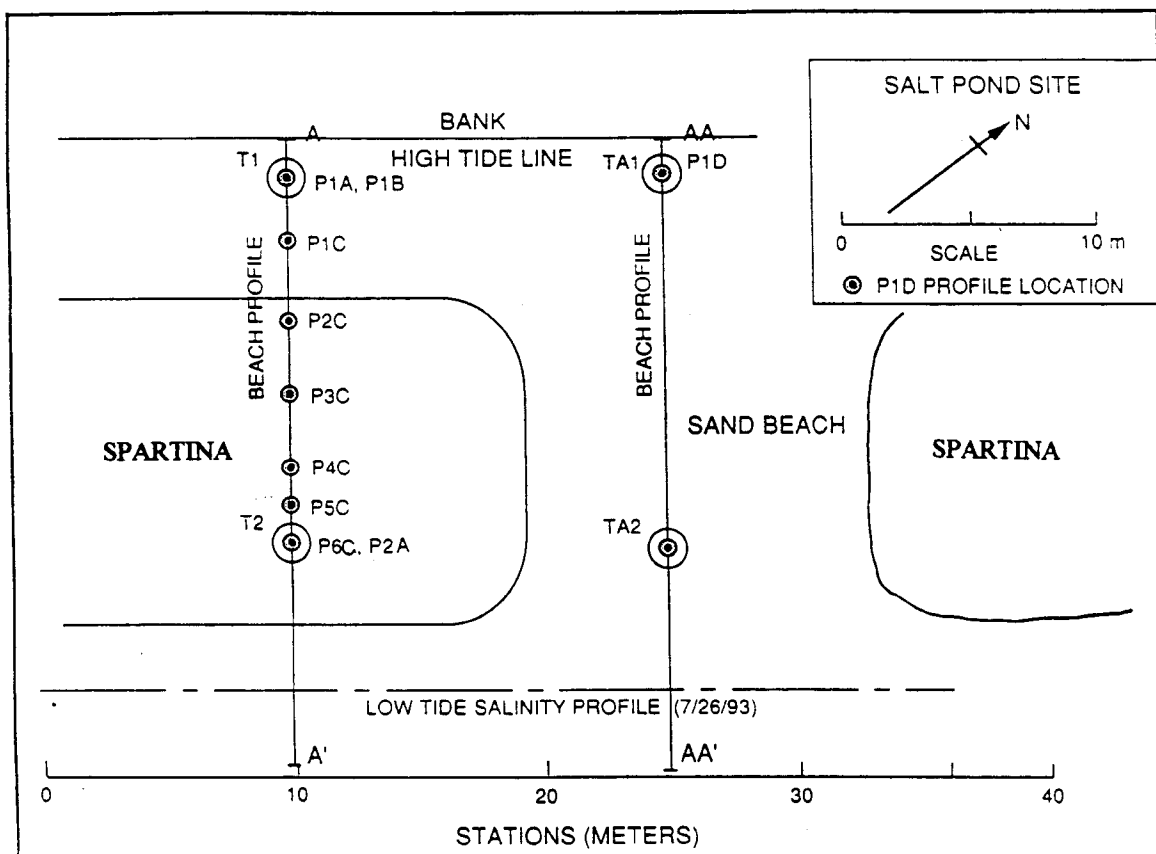
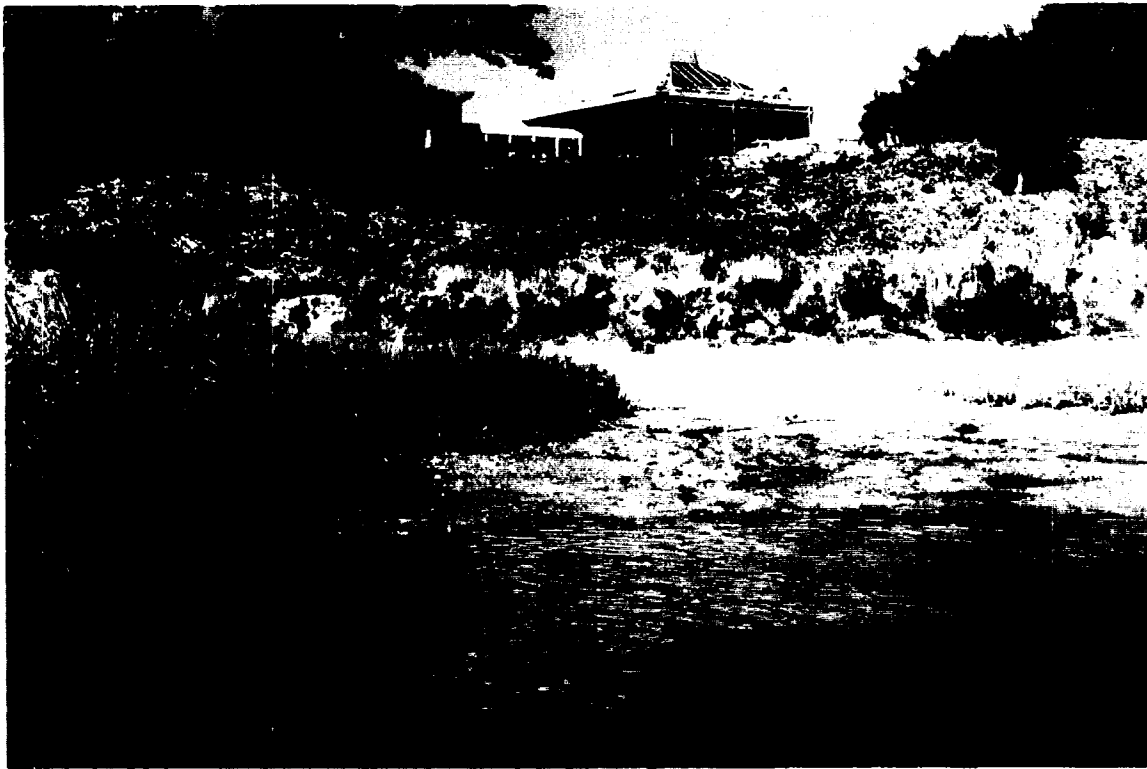


Fig. 1.5 Plan view and beach profile of Salt Pond Site



A) Beach face looking northwest.



B) Beach line looking northeast.

Fig. 1.6 Salt Pond beach photos.

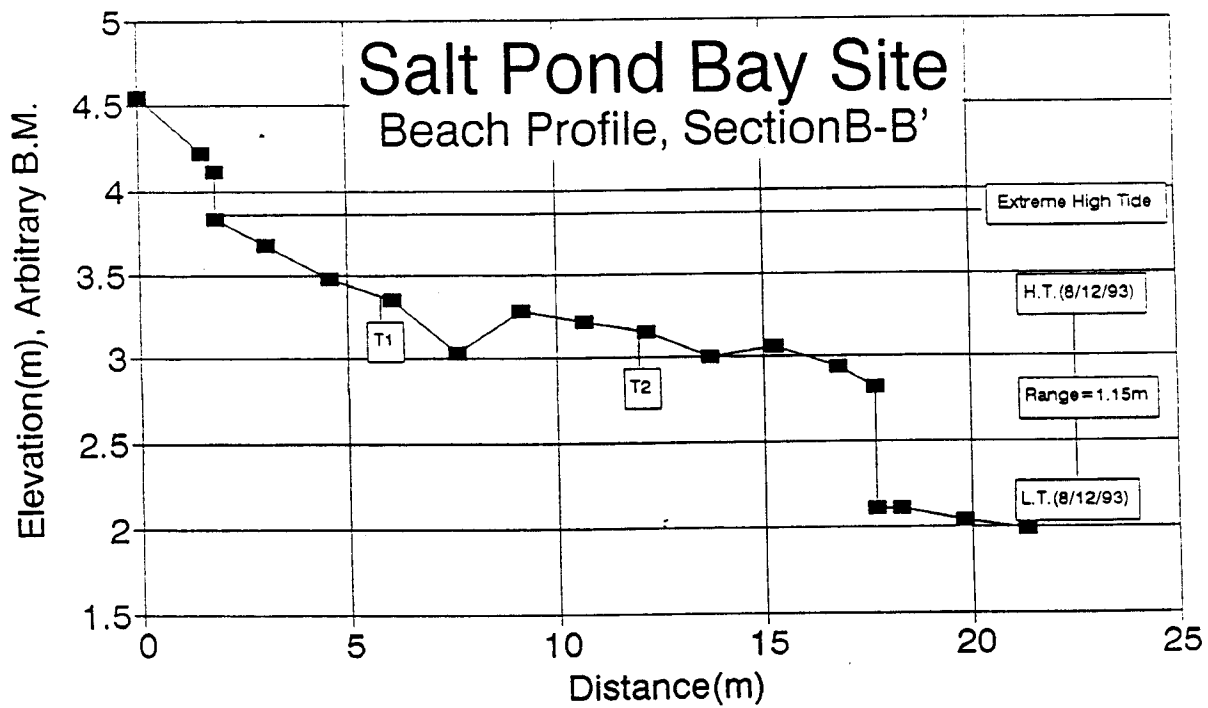
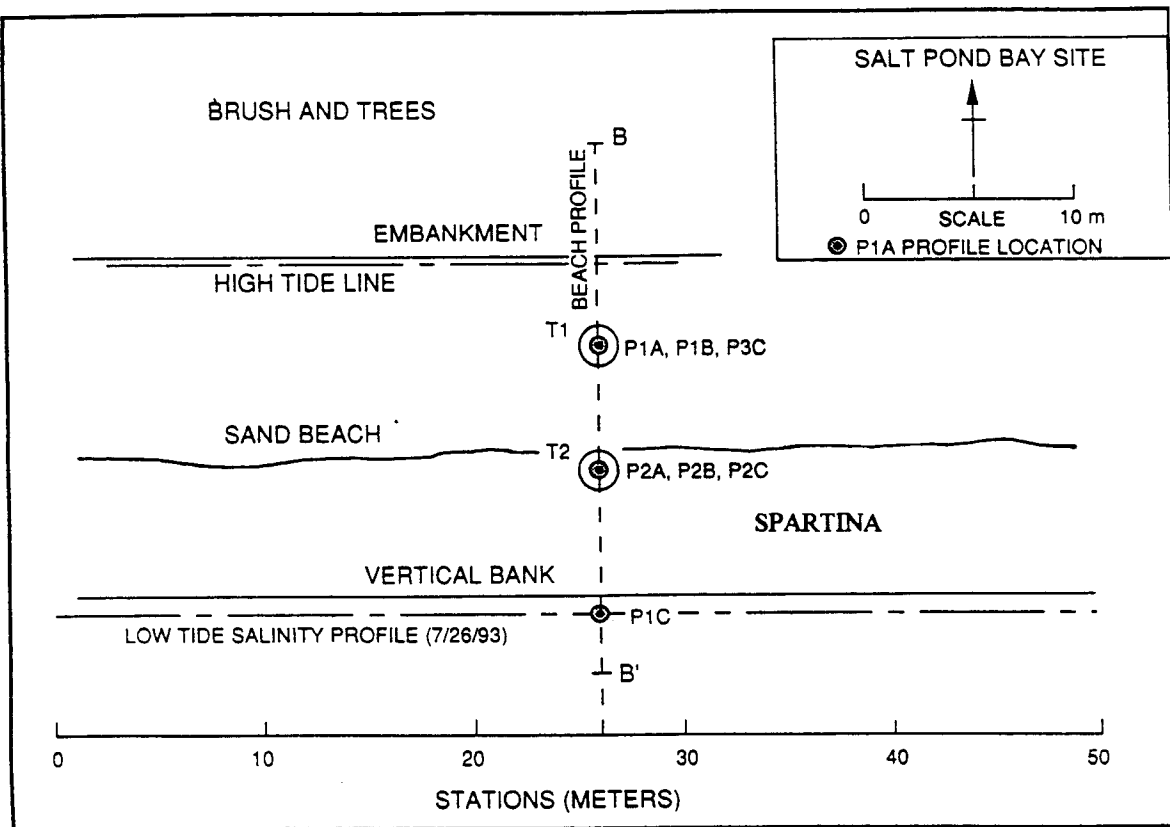


Fig. 1.7 Plan view and beach profile of Salt Pond Bay Site



A) Beach face looking northwest.



B) Beach line looking northeast.

Fig. 1 8 Salt Pond Bay beach photos .

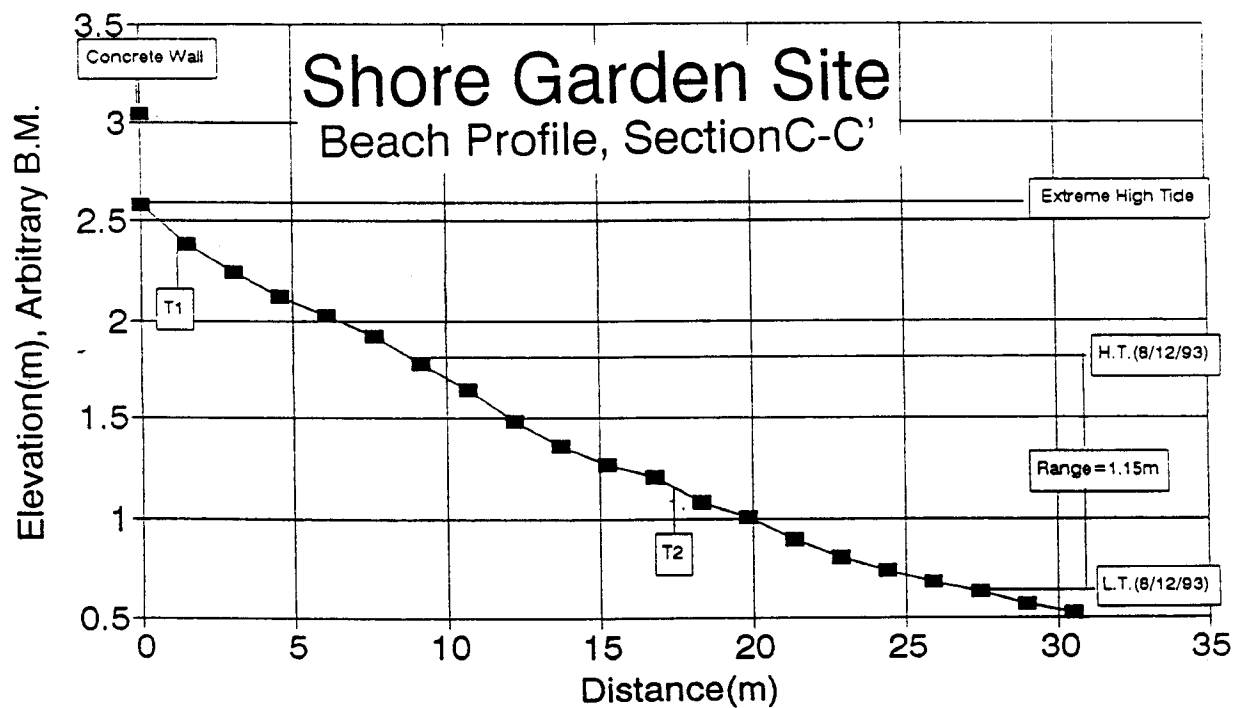
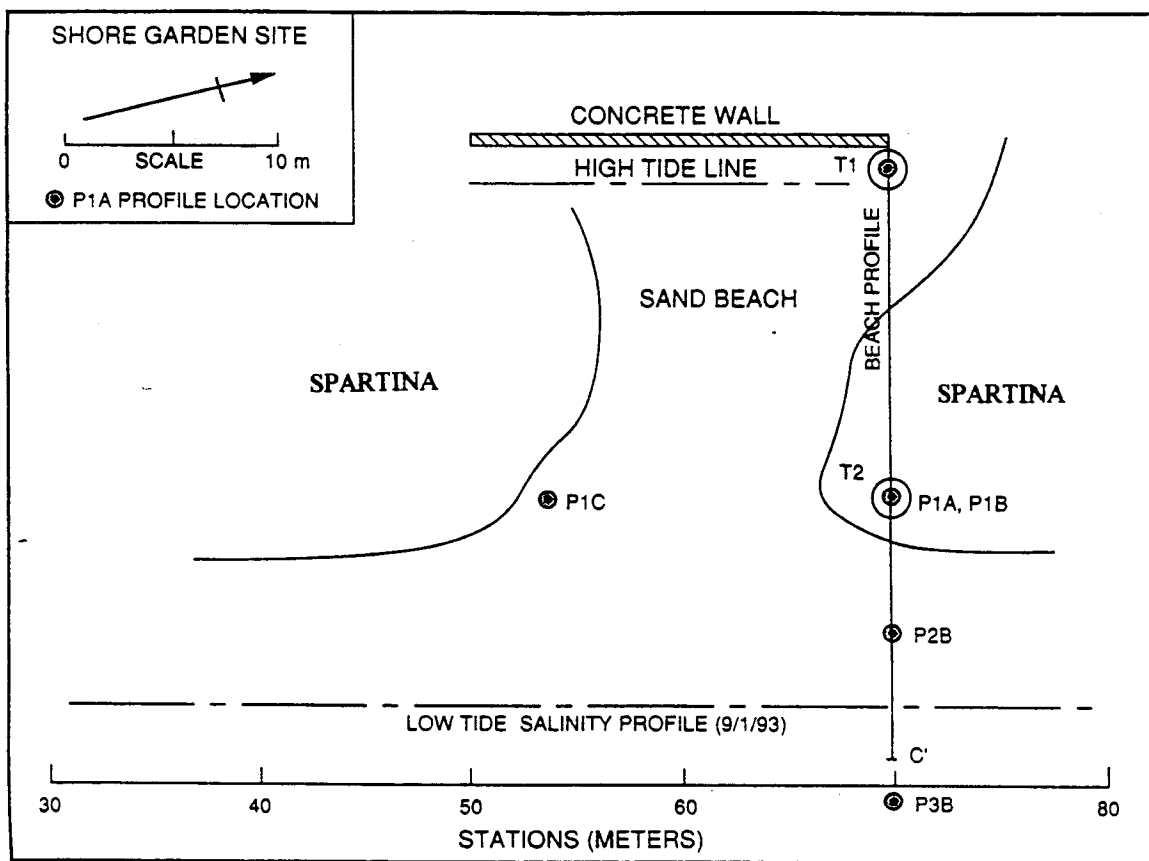


Fig. 1.9 Plan view and beach profile of Shore Garden Site



A) Beach face looking northwest.



B) Beach line looking northeast.

Fig 1 10 Shore Garden beach photos.

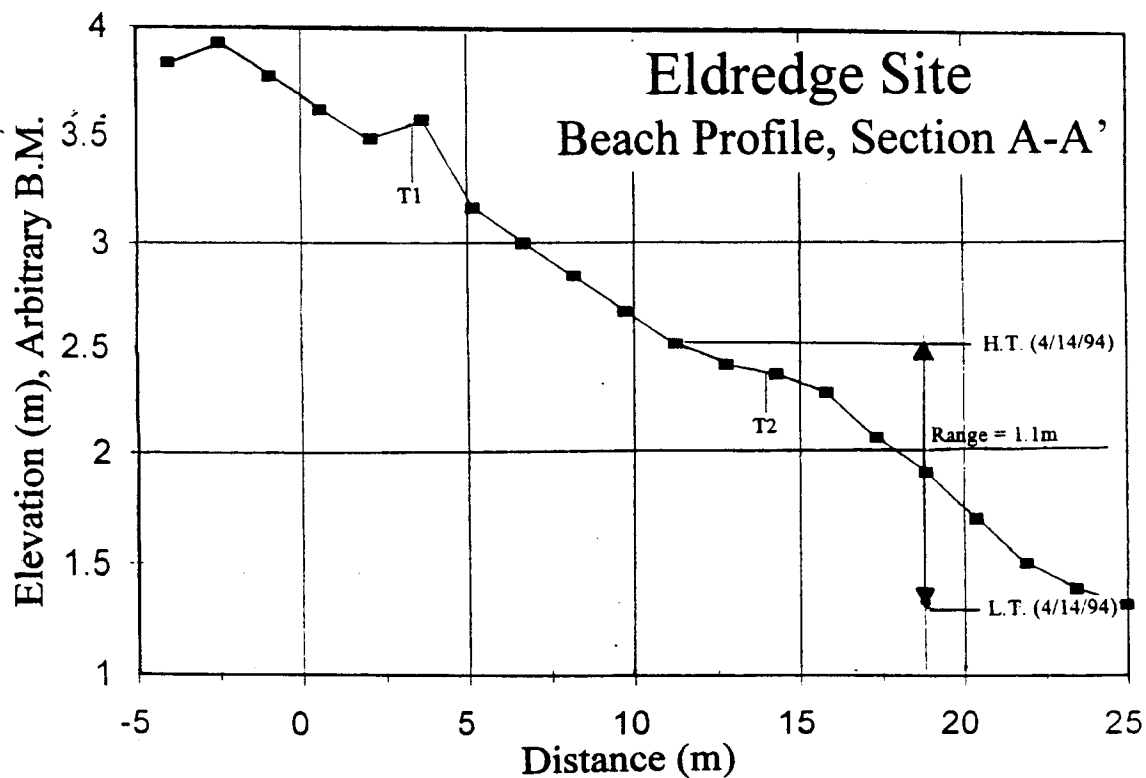
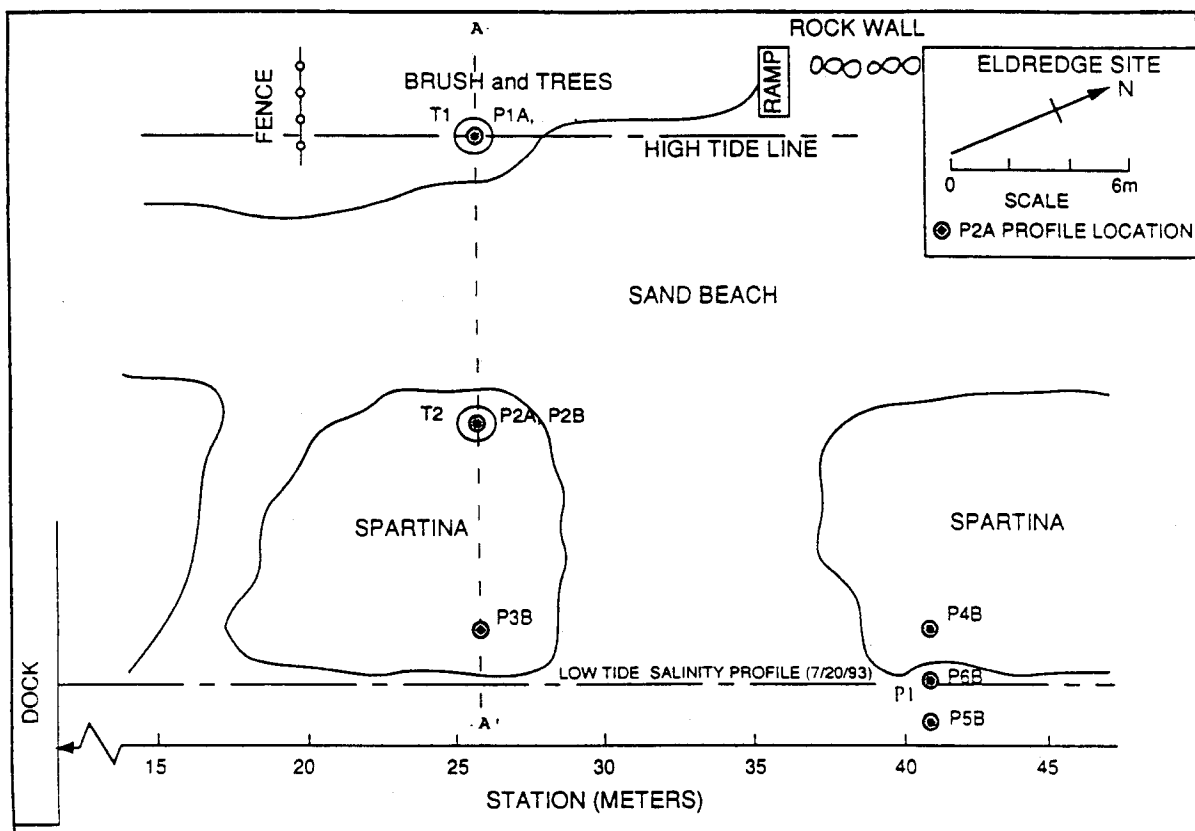
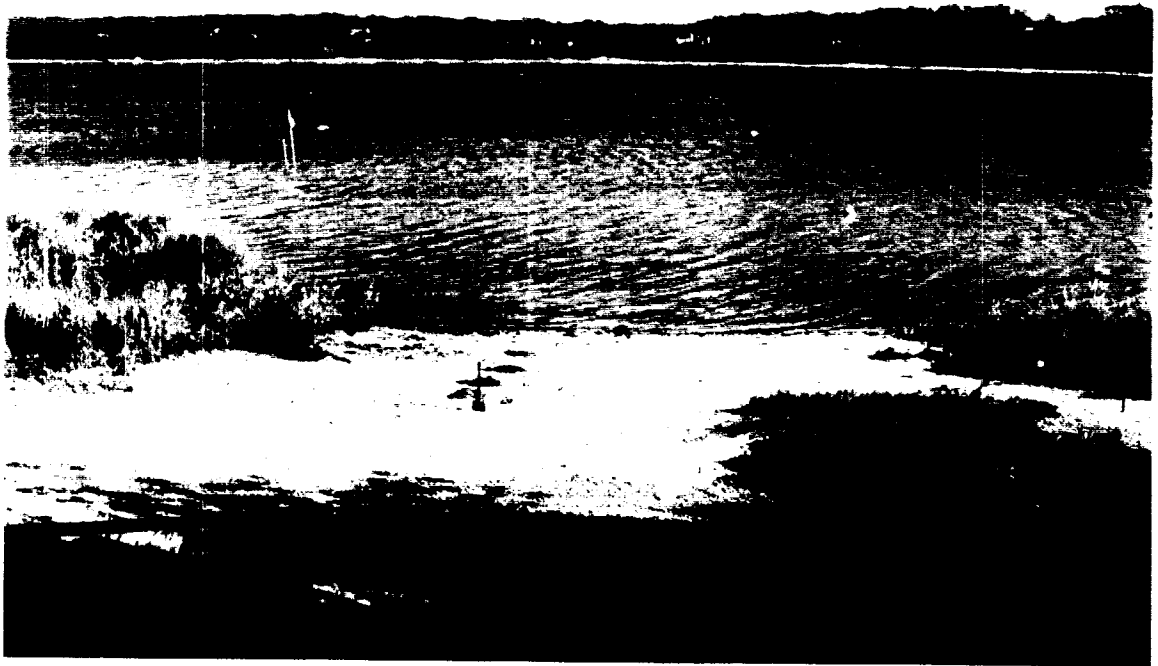


Fig. 1.11 Plan view and beach profile of Eldredge Site



A) Beach face looking southeast.



B) Beach line looking northeast.

Fig. 1 12 Eldredge beach photos.

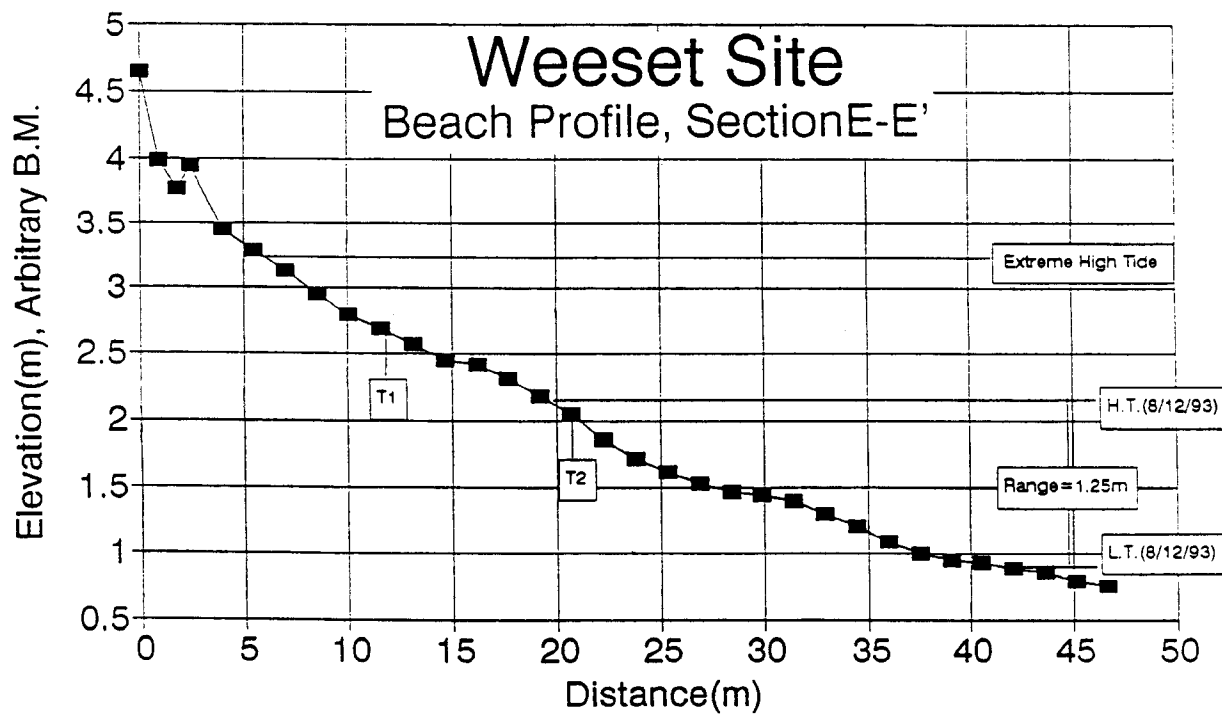
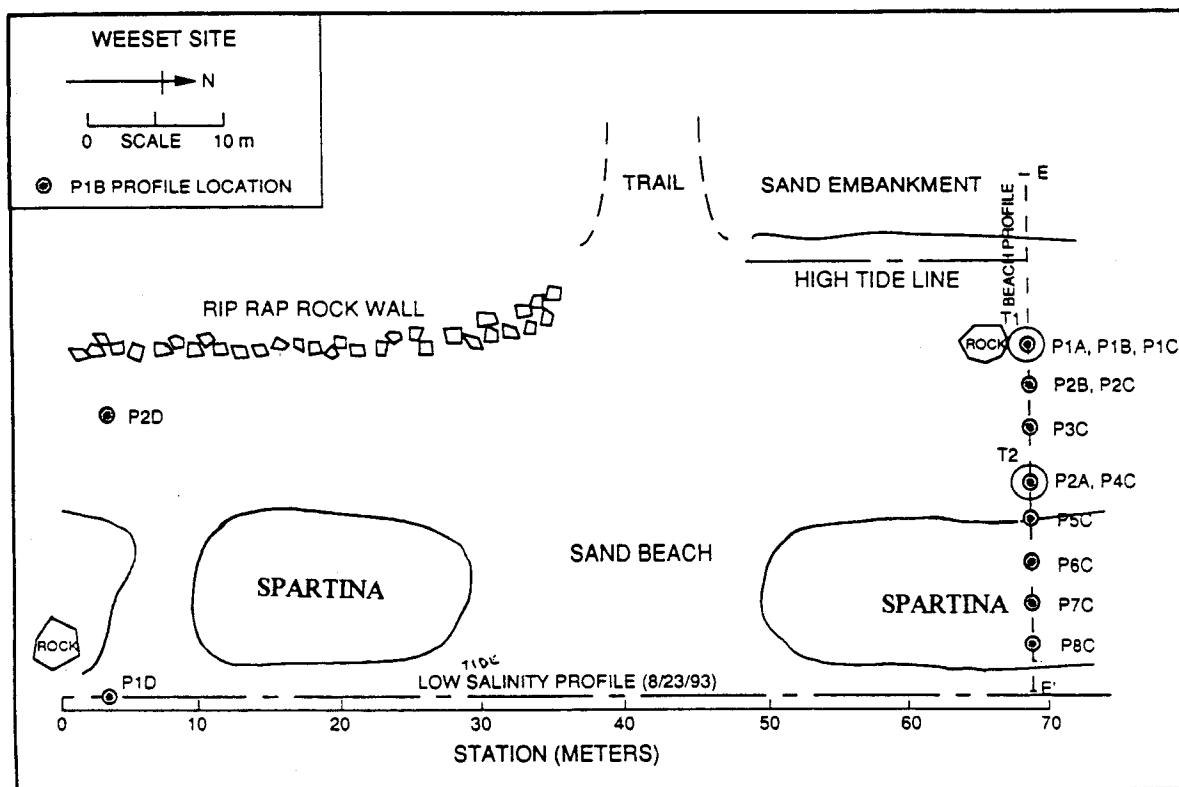


Fig. 1.13 Plan view and beach profile Weeset Site



A) Beach face looking east.



B) Beach line looking north.

Fig. 1.14 Weeset beach photos.

2 METHODOLOGY

2.1 Beach Hydrogeologic Parameters

Grain size distributions of beach sands were determined using standard ASTM sieve analysis procedures. Samples were oven dried and then passed through sieves to determine different grain size distributions by weight. The results were then plotted as distribution curves and the key characteristics of the sample determined.

The hydraulic conductivity of beach sand samples were determined using the "falling head" permeameter test. This involves passing a quantity of water through a measured sand sample while concurrently measuring the drop in hydraulic head as the water passes through the sample. Analysis of the resultant data provides a determination of the hydraulic conductivity. All values were standardized to 20° C.

The porosities of samples were measured using the "dry weight-volume" method. In this method a measured volume of oven dried sample is weighted. Using an assumed specific density for sample solids of 2.65, the volume of solids in the sample can be directly calculated. The remaining volume of the sample is then the volume of voids, from which the per cent of voids (porosity) in the sample can be readily determined.

2.2. Water Level Measurements

Water level measurements are essential for the determination of direction and magnitude of groundwater flow. In cases requiring limited measurements water levels were measured and recorded manually, while in cases involving continuous measurements, automatic data loggers (Environ-lab Model 150) with 5 and 15 psi pressure transducer probes were used.

2.2.1 Piezometer Installation and Monitoring

Sets of temporary piezometers were installed to measure the dynamics of the groundwater fluctuations with the tidal surface water fluctuations, and also to determine the groundwater gradient toward the bay. Measurements were taken in two ways:

1. Water level readings, which were taken using data loggers with pressure transducer probes. The transducers function is to transfer water pressure into electrical signals then to be sent to two data loggers through cables. To avoid atmospheric pressure interaction, each cable includes an atmospheric pressure compensating tube. Each data logger contains a memory where all the collected data was stored and then transferred to special computer software, which is able to transform the information into a spreadsheet format imported by QuatroPro computer program.
2. Manual readings using measuring tape and measuring the water depth from the top of the monitor wells. Then water elevations can be determined by subtracting these reading from the elevations of the predetermined monitor well tops.

In order to obtain long term monitoring capability for water quality and water levels during the period of study, two categories of monitor wells were installed:

1. Monitor wells consisting of 3.2 cm inside diameter PVC pipe fitted with 7.6 cm well screen.
2. Mini-wells consisting of 3.2 mm plastic tubing fitted with a small 1 inch aluminum cone at the bottom.

The 3.2 cm PVC pipe was placed to selected depths by first hand digging to the water table, then hand driving the pipe to the desired depth. The pipe screen was cleared and the well the well was pumped until clear water was obtained. To verify the proper functioning of the well the water level was measured and the rate of recovery was obtained. A rapid rate of recovery indicates a good aquifer communication and an ability of the well to respond to water table fluctuation. The mini-wells were installed at multiple depths at the same location creating in effect a nested series of sampling points at different depths.

2.2.2 Tide and Groundwater Measurements

In order to examine the time dependent relationship of the tide on beach groundwater discharge, detailed hydraulic studies were made at two of the locations, Sites B and D. Piezometers were placed along a transect in the beach face perpendicular to the shoreline. Water levels, indicating hydraulic head relative to the tide, were measured on 15 minute intervals over several tidal cycles using pressure transducers with an Environ-lab Model 150 data logger. Piezometers consisted of 3.5 cm inside diameter PVC well points with a 12 cm long screen set 45 cm below the beach face, and below the lowest position of the water table.

Measurements for the tidal and the groundwater fluctuations were taken as follows:

1. Surface water tidal fluctuations in Nauset Marsh were monitored over several tidal cycles using an automatic data logger with a pressure transducer to determine local mean sea level. Additionally, piezometer locations in the beach were used as long term points to determine the tidal fluctuation of the ground water as well as to sample the groundwater quality. Using pressure transducers, groundwater and tidal fluctuations were measured at 15 minutes intervals during several tidal cycles at three sites: Salt Pond (A), Salt Pond Bay (B) and Eldredge (D).
2. Special attention was given to the Salt Pond Site and the Eldredge Site to examine in detail the nature of groundwater discharge through the beach. At the Eldredge Site, based on the collected data from the low tide salinity profiles determined as described in Section 2.3, a fresh groundwater outflow location was chosen at a point 17 m north of monitor well PLA Nine 3.2 cm diameter monitor wells were installed along this line to monitor the groundwater

hydraulic heads from the upper beach towards the low tide groundwater discharge location. Monitoring at these locations was accomplished using pressure transducers and automatic data loggers during five tidal periods. At the Salt Pond Site a similar series of monitor wells perpendicular to the shore line were also installed and hydraulic data collected using pressure transducers and automatic data loggers.

2.2.3 Water Table Mapping

In order to delineate the groundwater flow path to the shore, a hydrogeological flow map was developed. This map was prepared based on the water table map prepared by Guswa and Leblanc, (1985) and further described by Barlow, 1994). Lines plotted perpendicular to the water table equipotential lines represent the groundwater flow paths. In areas not covered by equipotential lines, water table divide locations and flow paths were determined according to the probable water table levels and the ground topography. It is to be noted that much of the regional water table mapping is based on best judgement, not direct measurements. Field surveying for determination of elevation of ground and surface water at the specific study sites was referenced to the National Geodetic Vertical Datum (NGVD) of 1929 where possible. In other cases the reference datum is arbitrary, which allows for an accurate evaluation of each individual site, but does not permit a comparison of actual elevations between sites. Analysis was conducted to determine the flow paths to sites and assign boundaries for watershed sectors.

The entire Nauset watershed was divided into ten sectors as shown on Figure 2.1 based primarily on receiving water significance. That is, the groundwater discharged into a specific receiving water region can be determined by calculating the water budget of the adjoining land sector. For example the source of all water input into Salt Pond is Sector 2.

The amount of the discharged water from a specific area of interest was calculated from the following basic water budget equation:

$$Q = L \times W \times R \dots\dots\dots (2.1)$$

where:

Q = Average annual discharge (m³/year)

L = Length of the flow path from the divide to the seashore (m)

W = Width of the flow path (m)

R = Average annual recharge (40 cm/yr at Cape Cod)

2.3 Groundwater Sampling

In order to ascertain the distribution of salinity at the upper part of the water table and the seepage areas, shallow water quality sampling was done at a series of separated locations about 1 m to 1.5 m apart along transects both parallel and perpendicular to the beach line.

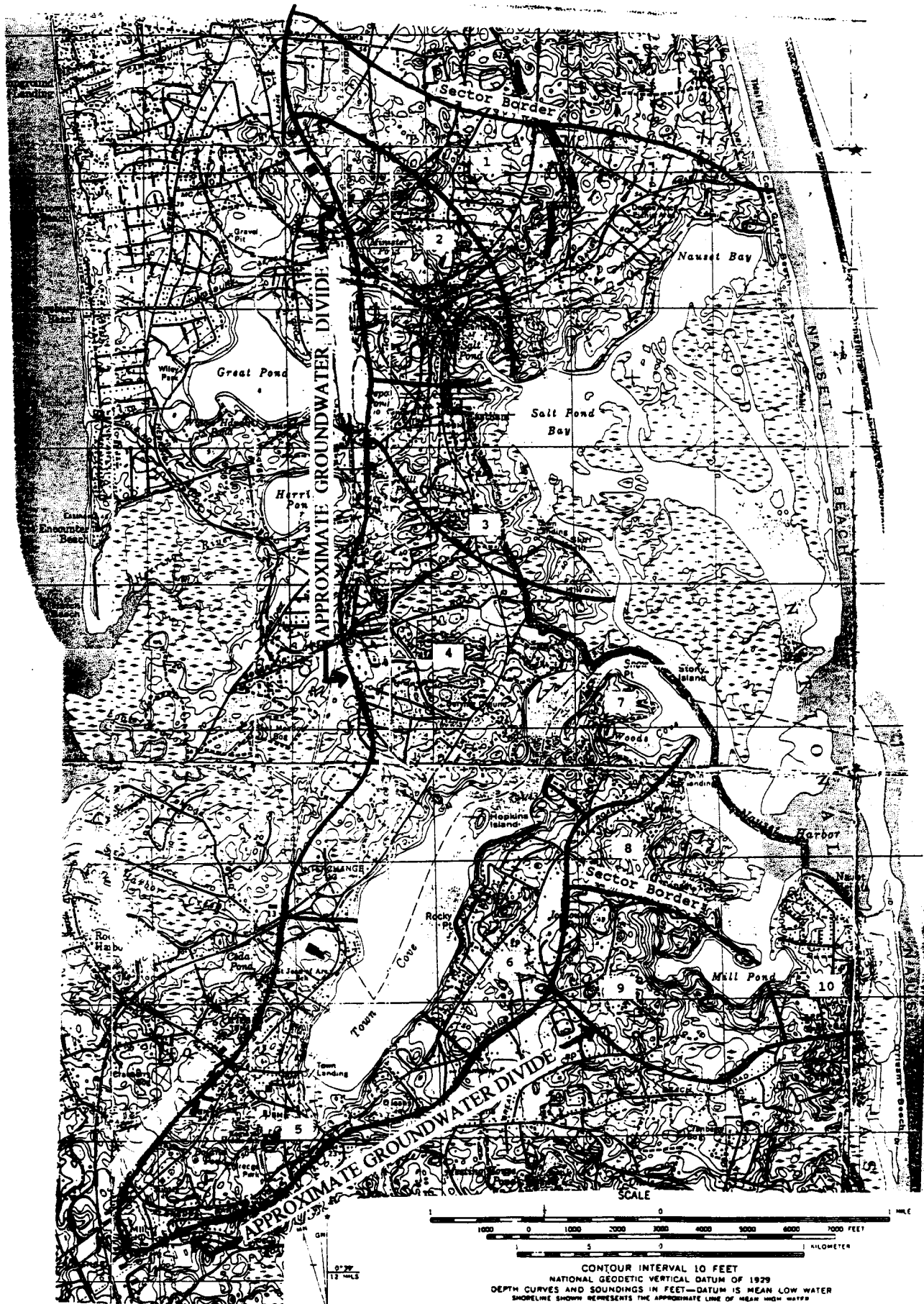


Fig. 2.1 Nauset Marsh watershed sector map

Samples were taken with a one meter long 3.2 mm diameter stainless steel tube with a small slotted tip which was inserted through the ground to the water table. A water sample was then withdrawn through this tube using a hand vacuum syringe attached to the other end. The water sample was extracted and the syringe was detached from the tube, and the sample was discharged on a hand held refractometer for salinity analysis. Some of the collected samples were sampled for nitrate-nitrogen and ammonium-nitrogen content by the National Park Service Biological Laboratory in Cape Cod. This process has been repeated at the sites for at least two different seasons of the year. The resultant data was then plotted and analyzed for trends in salinity, and nitrogen content.

In order to ascertain the vertical distribution of fresh and salt water in the beach zone, deep vertical profiles extending to four meters were made at selected locations. Temporary probe points were also used for depth profiling. These were typically 1.2 cm inside diameter PVC pipe, 1.34 m long with a 6.0 cm screen section at the bottom. Water samples were withdrawn from each location at about 0.34 m intervals with a hand operated vacuum pump. The samples were analyzed for salinity, electrical conductivity and temperature, and then plotted.

2.4 Groundwater Quality Measurements

2.4.1 Salinity, Electrical Conductivity and Temperature Measurements

Measurements of salinity, electrical conductivity, and temperature for groundwater samples were made at all sites. For rapid shoreline exploration, a field optical refractometer was used to determine salinity. Electrical conductivity was used as a more precise, though indirect, measure of equivalent salinity, particularly at low salinity values. The temperature was used to standardize readings to 25° C as well as to investigate the in situ temperature distribution. In addition to the field refractometer readings for salinity, measurements for temperature, electrical conductivity and salinity were made in the field using a YSI Model 33 meter.

2.4.2 Nitrogen Measurements

Groundwater samples were collected and analyzed for nutrient content by personnel of the Cape Cod National Seashore Biological Lab according to the following methodology (Portnoy, 1993). Water samples for nutrient analysis were collected in polyethylene bottles and stored at 4° C until analysis. Samples were filtered through 0.45 µm Millipore filters within 4 hours of collection. Samples were analysed for ammonium-nitrogen (NH₄-N) by the phenolate method within 6 hours of collection, and for nitrate-nitrogen (NO₃-N) by cadmium reduction within 36 hours. Nutrient analysis was conducted using a flow-injection autoanalyzer. Distilled water was used as the diluent and carrier solution.

2.5 Thermal Infrared Aerial Photography

Thermal infrared aerial photography was accomplished by Aero-Marine Surveys, Inc. of New London, Connecticut under contract with the National Park Service. This method works on the concept that waters of different temperatures emit different energy wave lengths. Additionally, in the case of fresh groundwater discharging along a coastline, the discharge will be more buoyant because

of its lighter density and tend to stay on the surface. The photography was done during a low tide event on 7 August, 1994 when groundwater discharge was greatest and temperature contrast between discharging groundwater and the warmer receiving water was about 7° C. This contrast is sufficient to delineate distinct zones of fresh groundwater discharge along coastline. Photographic runs were made at an elevation of 610 meters, and at two different times in order to ascertain the movement of the groundwater as it merges with the tidally affected receiving water; this enables the moving fresh water plume to be distinguished from permanent shoreline features which might also give a thermal signal.

3. RESULTS AND DISCUSSION

3.1 Beach Hydrogeologic Parameters

3.1.1 Comparison between sites

The basic hydrogeologically significant parameters of grain size, porosity and hydraulic conductivity were determined for representative beach sand samples from each of the five sites. The results are summarized in Table 3.1. Detailed grain size analysis results and hydraulic conductivity test results are contained in Appendix A.

There was wide variation in grain size and hydraulic conductivity between the sites. The highest hydraulic conductivity values of 124 m/day were found at the Eldredge Site (D) and the lowest, 0.5 m/day, at the Shore Garden Site, would be expected from the general Hazen equation relationship. The D_{10} and D_{50} grain sizes tend to follow the trend of hydraulic conductivity; in theory this should be a direct relationship between hydraulic conductivity and the square of the effective grain size. Except for the root mass sample from the Salt Pond Bay Site (B), the porosity shows relatively little difference between samples.

3.1.2 Effect of spring flow

In order to evaluate the effect of spring flow on grain size, additional analysis were conducted for three samples from the Eldredge Site, two from the spring area and one from the no-spring area. This is summarized in Table 3.2. It is noted that the average median grain size for the spring sample is 1.50 mm and for the no-spring sample it is 0.70 mm. As a general rule it is expected that finer grained material has a lower hydraulic conductivity than coarse grained material. Thus, discharge zones, or springs, will tend to form in the areas of higher hydraulic conductivity, and develop even greater permeability as fine grained material is washed out. Confirming results from the falling head permeameter test for a sample from a spring location at the Eldredge Site show that the hydraulic conductivity is 66 m/day. Calculations for hydraulic conductivity using Hazen's equation give values of 78 m/day for the spring location and 20 m/day for the no-spring location. Hence, the spring location has a capability for groundwater discharge almost four time that of the no-spring location.

Porosity determinations for samples has shown that the value of the porosity is between 0.22 to 0.34 with an average value of 0.30. Porosity values for the spring and the no-spring areas are 0.34 and 0.33 respectively.

Table 3.1 Site Soil Parameters Summary.

SITE (LOCATION)	SAMPLE	GRAIN SIZE				HYDRAULIC	
		D ₁₀ (mm)	D ₅₀ (mm)	Cu (1)	Cc (2)	POROSITY	CONDUCTIVITY (m/day)
A (Salt Pond)	1	0.21	0.69	4.05	1.09	0.31	4.3
	2	0.09	0.42	6.00	1.09	0.34	22.0
	3	0.18	0.60	4.19	1.07	-	-
B (Salt Pond Bay)	1	0.16	0.64	4.67	1.32	0.33	8.0
	2*	0.03	0.21	10.37	1.18	0.82*	13.3*
	3	0.11	0.41	12.73	0.58	-	10.5
C (Shore Garden)	1	0.20	0.42	2.60	0.73	0.30	18.0
	2	0.09	0.27	4.89	0.59	0.35	0.5
D (Eldredge)	1	0.30	1.20	6.67	0.94	0.30	80.0
	2	0.37	0.91	4.05	0.74	0.31	43.0
	3	0.25	0.80	3.80	1.05	0.32	45.0
	4	0.25	0.94	8.20	0.53	0.30	34.0
	5	0.38	0.90	2.89	0.92	-	125.0
	6	0.36	0.60	2.03	0.82	-	111.9
	7	0.35	1.90	8.82	0.63	-	105.6
E (Weeset)	1	0.28	1.04	7.68	0.87	0.25	54.0
	2	0.16	0.46	3.82	0.81	0.31	3.5
	3	0.16	0.50	5.00	0.70	-	22.1

- Notes: 1) Cu is uniformity coefficient equal to D_{60}/D_{10}
 2) Cc is correlation coefficient equal to $D_{30}/D_{10}D_{60}$
 3) *Root mass-sand-silt core sample.

Table 3.2 Eldredge Site Soil Parameters Summary.

Sample Location	Porosity n	d ₁₀ (mm)	d ₅₀ (mm)	K _{Hazen's eq} (m/day)	K _{permeameter} (m/day)
spring (averages)	0.34	0.3	1.5	78	66
no-spring	0.33	0.15	0.7	20	N/A

3.2 Groundwater-Surface Water Interactions

3.2.1 Groundwater-Tidal Relationships

Tide induced groundwater fluctuations are significant in that they affect both the boundary location as well as the timing of groundwater discharge. Additionally, tide measurements are a necessary component for evaluation of the flushing characteristics of receiving waters. The general pattern of coastal groundwater and tide fluctuation was examined in detail at the Salt Pond and Eldredge Sites. The results are shown in Figures 3.1 and 3.2 respectively and described in the following paragraphs.

Salt Pond Site (A) Water elevations at the Salt Pond were referenced to the 1929 National Geodetic Vertical Datum (NGVD) and measured for three days. The measuring location for groundwater was 10.0 m from the mean tide position. Inspection of the groundwater curve relative to the pond tidal curve in Figure 3.1 reveals that attenuation and lag time, as well as distortion, occurs as the tidal wave translates through the ground. Groundwater flow is generally in a line perpendicular to the beach and its direction (up or down the beach) can be ascertained by the relative position of curve points at any specific time. Thus, when the groundwater curve is higher than the tide, as at time 0.4 hours on 1 April, 1994, the groundwater flow is outward, but at time 0.7 hours the tide is at a higher level than the groundwater, resulting not only in a blocking of flow, but a reversal in direction as salt water infiltrates.

The coastal groundwater condition is therefore highly dynamic with the groundwater moving in the direction of the instantaneous gradient. A more quantitative evaluation will show that outward flow occurs more often than inward flow. Hence, there is a net groundwater outflow.

Eldredge Site (D) At the Eldredge Site elevations were referenced to an arbitrary benchmark since there was no readily accessible U. S. Geological Survey marker. A continuous tide and groundwater record was made for 7 days. The groundwater measuring location is about 15 m inland of a midtide location, 50 % farther than that of the measuring point at the Salt Pond Site. Thus, when Figure 3.2 is examined, it is observe that tide range attenuation and lag time are greater than that illustrated by Figure 3.1 for the Salt Pond Site, reflecting the distance factor. At the Salt Pond Site the range is attenuated to about 1/2 that of the tide, but at the Eldredge Site the range is attenuated

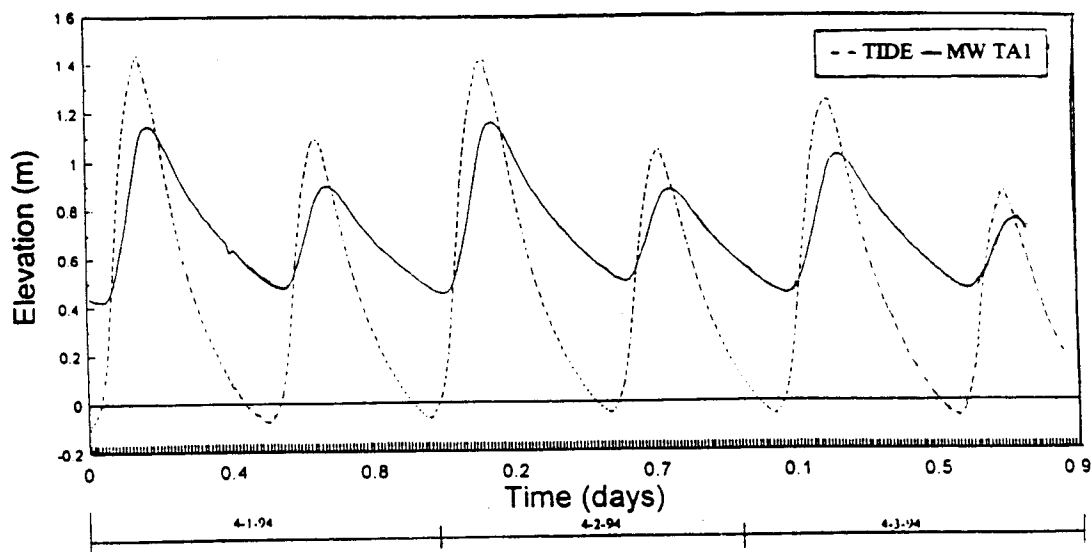


Fig. 3.1 Salt Pond Site (A) water elevations vs time (1-3 April, 1994)

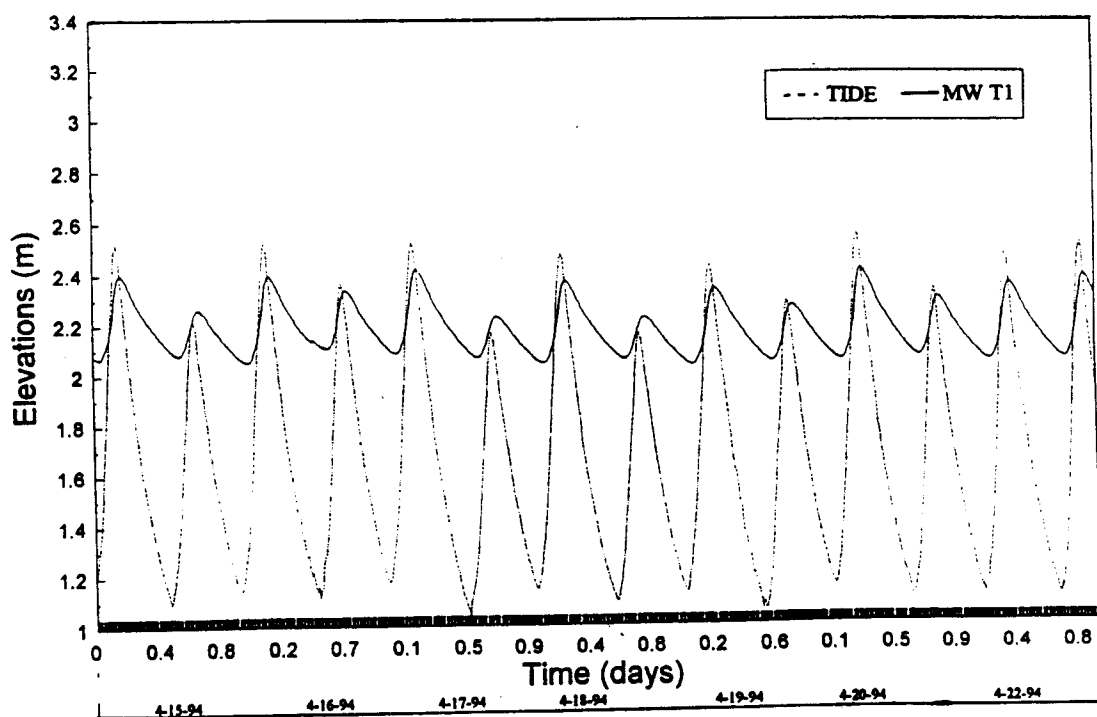


Fig. 3.2 Eldredge Site (D) water elevations vs time (15-22 April, 1994)

to about 1/4 of the tide. Also, because of the location farther up the beach, the flow at this location is reversed for a much shorter time, namely only at a diurnal high tide.

3.2.2 Salt Water Infiltration:

Monitor well water level measurements in the beach at the Eldredge site illustrate the relationships between beach groundwater and tidal waters during low and high tide episodes (Figure 3.3). Groundwater piezometric head measurements at the low tide line (location P1) and surface water elevations were monitored for seven days by automatic data loggers. During much of the period of monitoring both the groundwater head and the surface water elevations were higher than the ground surface elevation at this particular point (P1).

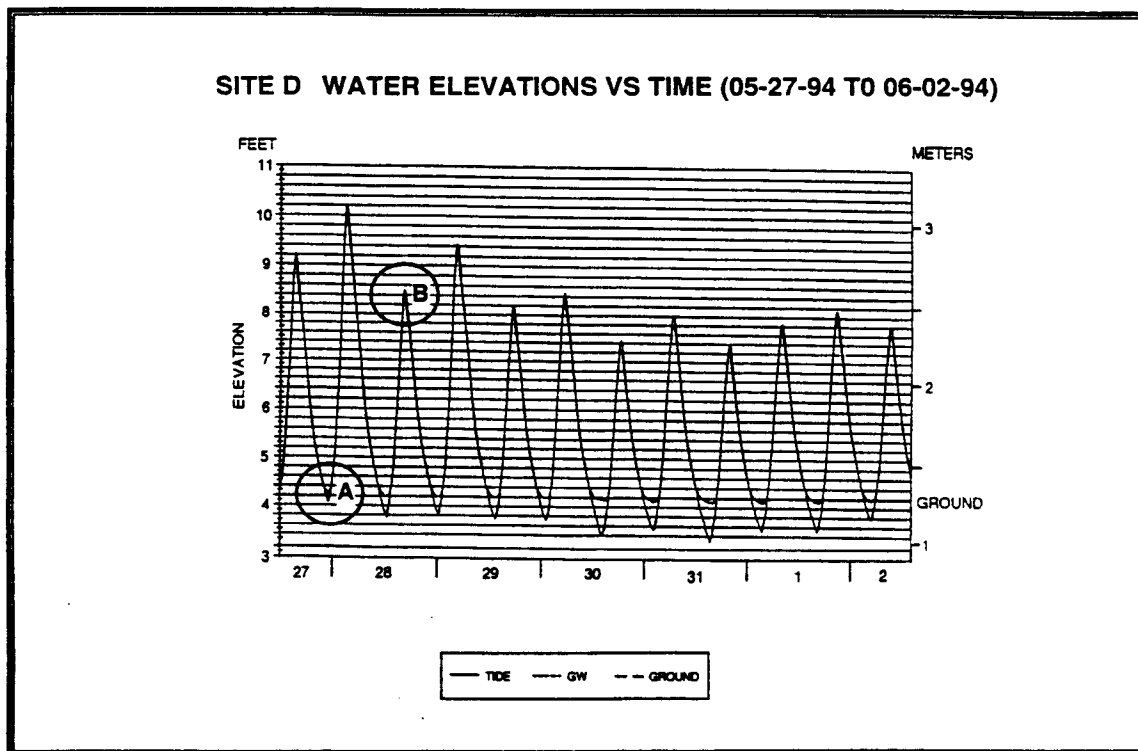


Fig. 3.3 Tide and groundwater elevations vs time at monitor well P1, Site D

Results from water level measurements made at Eldredge Site location P1 and the bay show that in order for salt water infiltration into the beach to occur two conditions need to exist, namely:

1. The salt water head has to be higher than the ground elevation, and
2. The salt water hydraulic head has to be higher than the groundwater hydraulic head.

It is apparent from examination of Figure 3.4 that salt water infiltration into the beach occurs

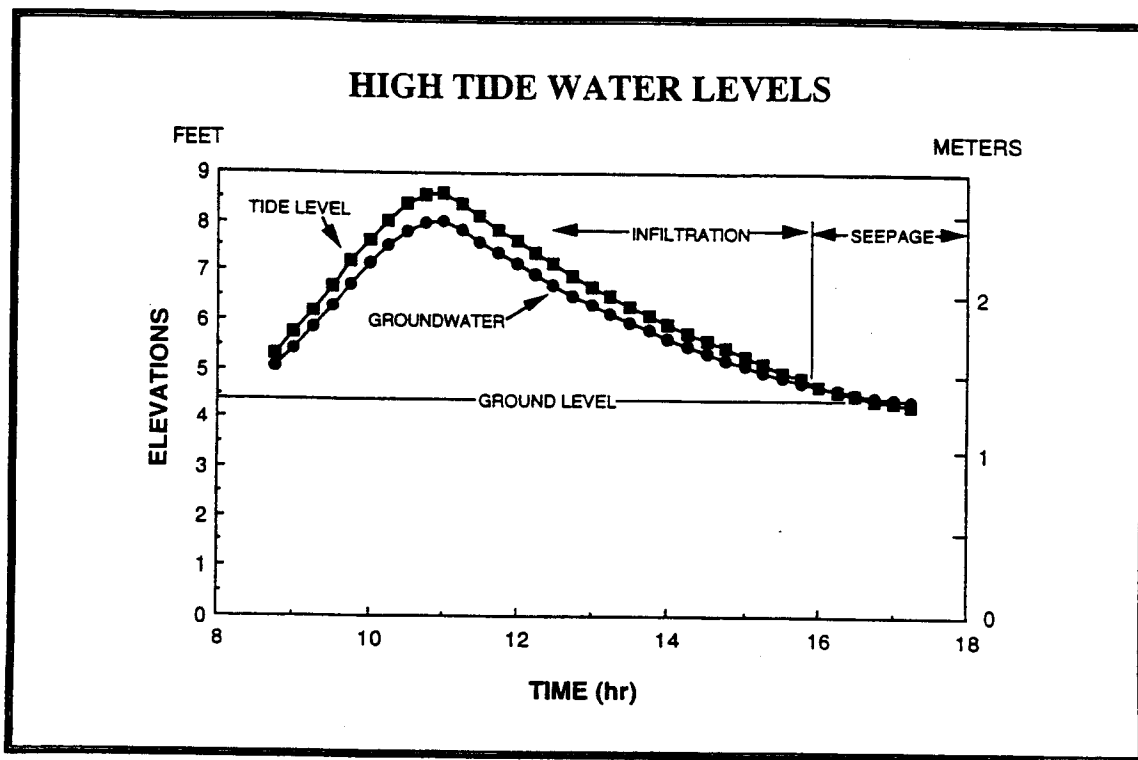


Fig. 3.4 Seepage-infiltration relationships at high tide at monitor well P1, Site D

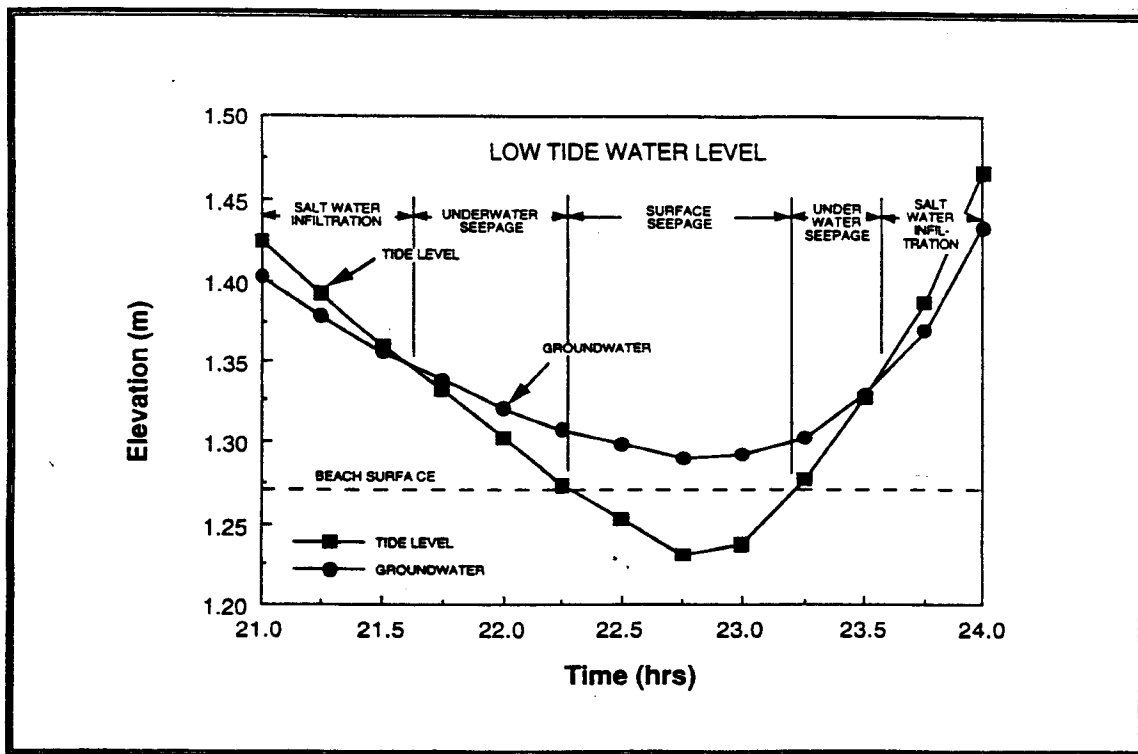


Fig. 3.5 Seepage-infiltration relationships at low tide at monitor well P1, Site D

during the high phase of the tidal cycle, namely time 8.0 and 16.0 hours. During this period the surface water hydraulic head is always higher than the groundwater head, thus according to Darcy's Law, flow will occur in the direction of the hydraulic gradient. This in turn causes a layer of salt water to develop over the previously outflowing freshwater.

3.2.3 Groundwater Discharge:

At the same point, P1, a specific period of monitoring were chosen to determine the groundwater seepage conditions. Figure 3.5 shows the hydraulic characteristics of the groundwater and the surface water at the low tide zone. This is summarized in stages as follows:

1. Prior to time 21.6 hours the surface water head is higher than the groundwater head and the beach surface, resulting in salt water infiltration.
2. From time 21.6 to 22.2 hours the groundwater head is higher than the tide level and the tide water elevation is higher than the beach surface elevation at this point, resulting in submarine groundwater outflow.
3. From time 22.2 to 23.2 hours the groundwater head is higher than the tide water level and the beach surface, but the tide level is lower than the ground elevation, resulting in surface seepage.

3.2.3.1 Groundwater Seepage Times:

Figure 3.6 shows a detailed plotting of the hydraulic head changes during a low tide period on the beach at monitor location P1 at the Eldredge Site. It is observed that the groundwater elevation for a time period of 2.25 hours is higher than the surface water elevations and also higher than the groundwater elevation. This causes a groundwater seepage phase to occur after an infiltration phase. As the seepage begins during an ebbing tide the infiltrated salt water from a previous high tide period will start to flow out and then fresh groundwater will flow to discharge. From inspection of Figure 3.5 it is apparent that the seepage of the groundwater occurs in two phases. The first is submarine seepage at the beginning and the second is beach surface discharge.

3.2.3.2 Groundwater Seepage Calculations:

To calculate the groundwater flow during the submarine seepage phase the net resultant hydraulic heads are calculated by subtracting the surface water elevations from the groundwater elevations which results in a variable hydraulic head. During the surface seepage the effective hydraulic head can be calculated by subtracting the groundwater elevation from the groundwater head. Figure 3.6 shows how the net resultant hydraulic head changes with time during the two phases. The average value of the hydraulic heads which causes groundwater seepage during this period is equal to 1.91 cm

Figure 3.7 shows how the discharge and the actual velocity changes with time. The groundwater discharge was determined for a one meter square area, using Darcy's equation as

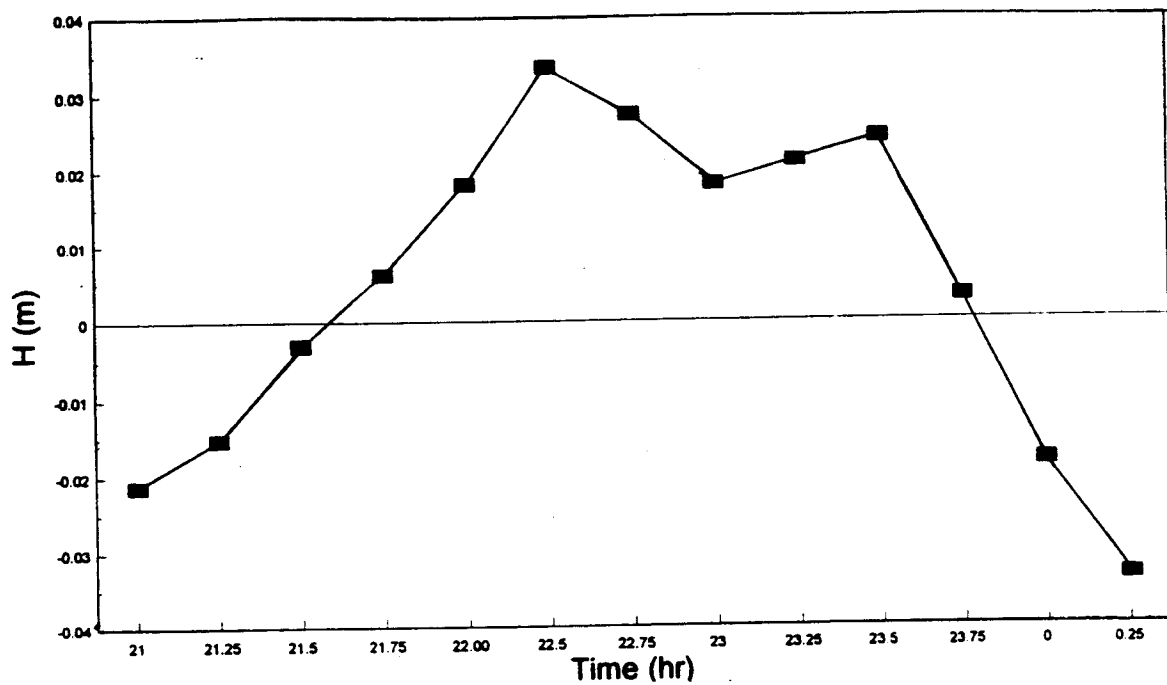


Fig. 3.6 Net resultant hydraulic head vs time at monitor well P1, Site D

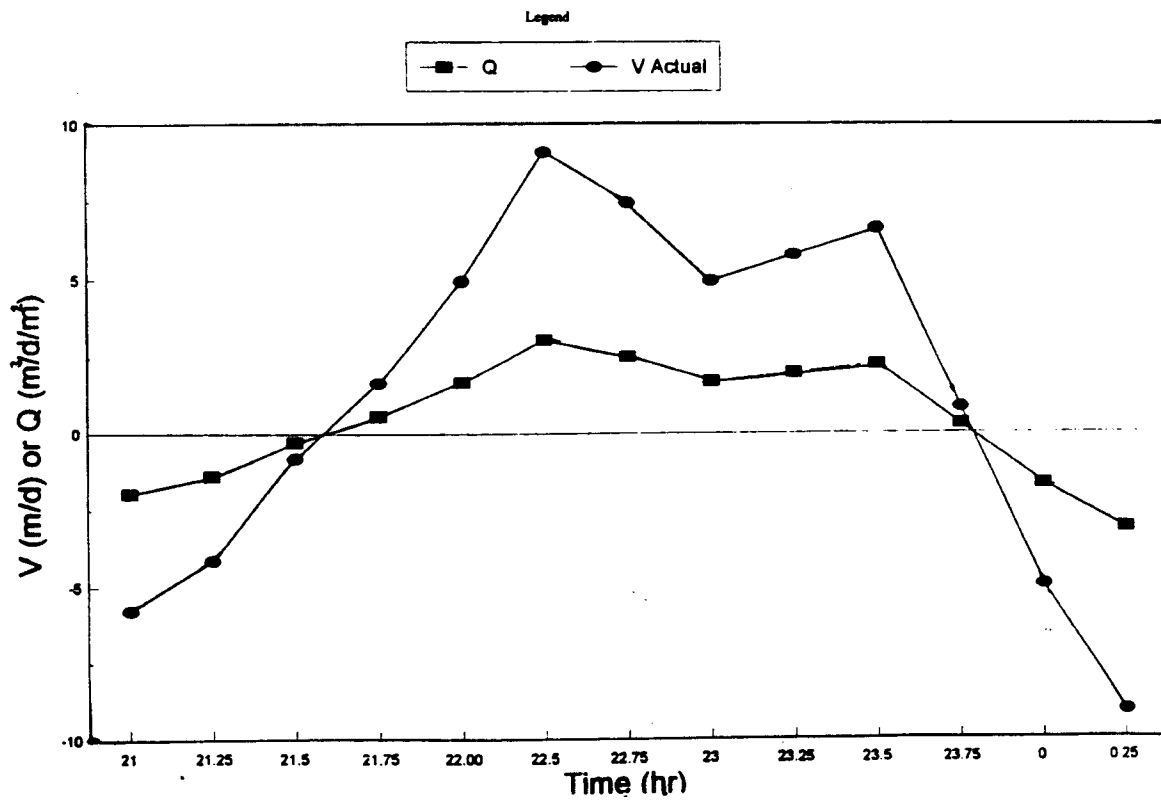


Fig. 3.7 Discharge and seepage velocity vs time at monitor well P1, Site D

follows:

$$Q = K I A \dots\dots\dots (3.1)$$

where:

K is hydraulic conductivity (m/day)

A is discharge area perpendicular to the flow line (m²)

and:

$$I = H/L$$

where:

L = Length of the flow path (m)

In this case the length, L, is equal 0.76 m, which to the distance from the ground surface to the center of the monitor well P1 screen.

The average hydraulic conductivity, $K_{Average}$, is equal to 70 m/day and the average porosity, n, is equal to 0.34.

therefore:

$$Q = (1.91 \text{ cm}/76 \text{ cm}) \times 70 \text{ m/day} \times 1 \text{ m}^2 = 1.76 \text{ m}^3/\text{day}/\text{m}^2$$

and:

$$V_{Actual} = K I/n = 1.76/0.34 = 5.16 \text{ m/day}$$

The calculated exit velocity represents the vertical component of the velocity which can be very close to the real velocity if the beach slope is small.

The volume of the groundwater outflow during the period of the seepage (2.25 hr) at monitor well P1 can be calculated as:

$$\text{Volume} = Q \times \text{Time} = 1.76 \text{ m}^3/\text{day} \times 2.25 \text{ hr}/24 = 0.165 \text{ m}^3$$

3.2.4 Temporal Pattern Of Groundwater Discharge

The temporal pattern of groundwater discharge was examined in detail for two sites, Salt Pond and Eldredge, by monitoring the relative tide and groundwater levels along the intertidal beach face during a tidal cycle. From these field measurements, along with the employment of the techniques for calculating groundwater discharge at any point, previously described, and overall view of the quantity and distribution of groundwater discharge along a beach can be ascertained.

A beach profile of the Salt Pond Site showing the placement of piezometers for water level monitoring is shown in Figure 3.8. also shown is the location on the beach face of high and low tides during the measuring period. Figure 3.9 shows plots of water table fluctuations at the various piezometer locations as well as the tide. When the shape characteristics of these curves are reviewed

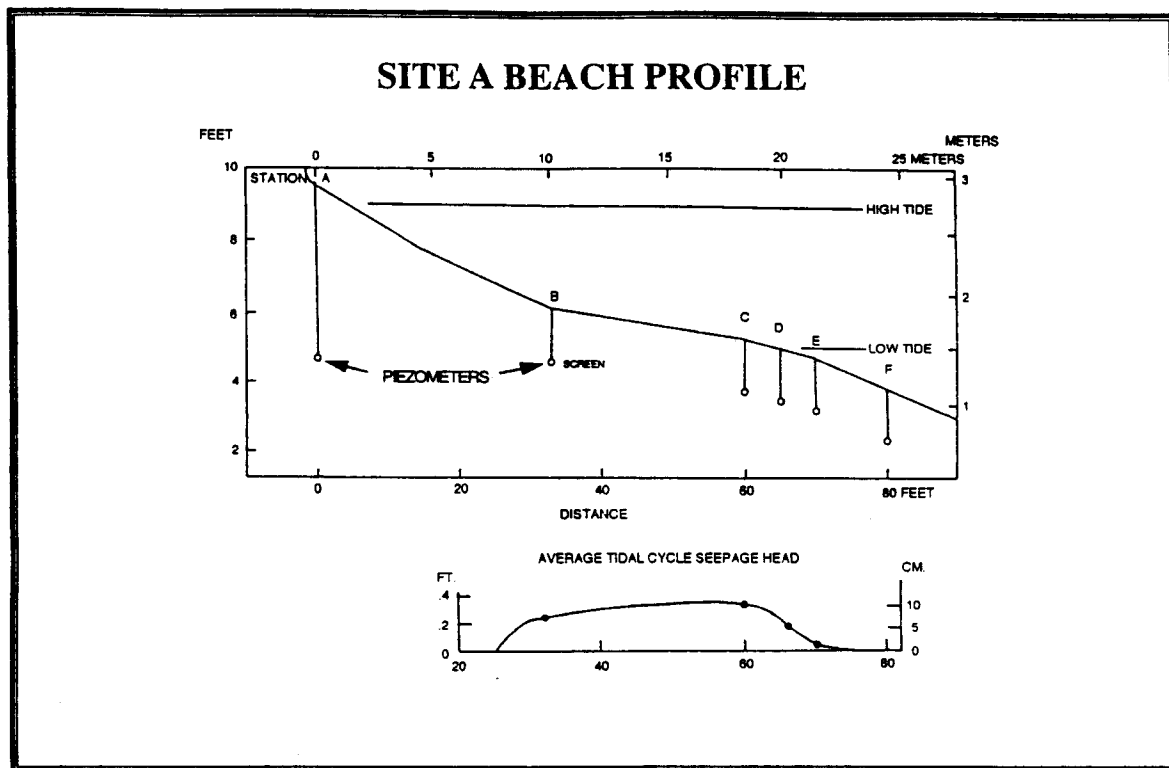


Fig. 3.8 Beach profile and seepage plot, Site A (July 26, 1994)

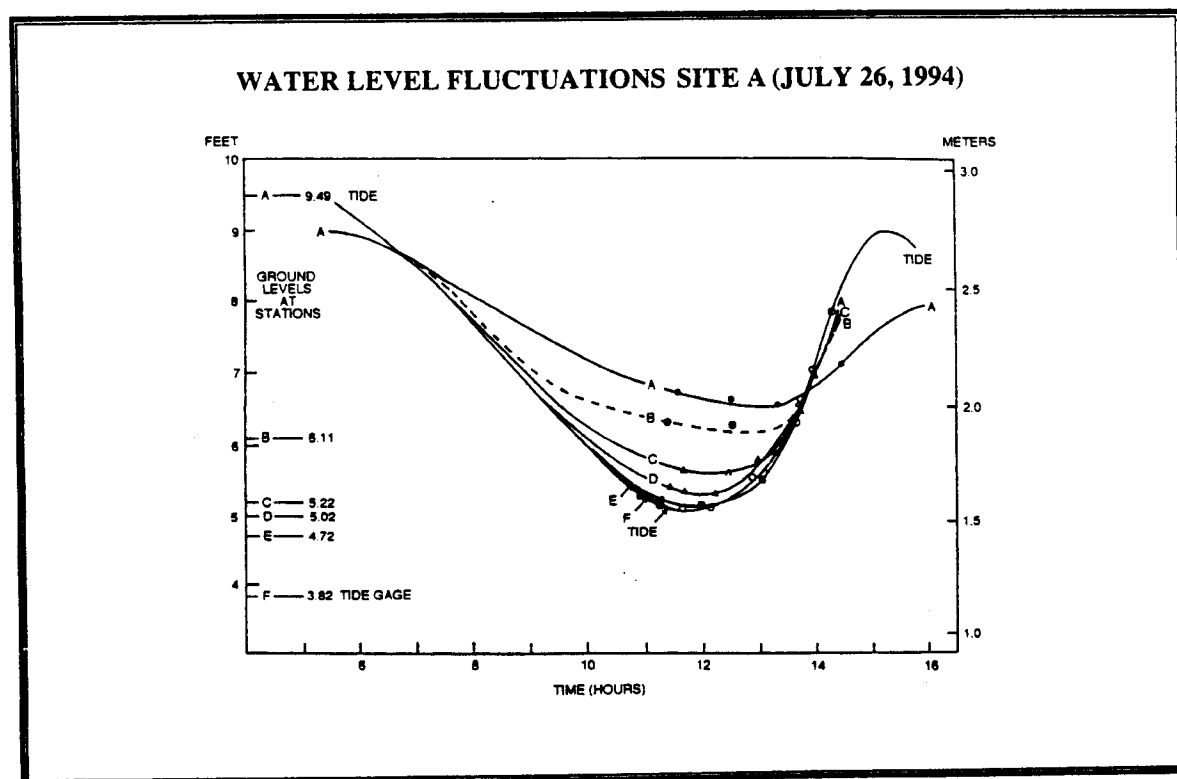


Fig. 3.9 Tide and groundwater fluctuations, Site A (July 26, 1994)

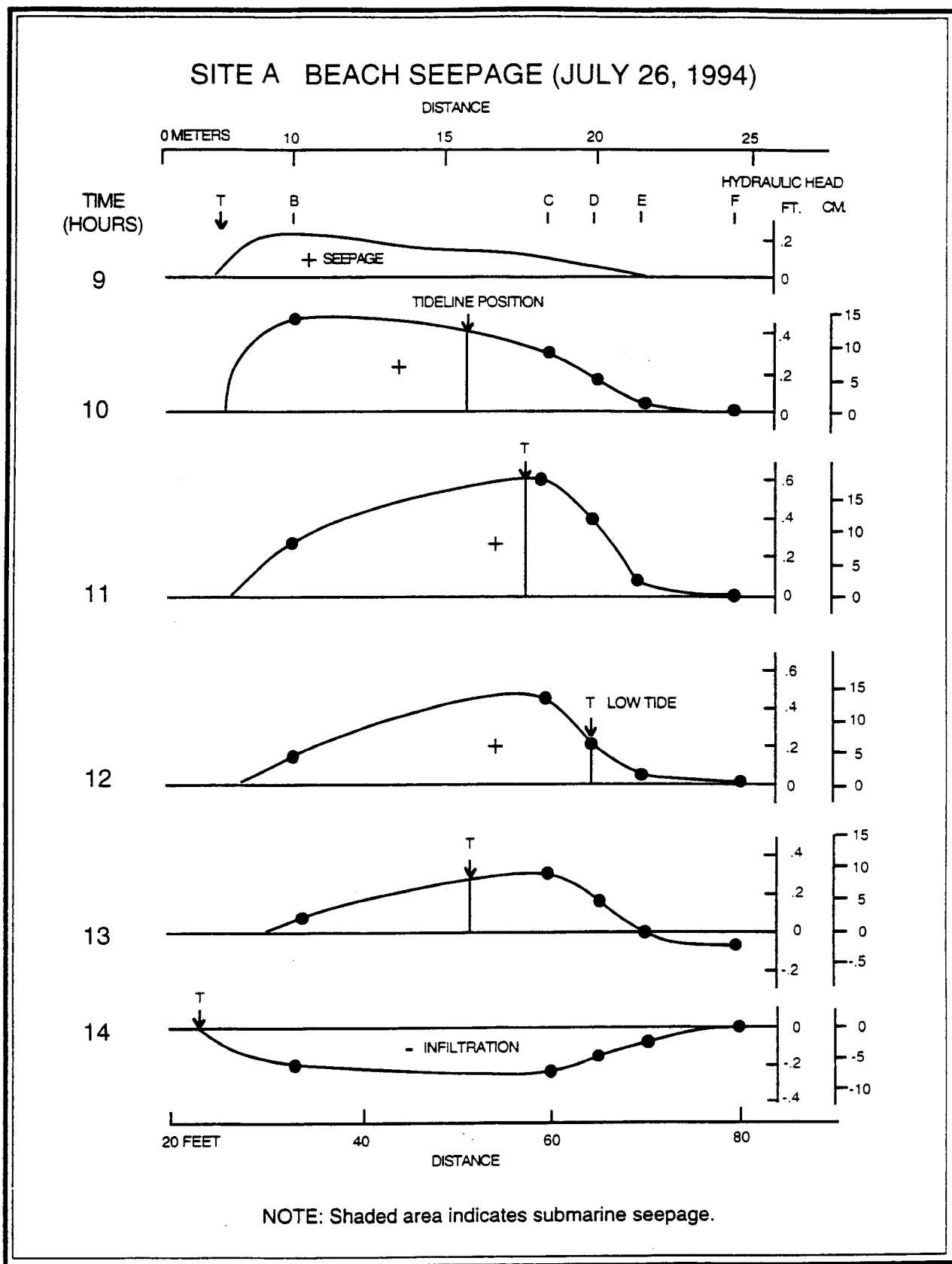


Fig. 3.10 Beach groundwater seepage during lower part of tidal cycle, Site A (July 26, 1994)

relative to their position in the beach, the sequence of lag time and tide attenuation are apparent.

A time sequence of plots (Figure 3.10) of the magnitude of net hydraulic heads along the beach face over the lower part of the tidal cycle provides an overview of the time-space pattern of groundwater discharge. When these sequential plots are integrated into a single plot (inset plot in Figure 3.8) by averaging hydraulic heads along the beach, the location and relative magnitude of groundwater discharge during this tidal cycle is apparent. From further analysis of Figure 3.10 the time and nature of the discharge can be ascertained. The shaded areas show when and where submarine discharge occurs. In the case of Site B, as shown in the inset plot of Figure 3.8, the discharge occurs over a distance of about 15 meters and during a 4 hour time period, but with strongest seepage occurring during the 2 hours of lowest tide. Submarine seepage extends some 2 meters seaward.

A similar field study was done at the Eldredge Site. Figure 3.11 shows the beach profile for this site and Figure 3.12 presents the water level fluctuation curves. The temporal pattern of beach seepage is illustrated in the plots of Figure 3.13. It is to be noted that at this location a larger amount of groundwater discharge occurs as submarine seepage than is the case at the Salt Pond Site.

As shown in the inset plot of Figure 3.11, the discharge occurs over a distance of 9 meters and a time duration of about 4 hours. The time duration of discharge and length of discharge zone are primarily a function of the vertical hydraulic conductivity of the beach, the rate of groundwater discharge, the tide range and the beach slope.

It is to be noted that the beach slope itself is a result of the rate of recharge. That is, greater flow tends to reduce the intergranular pressure (or stability) of sand grains. This in turn causes the loss of particles, particularly the fine grain sizes. This is manifested as a flatter beach slope in the discharge zone than at the upper beach. This discharge zone feature was noted at other beaches by Turner, 1993. At the Salt Pond Site this break in slope occurs at the 10 m position, and at the Eldredge Site, at the 17 m position as located on the respective beach cross-section figures.

The general pattern of beach groundwater discharge and salt water infiltration is shown in Figure 3.14 which illustrates the tidal-hydrological cycle. Beginning at high tide fresh ground water is prevented from discharge by a tide induced hydraulic dam, and salt water infiltrates into the beach. With an ebbing tide both fresh and salt water move toward the beach. Initially, most discharge is salt water then changes to brackish, and if sufficient fresh groundwater flow is present, the discharge will be fresh at low tide. However, in spite of the higher density of salt water than the underlying fresh water the intertidal beach zone tends to retain an upper layer of the infiltrated salt water immediately shoreward of the discharge zone. With a flooding tide the hydraulic gradient is again reversed, blocking the discharge of groundwater and beginning the process of salt water infiltration into the beach. Numerous vertical profiles of salinity in the intertidal beach have validated this concept.

The salinity of the discharge varies with location and with time. The freshest discharge, with a salinity of 2 ppt, occurred at low tide at the location of maximum seepage, while the least fresh was at the beginning of the discharge period. The early discharge includes considerable flushing of sea water which has infiltrated into the beach during high tide.

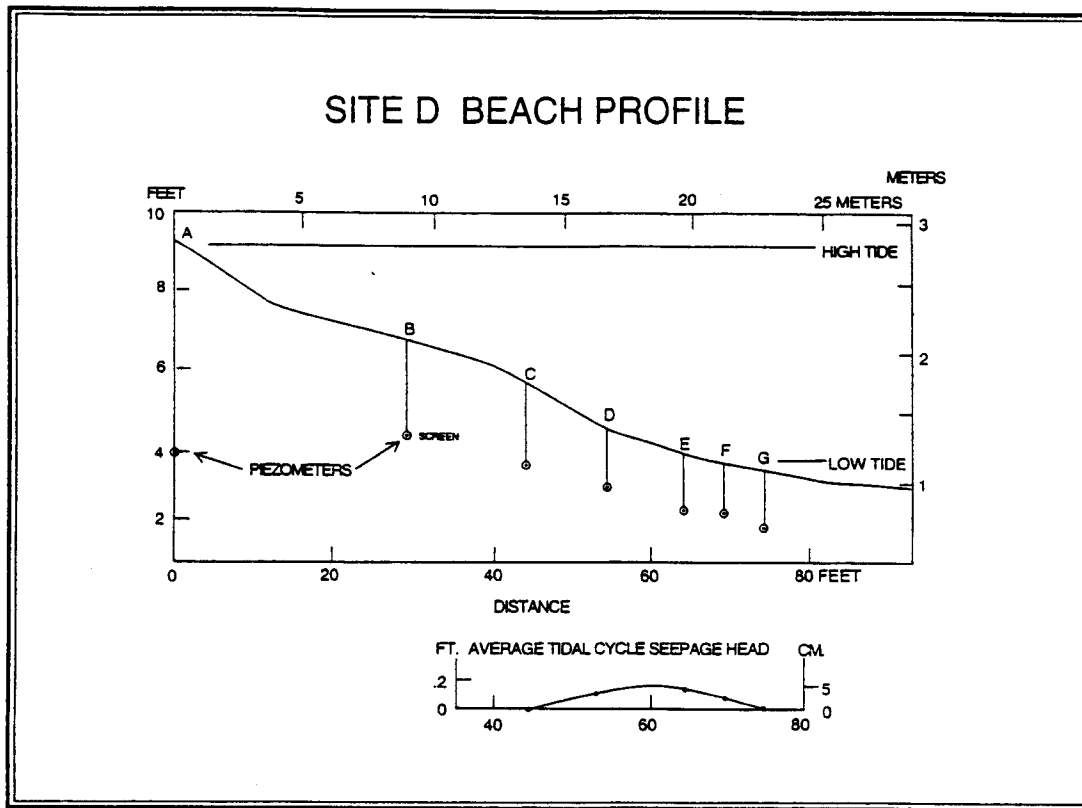


Fig. 3.11 Beach profile and seepage plot, Site D (Sept. 12, 1994)

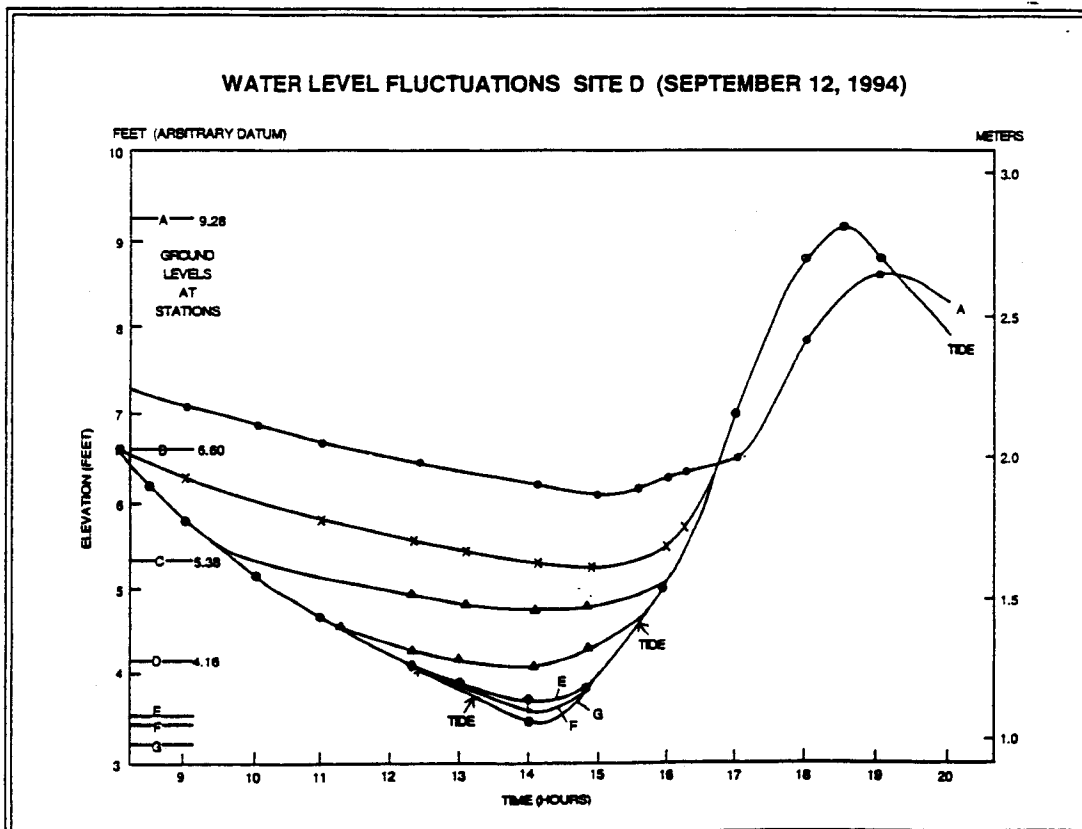
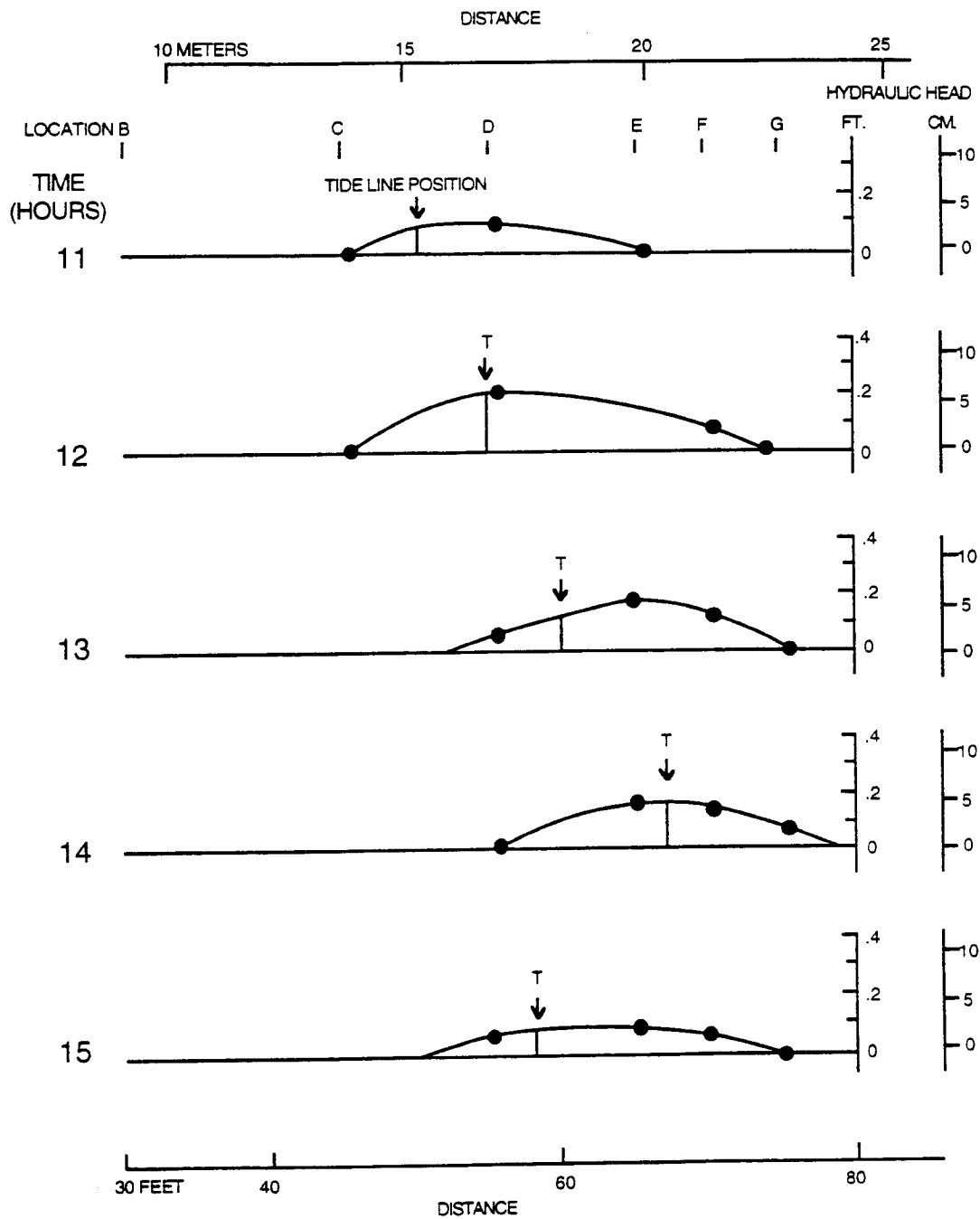


Fig. 3.12 Tide and groundwater fluctuations, Site D (Sept. 12, 1994)

SITE D BEACH SEEPAGE (SEPTEMBER, 1994)



NOTE: Shaded area indicates submarine seepage.

Fig. 3.13 Beach groundwater seepage during lower part of tidal cycle, Site D (Sept. 12, 1994)

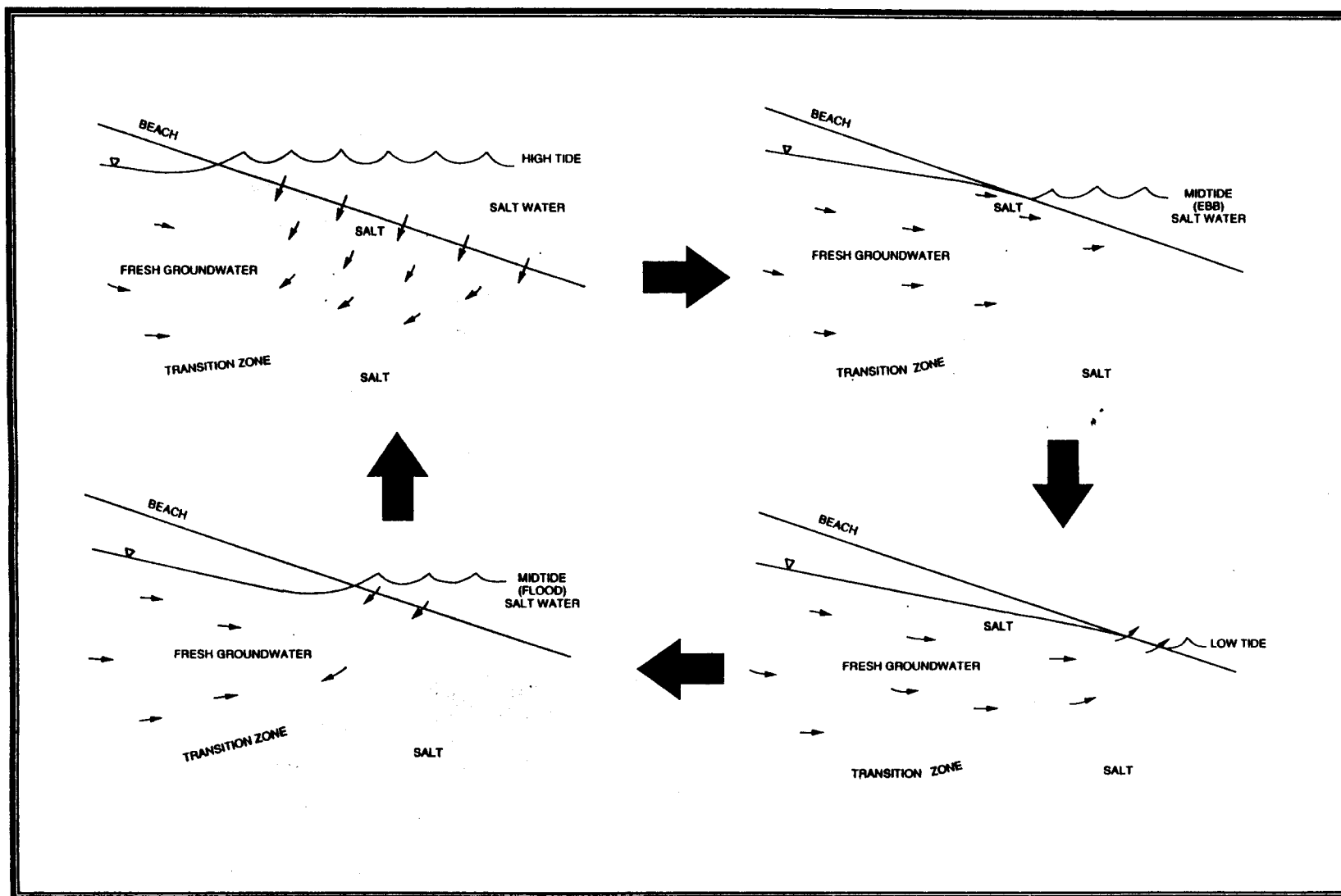


Fig. 3.14 Pattern of groundwater flow in a tidally influenced beach

3.3 Groundwater Quality Patterns in the Beach

3.3.1. Shoreline Salinity and Nitrogen Distribution Patterns:

Following are the results of analysis of water samples collected at equal distance intervals along the beach line at low tide. Data from the transects are presented as plots for each of the five sites.

Salt Pond Site (A) Salinity beach line transects (Figure 3.15) taken during low tide for two different seasons, summer and spring (March 15, 1994 and July 26, 1993) indicate the same variation of the salinity distribution along the transect. There is no point along this transect that shows a remarkable low salinity value though the south (left) part of the transect suggests that about 2/3 of the discharge is fresh water. This is no single strong fresh groundwater outflow along the beach line transect at this site. Salinity transects at the low tide beach line can provide a reliable method to locate fresh groundwater seepage locations. In general salinity values along the transect were lower during the spring season. This can be the result of a greater amount of groundwater recharge during the winter and spring with resultant high discharge in the spring.

The nitrogen transects (Figure 3.16) shows relatively high concentrations of nitrate and ammonium at most of the sampling points reaching highs of 180 $\mu\text{M/l}$ (for nitrate) and 770 $\mu\text{M/l}$ (for ammonium). There are marked highs of 770 $\mu\text{M/l}$ of ammonium at station 54 and 400 $\mu\text{M/l}$ at station 55.

Salt Pond Bay Site (B) Salinity beach line transects (Figure 3.17) for two different seasons, summer and spring (March 7, 1994 and July 26, 1993), show that salinity values at many points along the beach are lower during the spring season than the summer season. These transects show that there are a large number of points that have low salinity values. This is an indication of strong fresh groundwater discharge along the beach at these points, especially prominent at Section A-A'.

The nitrate-nitrogen and ammonium-nitrogen transect (Figure 3.18) shows low concentrations (1 to 11 $\mu\text{M/l}$) at all points of sampling with ammonium concentrations higher than the nitrate at many points. There seems to be a general correspondence of low salinity and high nitrogen content at Stations 10, 26 and 36.

Shore Garden Site (C) Salinity beach line transects (Figure 3.19) for two different seasons, spring and fall (March 15, 1994 and September 1, 1993), show a major difference between spring and fall with the salinity dropping very significantly during the spring season. This is most likely due to the higher rate of precipitation and fresh groundwater recharge in winter and spring, while the lack of recharge with attendant water table drop during the summer and the early fall seasons has decreased the groundwater flow. An additional consideration is that the period of May-August, 1993 was an extraordinary dry period, about half that normally expected. The samples along much of the transect on September 1, 1993 have salinities of 33 ppt indicating that most of the discharge is infiltrated sea water. This seasonal effect is most evident at the Shore Garden Site.

The nitrate-nitrogen and ammonium-nitrogen transect (Figure 3.20) shows relatively low

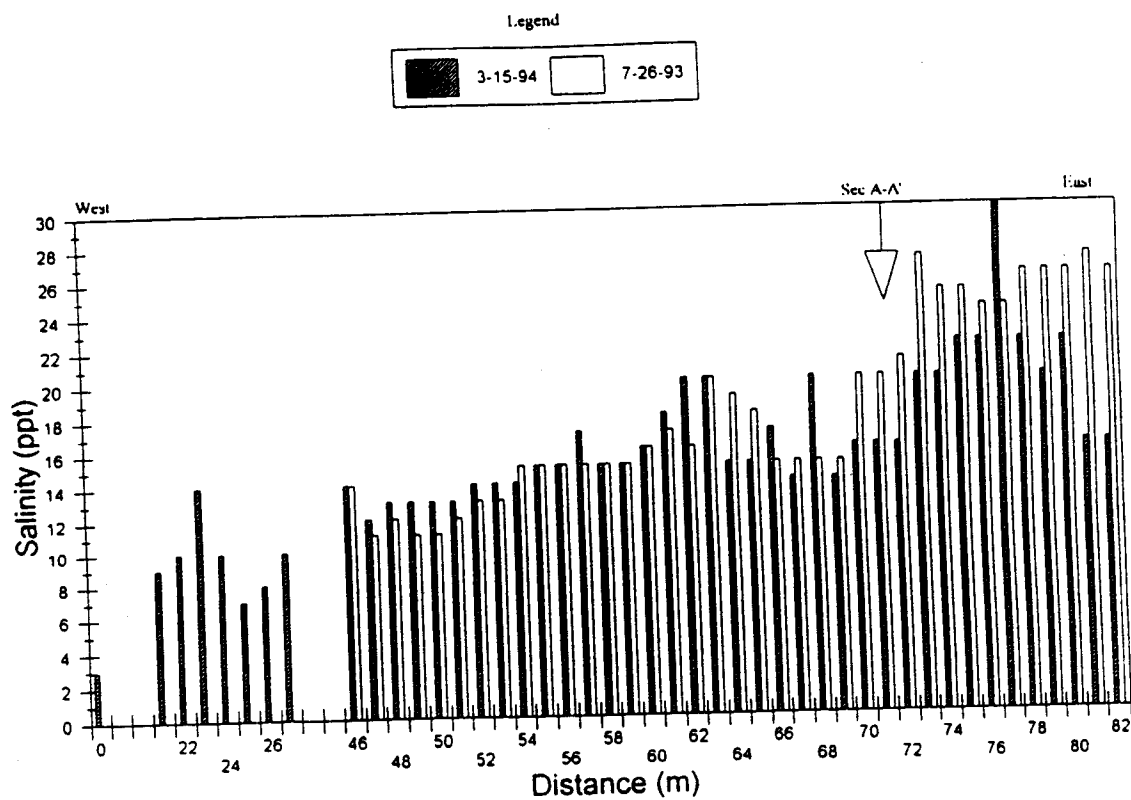


Fig. 3.15 Salt Pond Site (A) low tide salinity transects

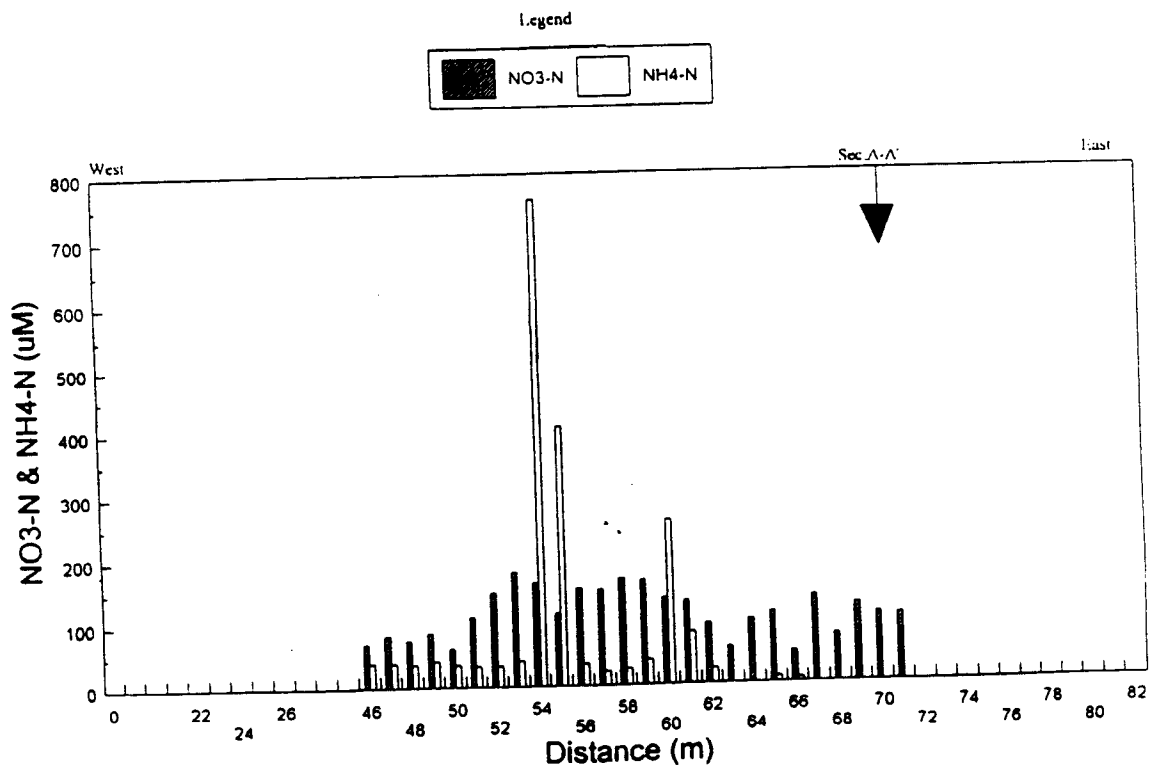


Fig. 3.16 Salt Pond Site (A) NO₃-N and NH₄-N transects

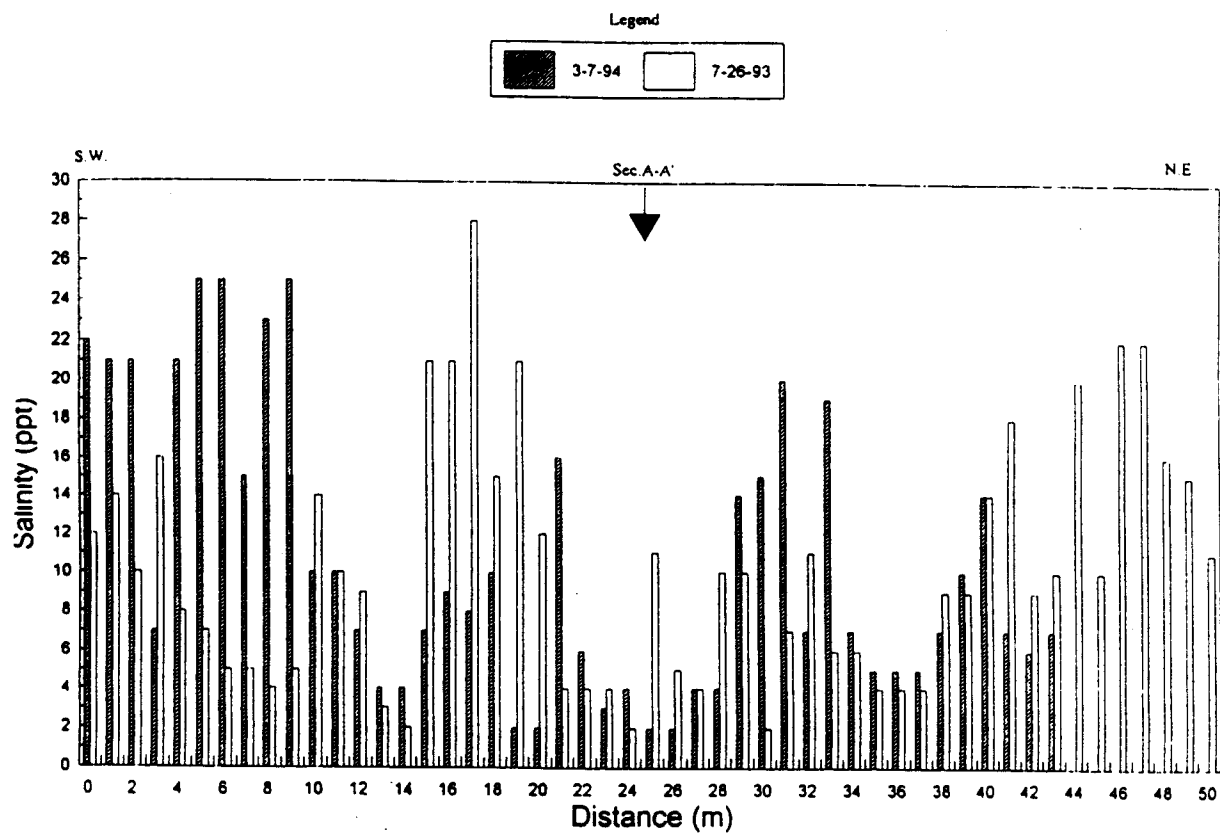


Fig. 3.17 Salt Pond Bay Site (B) low tide salinity transects

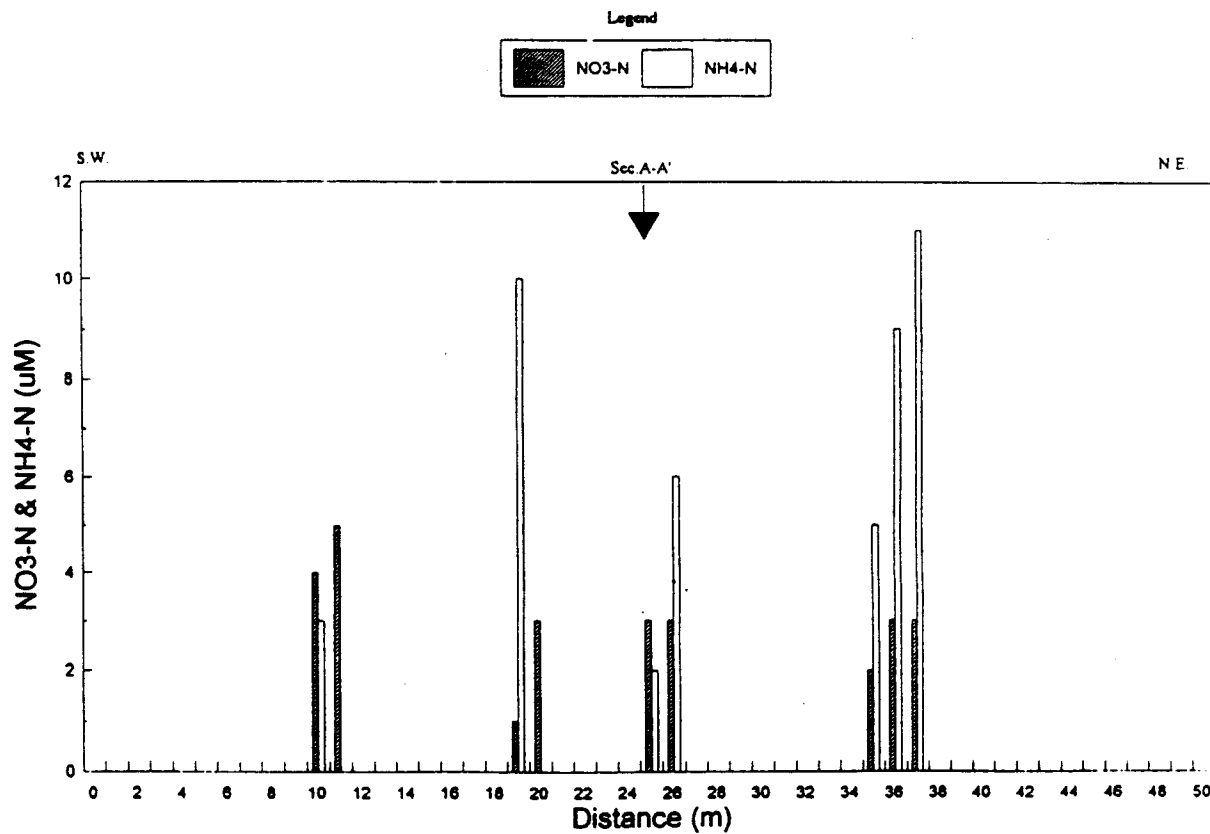


Fig. 3.18 Salt Pond Bay Site (B) NO₃-N and NH₄-N transects

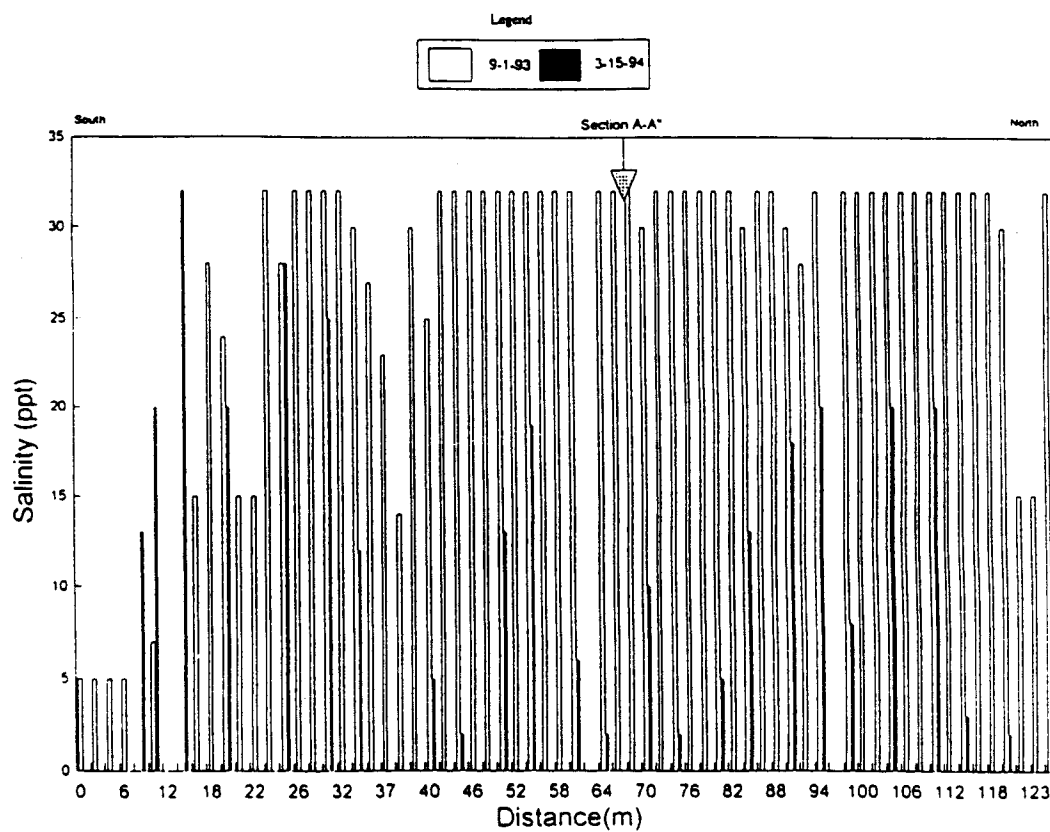


Fig. 3.19 Shore Garden Site (C) low tide salinity transects

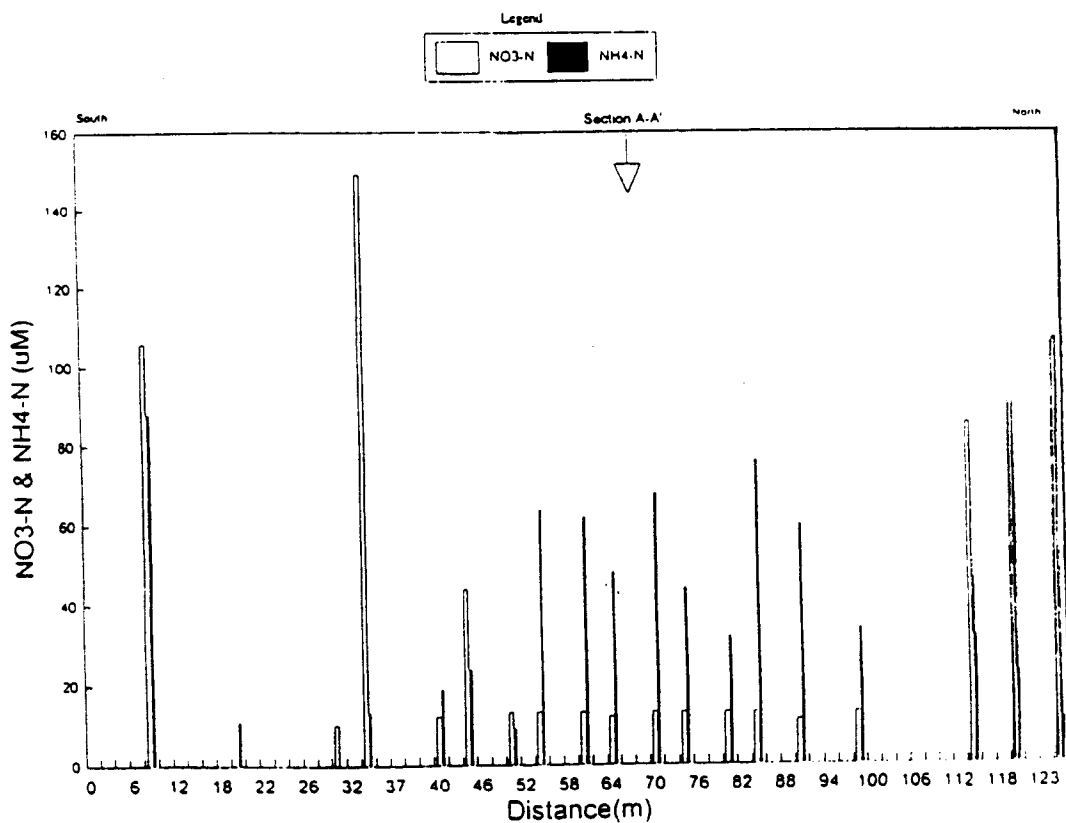


Fig. 3.20 Shore Garden Site (C) NO₃-N and NH₄-N transects

concentrations of nitrate and higher concentrations of ammonium, reaching 150 $\mu\text{M/l}$ at some points.

Eldredge Site (D) The salinity beach line transects (Figure 3.21) for two different seasons summer and spring (March, 15, 1994 and July 20, 1993), show the same pattern in the salinity values at most of the points along the beach. However, salinity values are generally lower during the spring season than the summer season. This can be related to higher rate of groundwater outflow caused by a higher rate of precipitation during spring season. These transects also show that there is an area (15-20 m north of section A-A') where the salinity is very low or approaching zero at both seasons. This area is a spring discharge area where strong groundwater seepage could be observed visually.

The nitrate-nitrogen transect (Figure 3.22) shows very high concentrations reaching 400 $\mu\text{M/l}$ at the low salinity points. Ammonium was not detected at most of the transect except for one point with a very low value of 4 $\mu\text{M/l}$. This site shows a strong inverse correlation between salinity and nitrogen, that is, samples with low salinity tended to have high nitrogen content.

Weeset Site (E) The salinity beach line transects (Figure 3.23) for two different seasons, winter and spring (March 15, 1994 and August 23, 1993) show much less a consistent pattern in seasonal salinity: in some cases, Stations 2 to 10 and Stations 29 to 37, the summer salinity is considerably lower than the spring salinity. There are three zones of consistently low salinity, at Stations 14, 24 and 36, where the salinity averages about 4 ppt, indicating strong fresh water discharge.

The nitrate-nitrogen transect (Figure 3.24) shows a high concentration of 340 $\mu\text{M/l}$ at Station 5 while ammonium was non-detectable except for one low value of 3 $\mu\text{M/l}$. There was no apparent relationship between salinity and the nitrogen content.

3.3.2 Thermal Infrared Aerial Photography

Thermal infrared aerial photography was quite successful in delineating plumes of colder water discharge along the coastal margin. With the assumption that the colder water is fresh groundwater, locations of major fresh water discharge could be identified by reference to shoreline features. The level of local discrimination is probably about 10 meters. The technique of taking two series of photos was effective in distinguishing a moving plume of water from a stationary feature which might also give a thermal signal. From analysis of the photographs it appears that the plume of fresh water forms in a thin layer on the higher density salty receiving water. In some instances a visual disruption of the plume is caused by a moving boat.

A general thermal infrared photographic overview of each of the sites is provided as Figures 3.25 through 3.29. In these figures the site is located on a color photo and a thermal infrared photo is superimposed near the site location. A set of larger, more definitive thermal infrared photos for the sites is contained in Appendix B.

The most remarkable observation from the thermal infrared photos is the high degree of nonuniformity of discharge along coastal zones, even where the coastline seems to be uniform in character. This is particularly evident at Salt Pond (Fig. 3.25) where strong discharge occurs on the

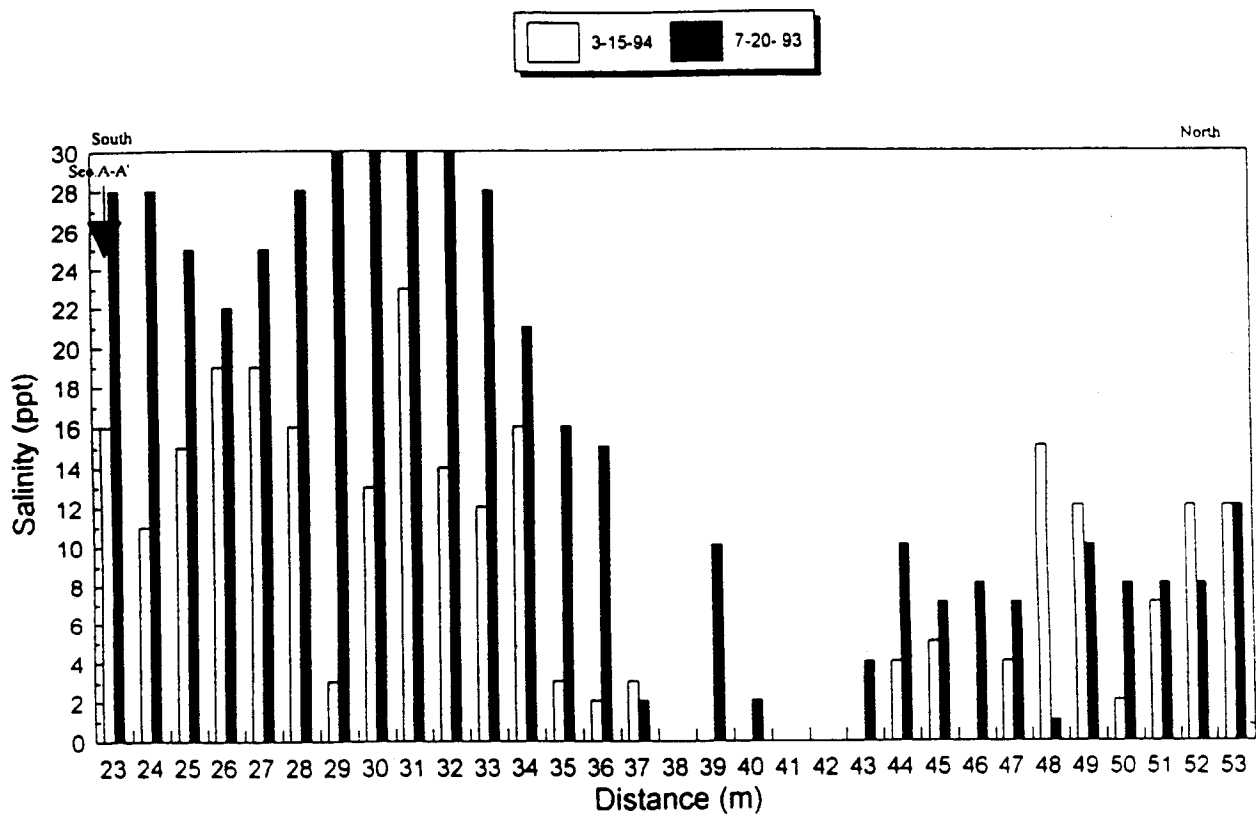


Fig. 3.21 Eldredge Site (D) low tide salinity transects

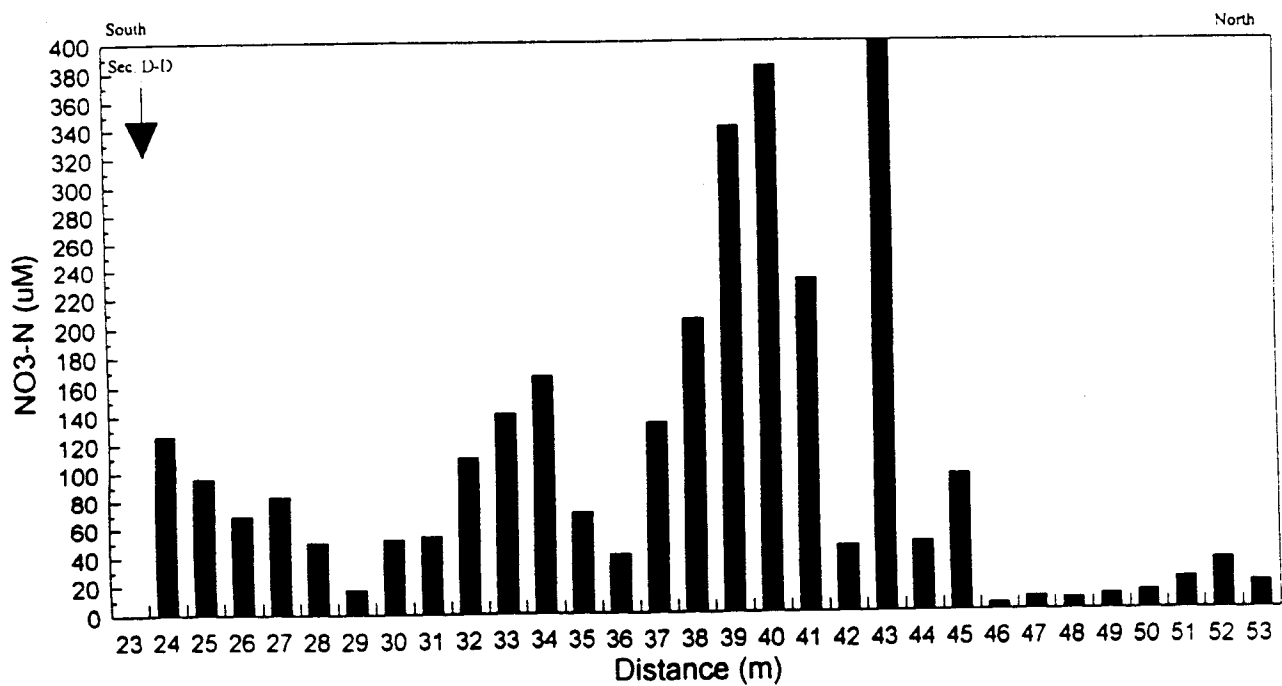


Fig. 3.22 Eldredge Site (D) NO3-N transect

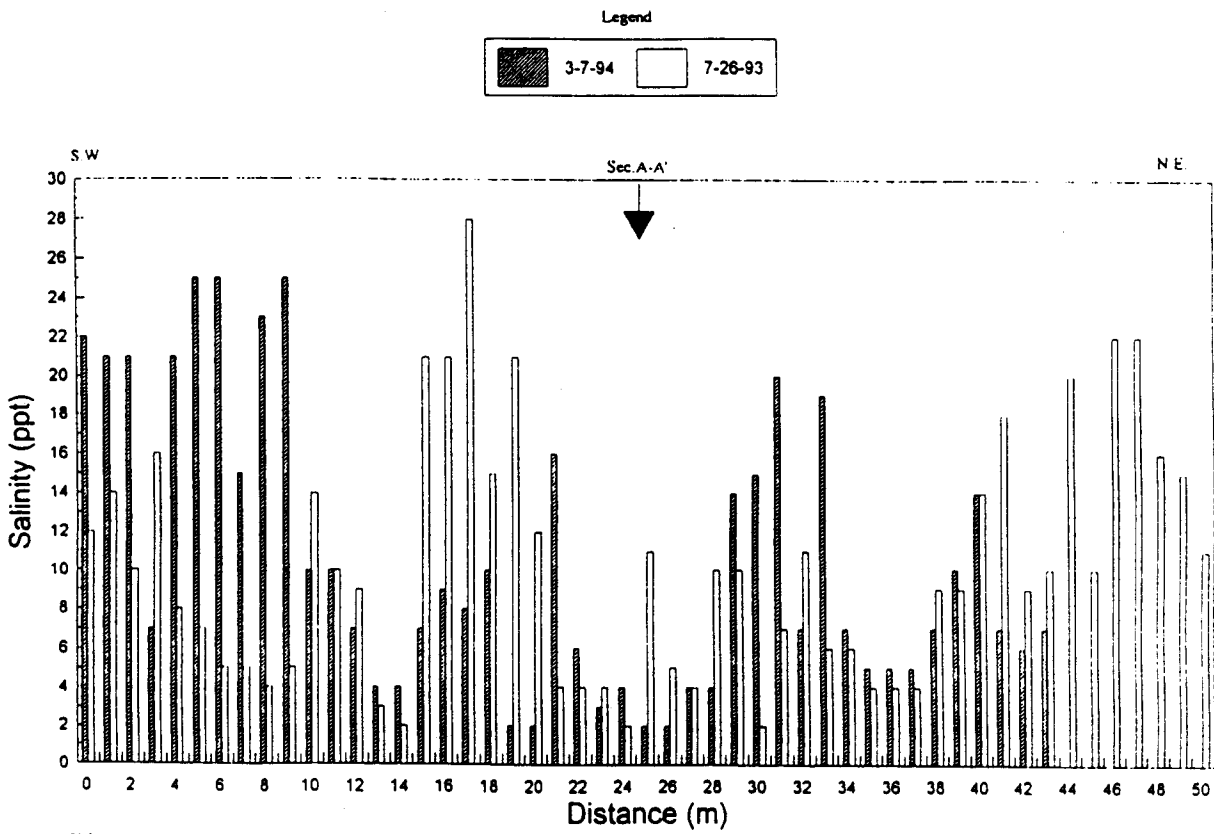


Fig. 3.23 Weeset Site (E) low tide salinity transects

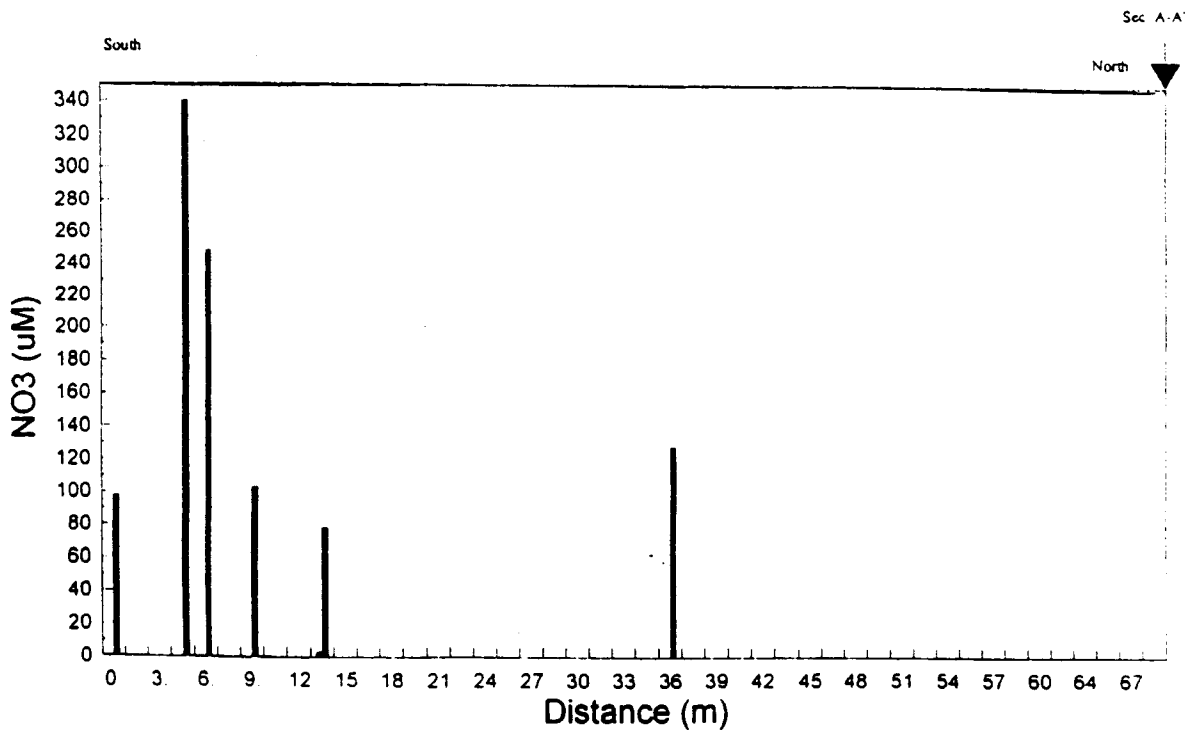


Fig. 3.24 Weeset Site (E) NO₃-N transect



Fig. 3.25 Air photo of Salt Pond (Site A) with thermal infrared inset photo.



Fig. 3.26 Air photo of Salt Pond Bay (Site B) with thermal infrared inset photo.



Fig. 3.27 Air photo of Shore Garden Beach (Site C) with thermal infrared inset photo.



Fig. 3.28 Air photo of Eldredge Beach (Site D) with thermal infrared inset photo.



Fig. 3.29 Air photo of Weeset Beach (Site E) with thermal infrared inset photo.

southwest side of the pond and on the upper east side. In other areas, such as Town Cove (Appendix B - photo D), discharge generally occurs all along the coastline. Closer examination, however, reveals that this discharge is composed of many small discrete plumes, some of which are darker than others, implying strong fresh groundwater discharge. This pattern is very similar to that displayed in the low tide shoreline salinity transects.

The thermal infrared photo technique is considered to be an effective tool for identifying especially significant fresh groundwater discharge locations. Unfortunately, in the case of Nauset Marsh study, it was accomplished too late to provide guidance in study site selection. In some cases the specific study sites could have been better located to intercept stronger groundwater flows. While there is a large difference in scale, interpretation of the thermal infrared photos does tend to support the findings from the low tide shoreline salinity transects. In this regard the analytical usefulness of the thermal infrared photos could be enhanced by using enlargements of locations of particular interest.

3.3.3 Depth Related Salinity Distribution

Vertical salinity profiles extending to depths below the water table provide insight into the fresh groundwater flow through the beach and the layering of fresh and salt water due to dynamic tidal movement over the beach face. The difference between the salinity profile patterns at different locations seems related to the non-homogeneous characteristics of the beach sediments as well as the dynamic hydraulics of fresh-salt water boundary. Layers of sediments of higher hydraulic conductivity will permit easier flow for the groundwater and will also respond faster to the dynamic effects of tidal fluctuation. On the contrary, the existence of high salinity water to depth at some locations may indicate a reduction of the fresh groundwater flow and flushing capability due to low hydraulic conductivity of the sediments. The variation in hydraulic conductivity leads to nonuniform groundwater flow through the beach area creating a number of distinctive groundwater flow paths. The location of fresh groundwater in the beach substrata is dependent on a complex mix of factors, some fixed, such as hydraulic conductivity, while others are highly variable with time, such as the range of the tide.

Most of the vertical salinity profiles show a change in salinity at different depths along the beach. High salinity water overlying low salinity water indicates the effect of salt water infiltration caused by an overflow of salt water onto the beach zone during high tide periods. As this overflow and fresh water discharging episodes occur repeatedly, multi layers of salt water and fresh water will be created successively. In general, salinity profiles at the upper beach above the high tide line show low salinity extending to sampling depth, while those in the intertidal beach show a layer of salty water overlying the fresh water. Most profiles taken in this study extended to depths of 3.5 to 4.0 meters below the water table.

Salinity was determined from electrical conductivity and temperature measurements of water samples (Montgomery, 1985). Sampling was done at depth intervals of one half meter. In this study the only ionic constituent of major interest was the salinity in the groundwater, which then was measured indirectly by electrical conductivity normalized to a standard temperature of 25°C.

The results of vertical salinity profiles are presented as plots for each of the five sites for various locations and times, and described in the following paragraphs:

Salt Pond Site (A). Salinity profiles were taken at points P1A, P1B, P1C, P2C, P4C, P5C, P6C, P2A and P1D as located on the plan view of the site (Figure 1.6). To avoid repetition only two of these points, P1A (Figure 3.30) and P1D (Figure 3.31) are presented in the text to demonstrate the salt-fresh water relationship at this site. All samples have shown the existence of higher saline layer of water which varies in thickness at the upper part of the water table. Salinity of the upper layer was in the range of 35 to 40 ppt at points P1A and P1D, while it does not exceed 15 ppt at point P1D. At both points P1A and P1D the salinity dropped to extremely low values below 8 ppt, while in point P2A the salinity drop was relatively low and the salinity values at deeper points were high (in the range of 20 to 35 ppt). Salinity profiles have shown a variation in salinity values between points at different depths.

Salt Pond Bay Site (B). Salinity profiles were taken at points P1A, P2A, P1B, P2B, P1C, P2C and P3C as located on the plan view of the site (Figure 1.7). Two of these points P2B (Figure 3.32) and P3C (Figure 3.33) were selected to demonstrate the salt - fresh water relationship and the fresh water delineations at this site. Points P2B and P3C show low salinity values across the depth, except for the upper part of the water table where the salinity increases slightly. This suggests a large volume of freshwater discharging through this area.

Shore Garden Site (C). Several profiles were taken at points P1A, P1B, P2B, P3B and P1C located on the site plan view (Figure 1.9). Two of these points, P1A (Figure 3.34) and P2B (Figure 3.35) were selected to demonstrate the relation between the salt water and the fresh water relationship and the fresh water locations at this site. All points show low salinity values and slight variation across the depth. One sample at point P1C is the only location which shows relatively high salinity (17 ppt) at the upper part of the water table. This suggests a strong flow of fresh water which flushes out the infiltrated salt water.

Eldredge Site (D). Several profiles were taken at points P1A, P2A, P1B, P2B, P3B, P4B, P5B and P6B as located on the site plan view (Figure 1.11). Two of these points, P1A (Figure 3.36) and P2A (Figure 3.37) were selected to demonstrate the salt water and the fresh water relationship and the fresh water delineations at this site. Points P1A and P6B show low salinity values across the depth with a slight variation in point P6B. The plot for point P2A shows high salinity values with a considerable increase at the upper part of the water table. Since these two samples are in the same line perpendicular to the beach, this suggests that the fresh water flow path is being diverted.

Weeset Site (E). Several profiles were taken at points P1A, P2A, P1B, P2B, P6B, P1C, P2C, P3C, P4C, P5C, P6C, P8C and PC as located on the site plan view (Figure 1.13). Two of these points, P2A (Figure 3.38) and P1D (Figure 3.39) were selected to illustrate the salt - fresh water relationship and fresh water delineation at this site. Point P1A and P2A show high salinity values across the profile specially at the upper part of the water table. Salinity fluctuation across the depth is almost the same in the two profiles. Point P1D shows low salinity values across the profile except for the upper part of the water table where the salinity is slightly high. It should be noted that point

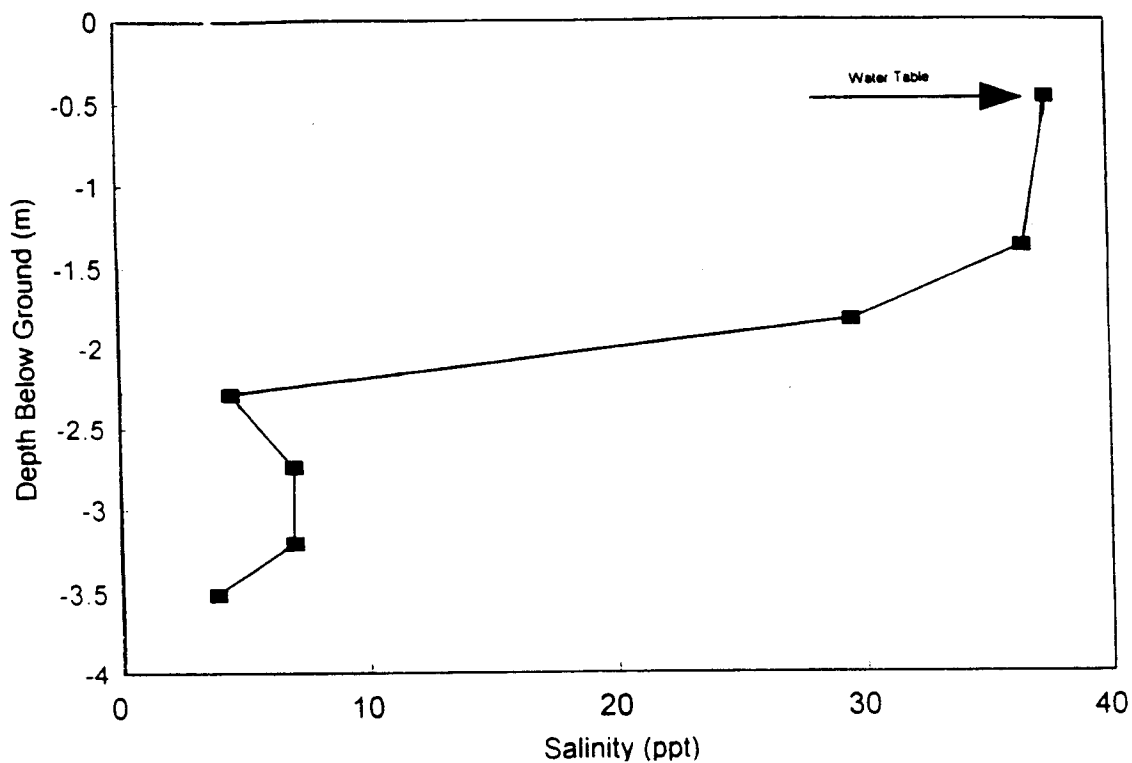


Fig. 3.30 Salt Pond Site (A) salinity profile P1A (June 9, 1992)

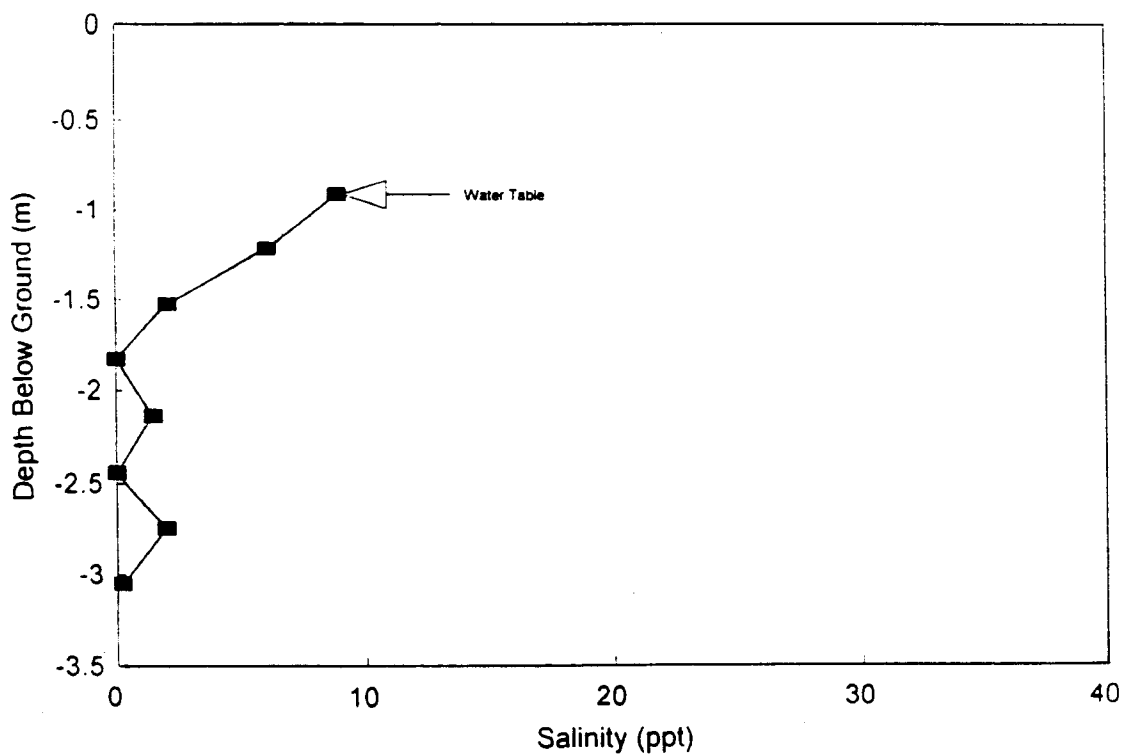


Fig. 3.31 Salt Pond Site (A) salinity profile P1D (Sept. 6, 1993)

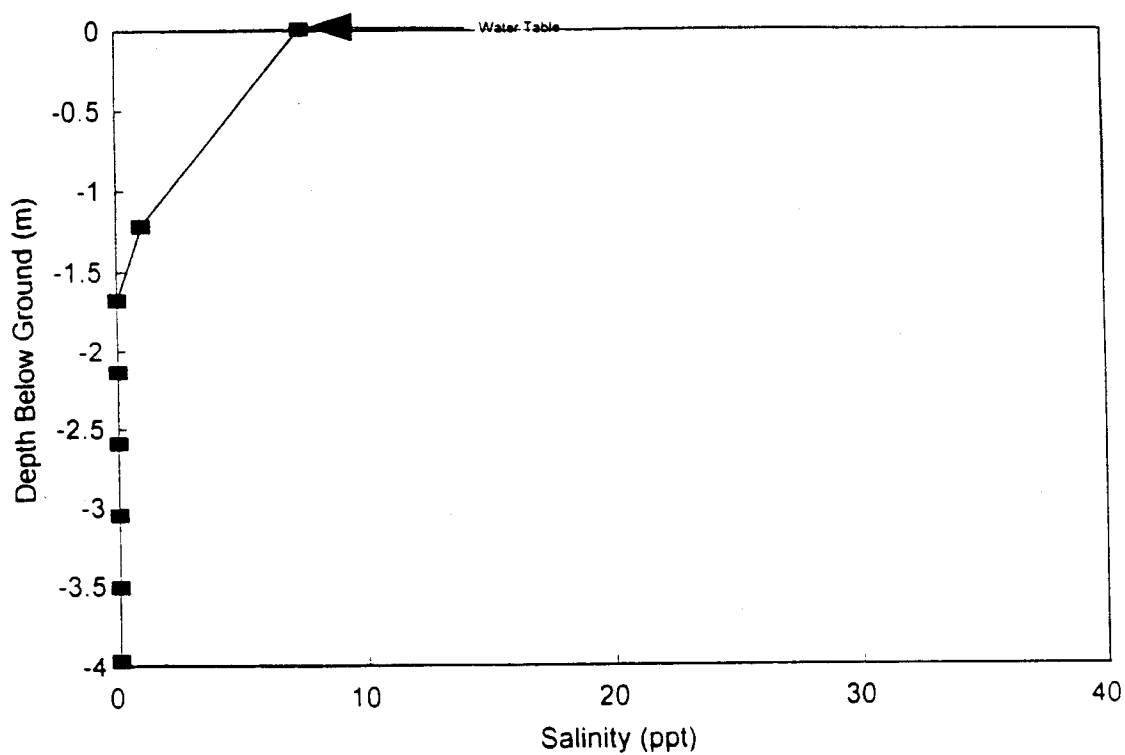


Fig. 3.32 Salt Pond Bay Site (B) salinity profile P2B (July 7, 1992)

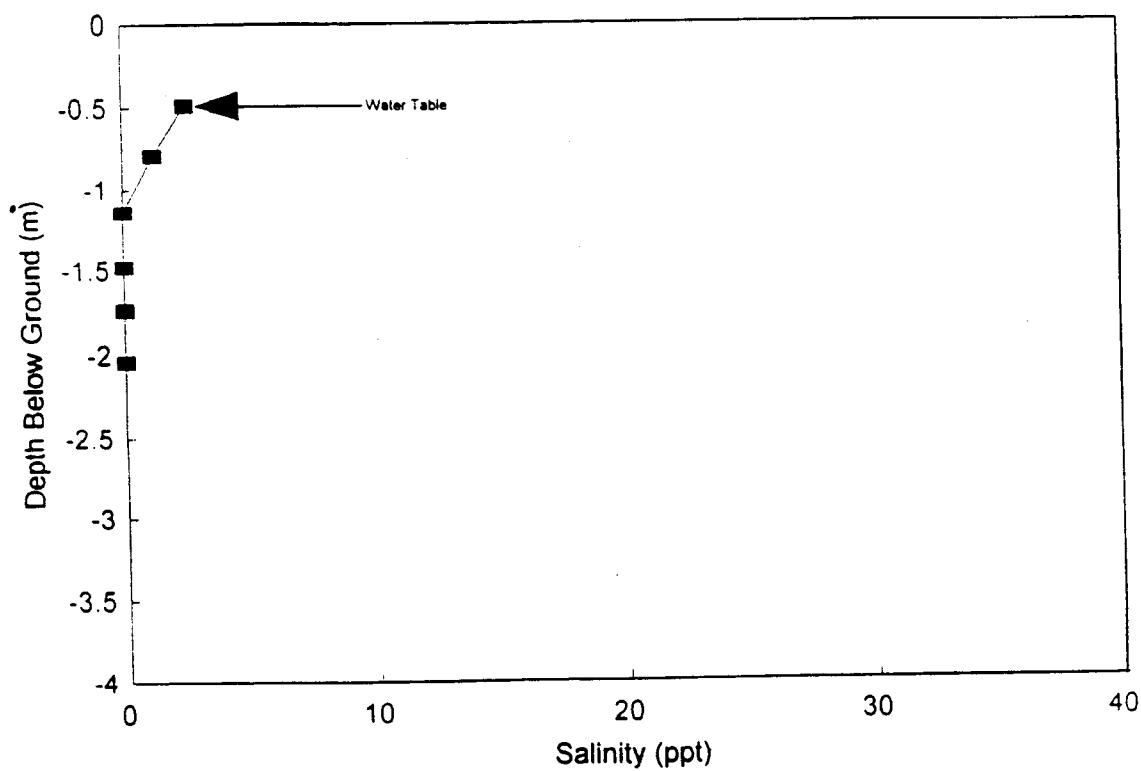


Fig. 3.33 Salt Pond Bay Site (B) salinity profile P3C (July 14, 1993)

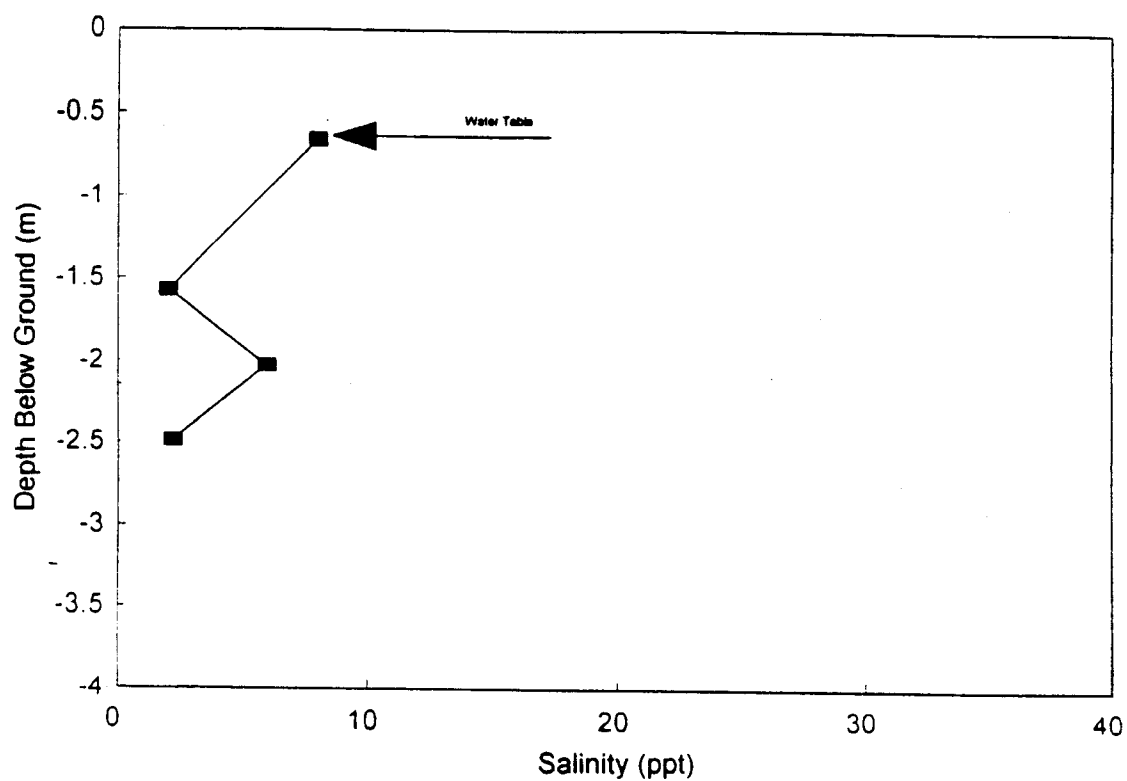


Fig. 3.34 Shore Garden Site (C) salinity profile P1A, (July 17, 1993)

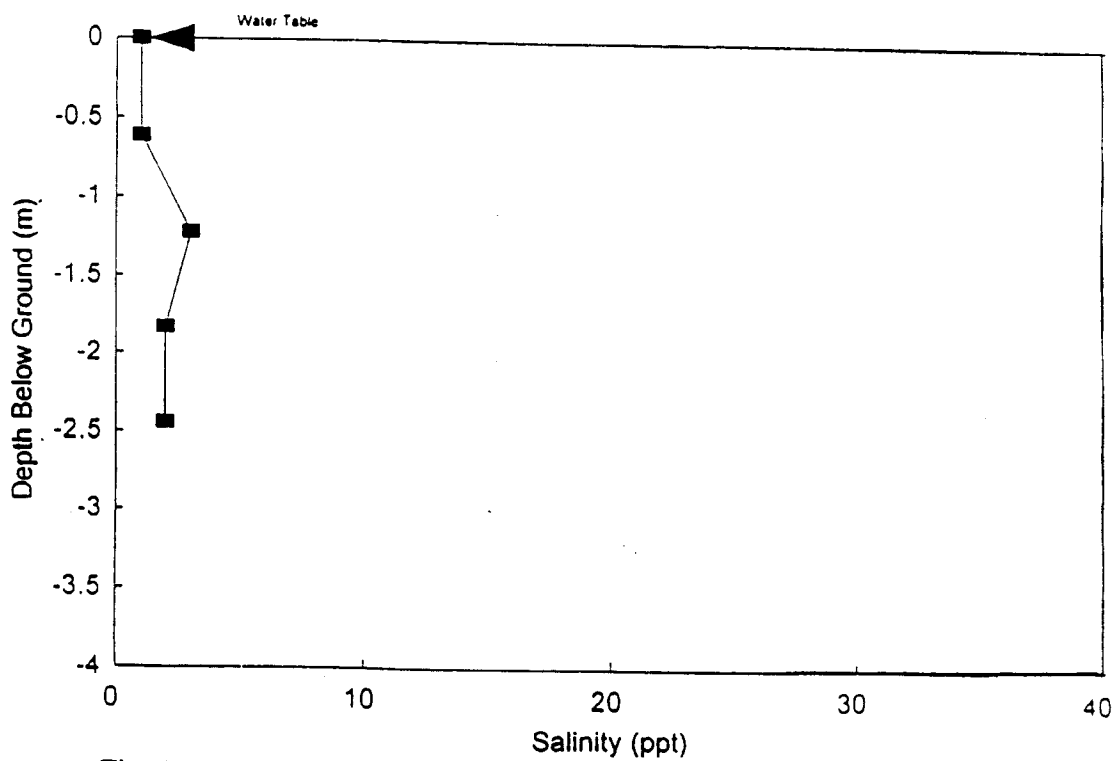


Fig. 3.35 Shore Garden Site (C) salinity profile P1B, (July 14, 1993)

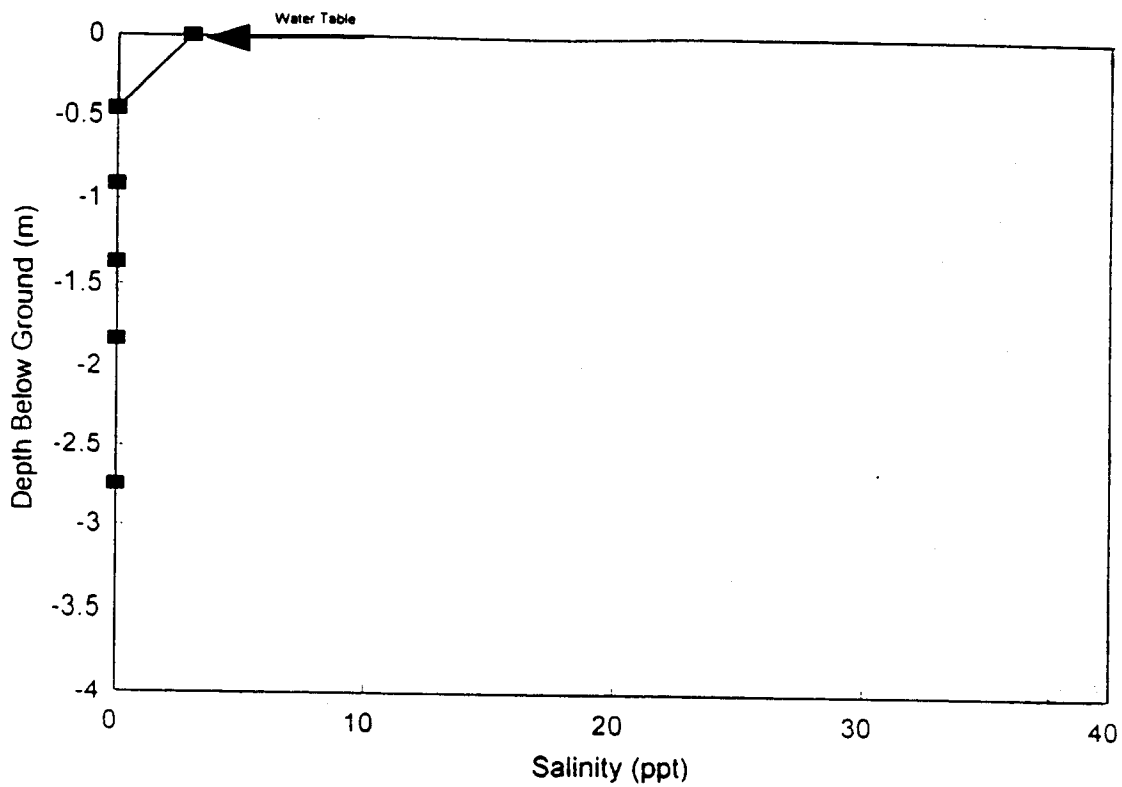


Fig. 3.36 Eldredge Site (D) salinity profile PLA, (July 8, 1992)

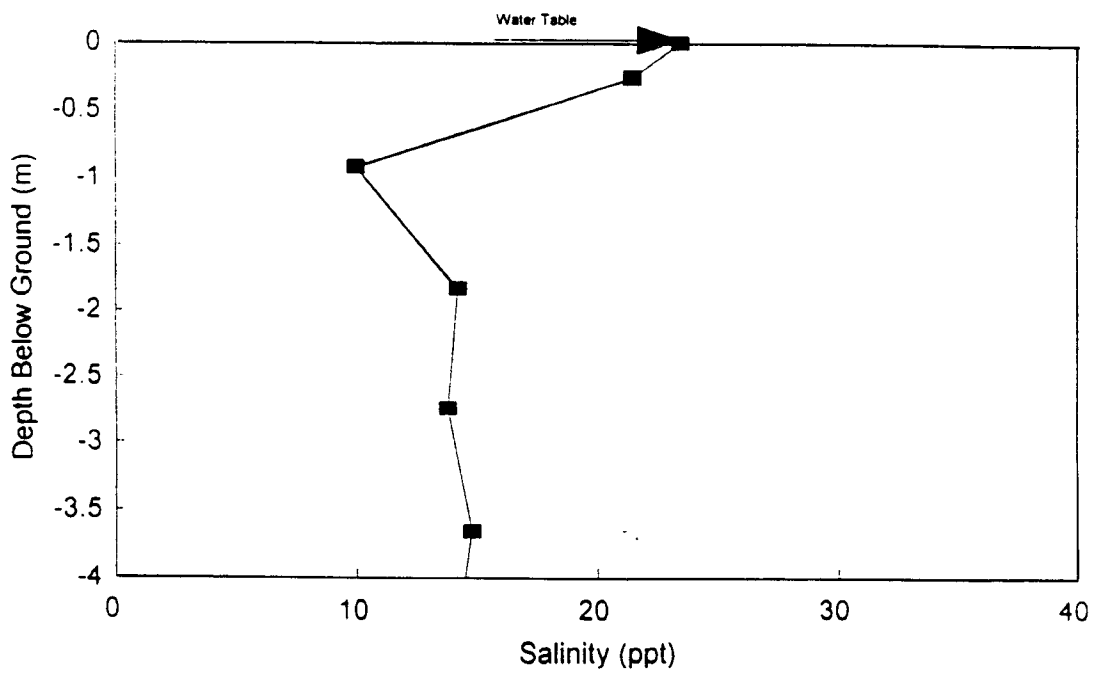


Fig. 3.37 Eldredge Site (D) salinity profile P2A, (July 8, 1992)

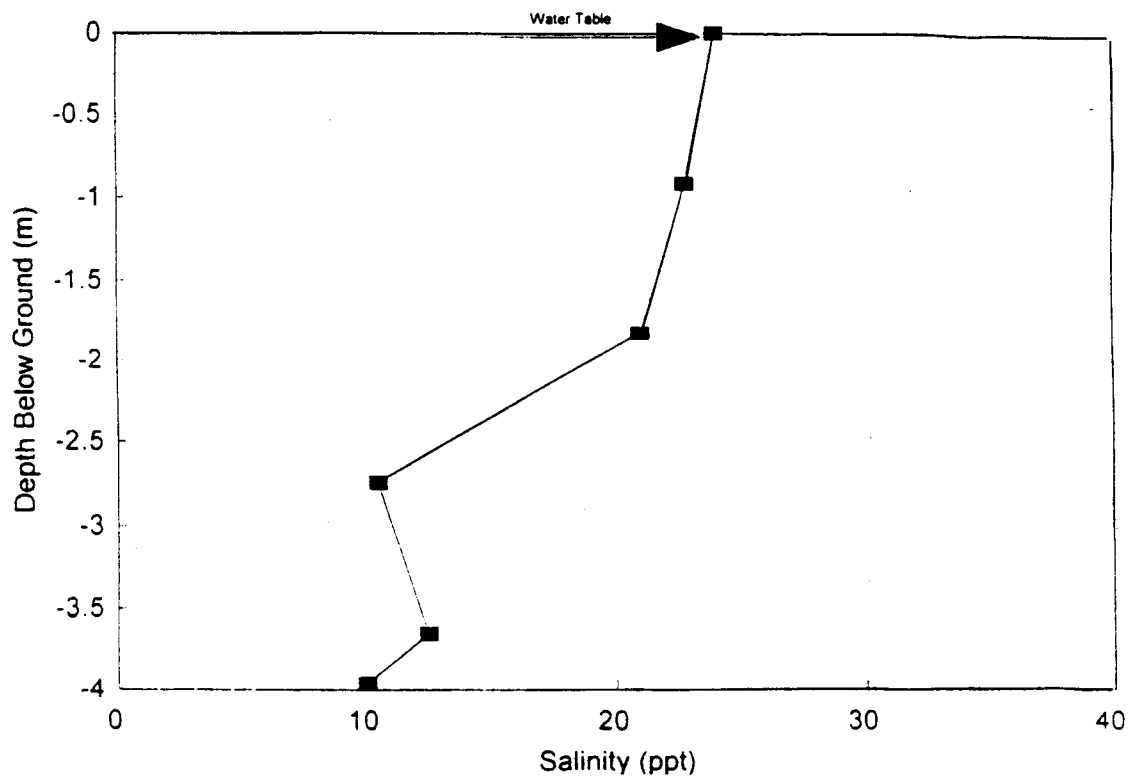


Fig. 3.38 Weeset Site (E) salinity profile P2A, (July 23, 1993)

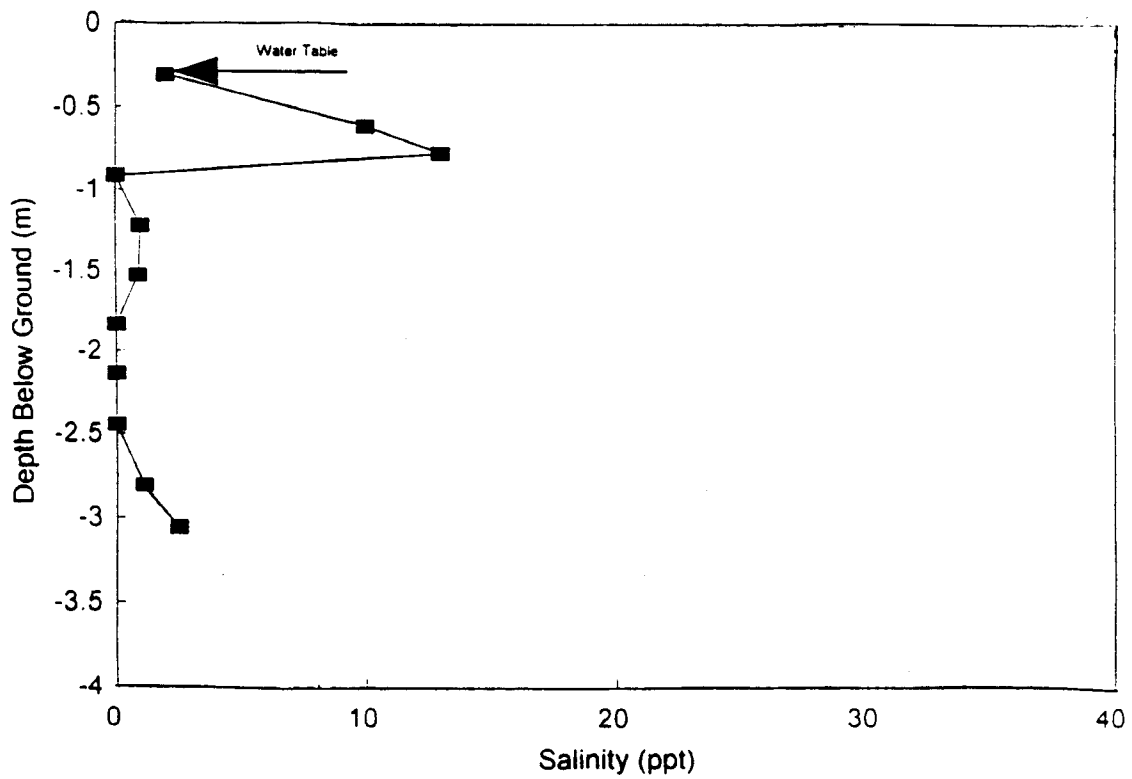


Fig. 3.39 Weeset Site (E) salinity profile P1D, (July 23, 1993)

Table 3.3 Nitrogen Concentrations at Sites.

SITE	(1)		(2)			
	ESTIMATED NITROGEN		MEASURED NITROGEN			
	(μ M)	(mg/l)	AVERAGE (μ M)	(mg/l)	HIGH (μ M)	(mg/l)
Salt Pond (A)	1478.0	20.7	213.0	3.0	250.0	3.5
Salt Pond Bay (B)	85.7	1.2	5.8	0.1	10.0	0.1
Shore Garden (C)	200.0	2.8	40.0	0.6	110.0	1.5
Eldredge (D)	257.0	3.6	146.0	2.0	400.0	5.6
Weeset (E)	164.2	2.3	280.0	3.9	570.0	8.0

Notes:

1. Estimates are based on annual water and nitrogen budgets for a 183 meter flowpath width extending from the groundwater divide to shoreline discharge at the site (see Figure 1.2).

2. These values are based on nitrogen water quality field data normalized to fresh water equivalents using plots of nitrogen versus salinity (see Figures 3.40 - 3.44).

P1D is located at a fresh water discharge spring at the low tide line found during low tide salinity transect measurements.

3.3.4 Relationships of Salinity and Nitrogen in Beach Groundwater Discharge

Groundwater samples were taken and tested for dissolved inorganic nitrogen content by the Cape Cod National Seashore Biological Lab. The results were evaluated for patterns of salinity-nitrogen concentration, both seasonally and spatially. For the most part these samples were taken along beach low tide transect lines at each of the five sites.

The data was plotted to evaluate a relationship between salinity and nitrogen. Additionally, the plots were used to normalize all nitrogen content results to a fresh water equivalent. This was done by plotting the nitrogen content versus the salinity content of the water samples. The average nitrogen concentration, relative to a base of fresh water, occurs when the salinity is zero. An inherent assumption, however, is that the nitrogen content is uniform for the native fresh water for all samples from each site. Depending on the proximity of the nitrogen source to the sampling point and the amount of dispersion during transport this may not be the case.

Two lines are shown in the plots: the first is a "line of best fit" for all data at the site, and the other is a line defining a high concentration envelope. Table 3.3 summarizes the results of this analysis along with nitrogen-water budget estimates calculated for a 185 m wide flow path leading to each of the five sites. Figures showing scatter plots of the data are identified with each of the following site discussions. Appendix C contains the statistical analysis (Ostle, 1994) for the data from each site.

Salt Pond Site (A). The Salt Pond Site data shows high concentrations of nitrate-nitrogen and ammonium-nitrogen (Figure 3.40). Nitrate nitrogen concentrations are in the range of 150 $\mu\text{M/l}$ (2.1 mg/l) to 200 $\mu\text{M/l}$ (2.8 mg/l), while ammonium-nitrogen exceeds 750 $\mu\text{M/l}$ (10.5 mg/l) at one of the points. The high concentrations of nitrate almost uniformly distributed is an indication of high contamination along the beach area of this site even when the fresh water contribution is not high along this transect. Although ammonium concentrations at most of the points is less than that for the nitrate as a result of the oxidation of ammonium to nitrate as mentioned above, the proportion of the ammonium concentrations to nitrate is high. In addition, points exist where ammonium concentrations is much higher than the nitrate concentrations. This may be a result of the existence of a near source of wastewater contributing to the pond, which can be Salt Pond Visitor's Center. The short distance from the Visitor's Center to the pond beach may be insufficient for the oxidation of the ammonium into nitrate.

Salt Pond Bay Site (B). At this site data from the nitrate and ammonium show low concentrations of nitrate-nitrogen and ammonium-nitrogen (Figure 3.41). Nitrate-nitrogen concentrations are in the range of 1 $\mu\text{M/l}$ (0.014 mg/l) to 5 $\mu\text{M/l}$ (0.072 mg/l), while ammonium - nitrogen is the range of 2 $\mu\text{M/l}$ (0.28 mg/l) to 11 $\mu\text{M/l}$ (0.155 mg/l). Nitrate-nitrogen concentrations are uniformly low. Ammonium concentrations at most of the sampling points are higher than that of nitrate.

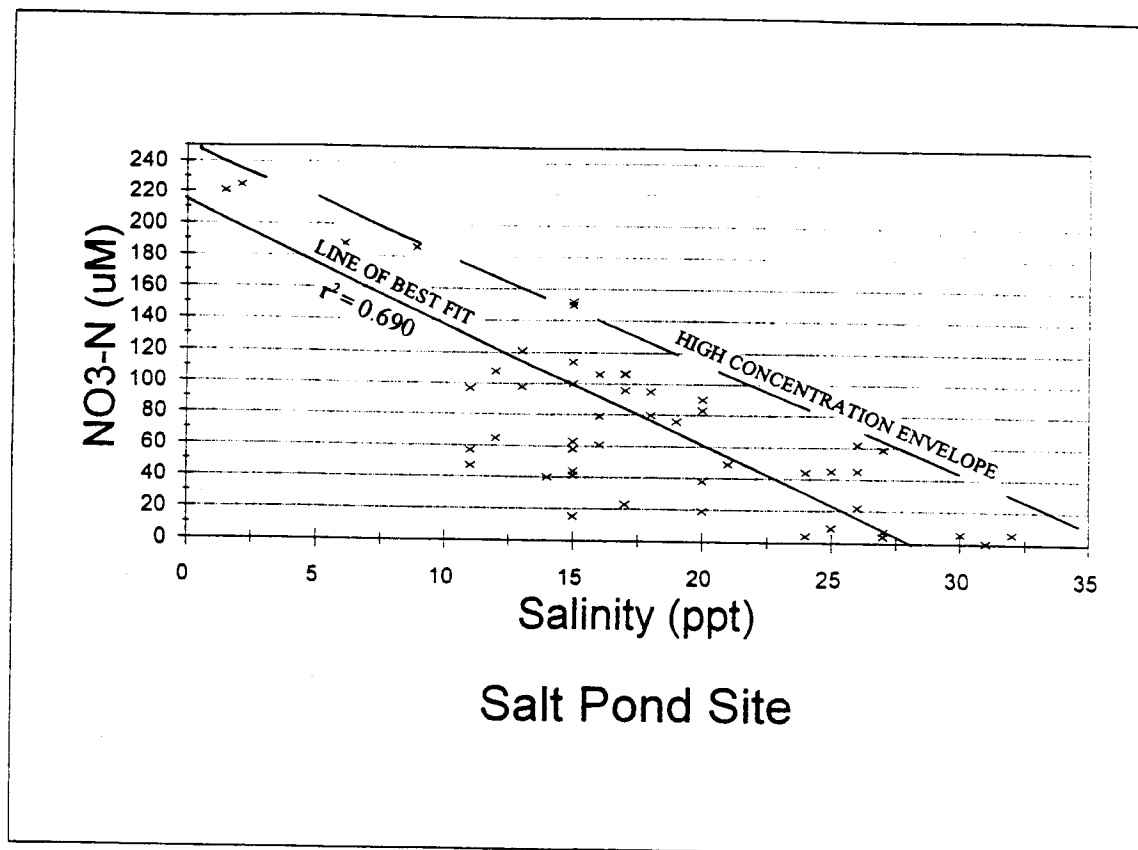


Fig. 3.40 Salt Pond Site (A) scatter plot of nitrogen vs salinity

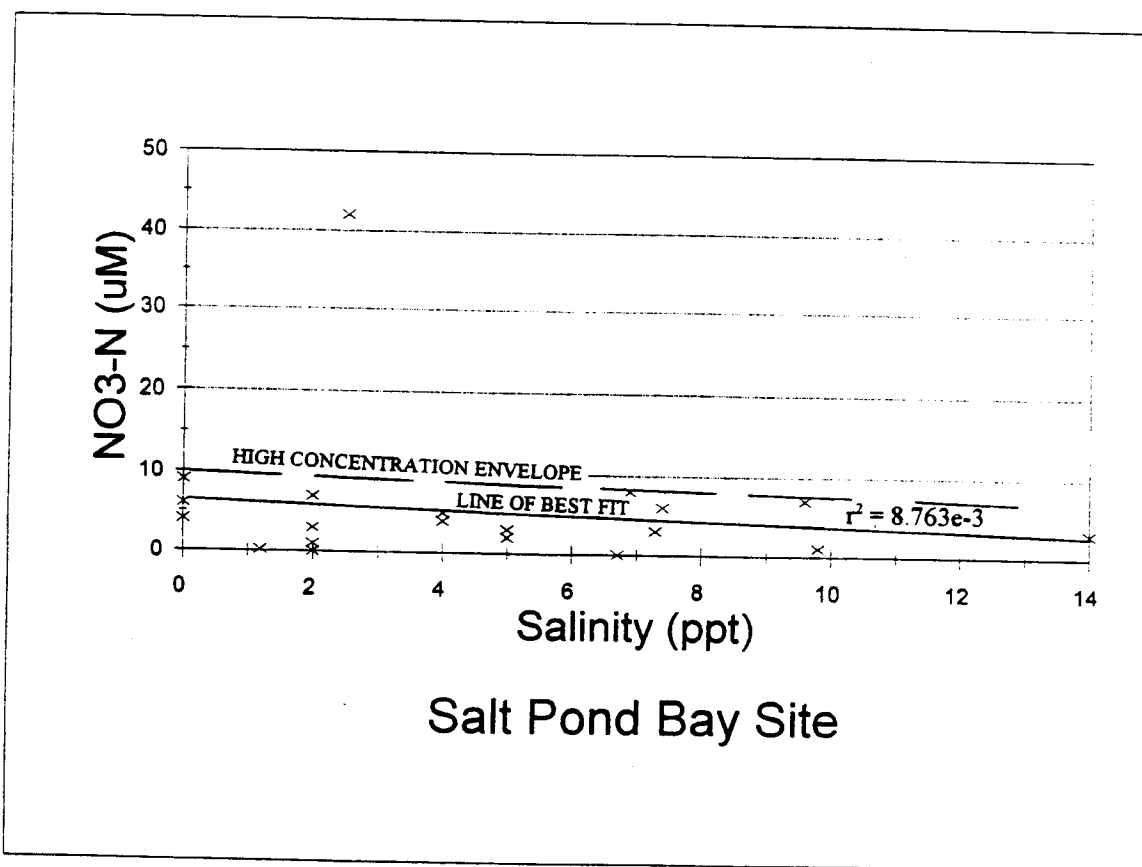


Fig. 3.41 Salt Pond Bay Site (B) scatter plot of nitrogen vs salinity

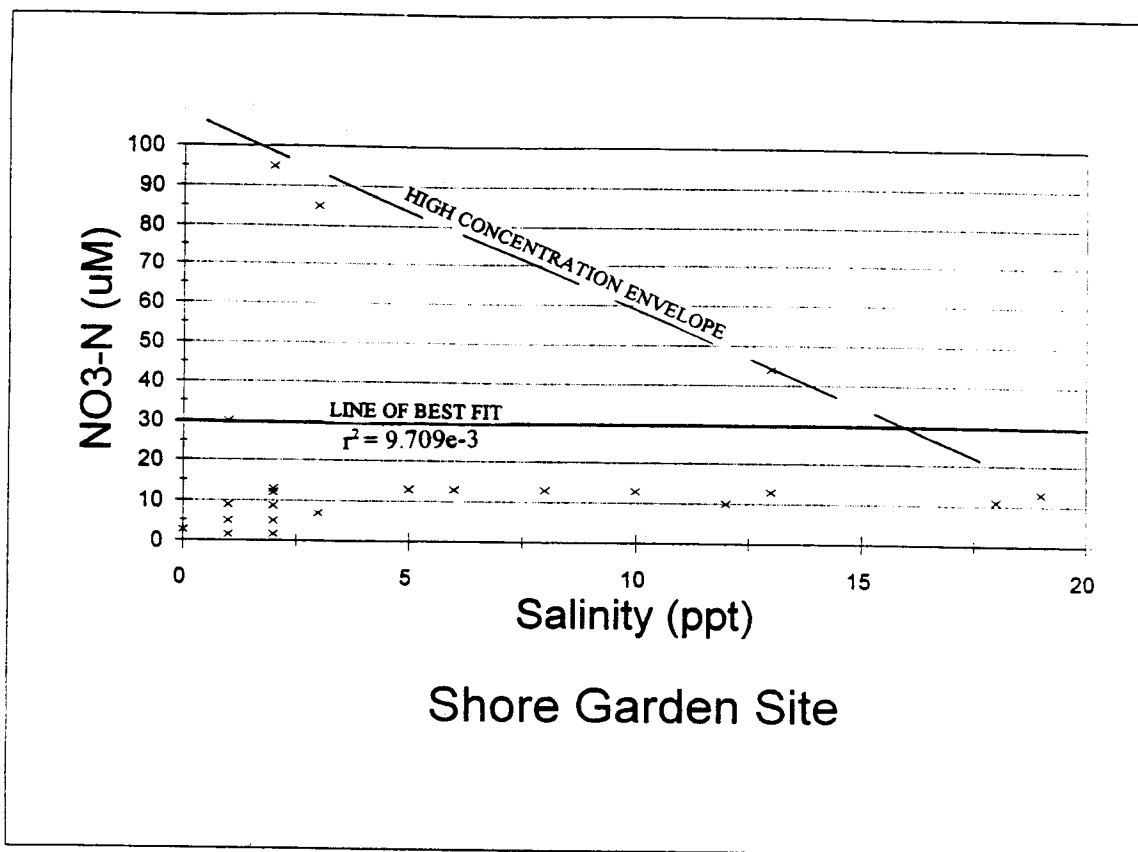


Fig. 3.42 Shore Garden Site (C) scatter plot of nitrogen vs salinity

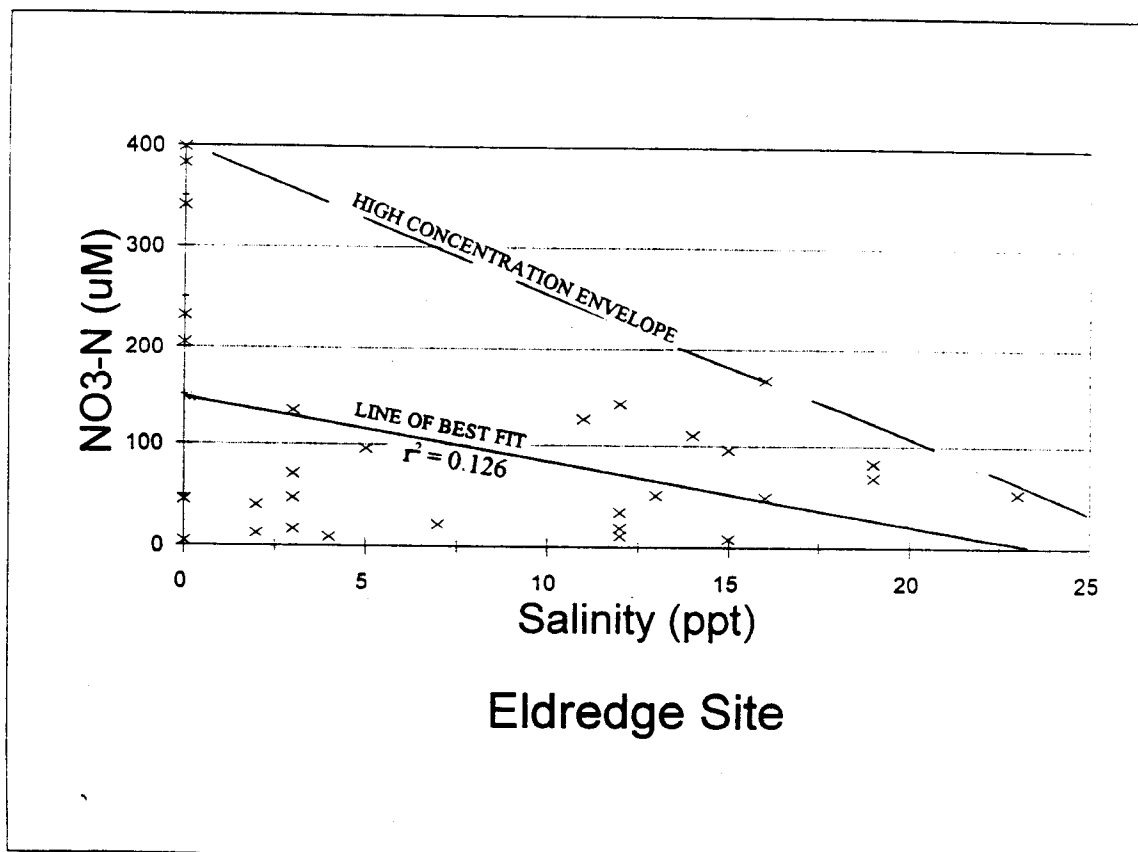


Fig. 3.43 Eldredge Site (D) scatter plot of nitrogen vs salinity

Shore Garden Site (C). At this site data from the nitrate-nitrogen and ammonium-nitrogen transect shows concentrations of nitrate and ammonium (Figure 3.42). Nitrate-nitrogen concentrations are in the range of 10 $\mu\text{M/l}$ (0.14 mg/l) to 150 μM (2.1 mg/l), while ammonium-nitrogen is between 10 $\mu\text{M/l}$ (0.14 mg/l) to 90 μM (1.26 mg/l). The transect shows that the concentration of nitrate at most of the points including the site sampling points is relatively low, while the concentrations of ammonium are higher at these points. This is an indication that there is a nearby source, which is the same case as for the Salt Pond Site. A residential compound which is very close to this site can be the source of concentrated nitrogen contribution.

Eldredge Site (D). At this site data shows high concentrations of nitrate and very low concentrations for ammonium (Figure 3.43). Nitrate-nitrogen concentrations are in the range of 5 $\mu\text{M/l}$ (0.07 mg/l) to 400 $\mu\text{M/l}$ (5.6 mg/l), while ammonium-nitrogen is between zero to 4 $\mu\text{M/l}$ (0.056 mg/l). The area where the highest contribution of nitrate occurs is the same area where there is a high groundwater outflow.

Weeset Site (E). At this site data shows high concentrations of nitrate and very low concentrations for ammonium (Figure 3.44). Nitrate concentrations are in the range of 80 $\mu\text{M/l}$ (1.12 mg/l) to 340 $\mu\text{M/l}$ (4.76 mg/l), while ammonium is between zero to 3 $\mu\text{M/l}$ (0.042 mg/l). The area where the highest contribution of nitrate occurs is the same area where there is a high groundwater outflow.

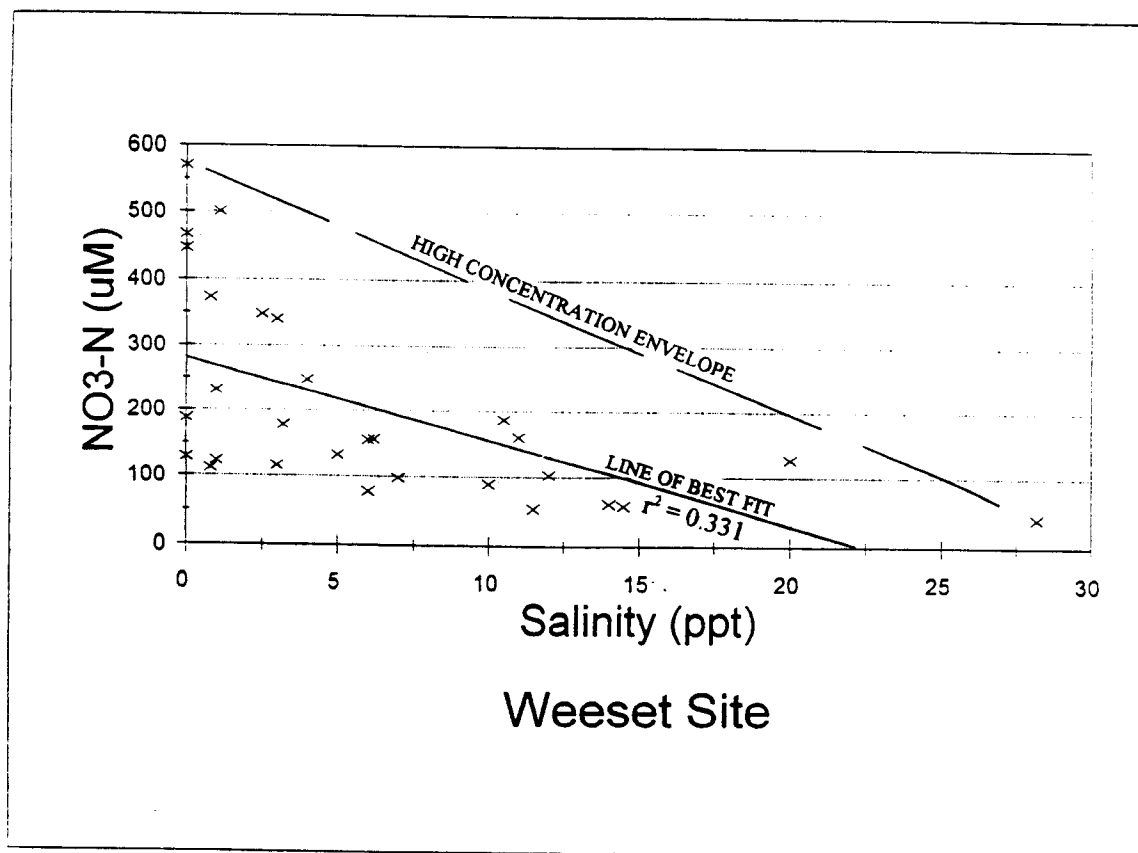


Fig. 3.44 Weeset Site (E) scatter plot of nitrogen vs salinity

3.4 Nitrogen Contributions to Nauset Marsh

The watershed area was divided into ten sectors for purposes of calculating a hydrologic budget and estimating the nitrogen input from on-site sewage disposal. The budget calculations assume an estimate of 40.6 cm/year average groundwater recharge over the Nauset watershed, and household wastewater release of 520 liters/day/residence with a nitrogen content of 35.0 mg/l (Frimpter et al, 1988; Eichner and Cambareri, 1991). It was further assumed that all nitrogen remained in the groundwater until discharge at the beach.

Table 3.4 provides a summary of estimated groundwater discharges, nitrogen levels and concentrations for each of the ten watershed sectors shown in Figure 2.1. The sum of these quantities represent total estimates of annual discharge and nitrogen loading to Nauset Marsh. The total estimated annual nitrogen contribution to Nauset Marsh from groundwater is 10,146 kg /year at an average concentration of 1.65 mg/l in the discharging groundwater, without allowance for denitrification. This value compares favorably with the average measured value of 1.92 mg/l. The estimated nitrogen concentration at individual sectors ranged from 0.64 mg/l at Nauset Bay to 3.52 mg/l at Nauset Heights. It is important to note that this estimate does not include other nitrogen sources of potential importance, notably lawn fertilizer input.

4. SUMMARY AND CONCLUSIONS

It is apparent from direct shoreline measurements of groundwater salinity, as well as the airborne thermal infrared photography that the discharge of fresh groundwater is highly variable in both time and space. Most discharge occurs only during low tide periods over about 25 % of the tidal cycle. Fresh water discharge also tends to focus in discrete, and sometimes widely separated zones along the shoreline. This is especially the case where the shoreline is interspersed with vegetated and peat layered zones. In these instances the groundwater flow tends to circumvent these zones in preference to open beach areas of higher permeability.

Water elevation measurements and salinity measurements at the coastal margin were used to examine a concept of the dynamic fresh-salt groundwater relationship that occurs in a coastal regime (Urish, et al, 1993). This relationship is illustrated in Figure 3.14 and can be described as follows:

- A) Salt water infiltration into the beach occurs when the hydraulic head of the surface water is higher than the hydraulic head of the groundwater during high tide. This will cause hydraulic damming of the outward groundwater flow, but as the tide moves down during ebb tide, the hydraulic gradient changes and the groundwater will move seaward.
- B) Groundwater discharge occurs when the hydraulic head of the groundwater is higher than the hydraulic head of the surface water during the period of ebbing and low tide. This creates a seaward groundwater gradient with coastal discharge. When the tide turns the gradient gradually reverses and salt water again overrides the fresher groundwater, and the cycle repeats itself.

Table 3.4 Sector Estimated Groundwater Discharge and Nitrogen Loadings.

SECTOR	NAME	AREA (hectare)	HOUSES	DISCHARGE ($\text{m}^3 \times 10^6/\text{yr}$)	DISCHARGE ($\text{m}^3/\text{m}/\text{day}$)	LOAD (kg/yr)	CONC. (mg/l)	CONC. (μM)
1	Nauset Bay	329	130	1.338	1.51	863	0.64	45.1
2	Salt Pond	129	209	0.584	1.05	1,374	2.36	168.5
3	Salt Pond Bay	131	99	0.466	0.56	657	1.41	100.7
4	Cove	306	264	1.168	1.05	1,752	1.50	107.1
5	Town Cove	201	324	0.798	0.96	2,151	2.70	192.8
6	Tonset	108	162	0.451	0.62	1,075	2.38	169.9
7	Freeman	49	31	0.196	0.22	206	1.05	75.0
8	Weeset	81	85	0.327	0.49	564	1.73	123.5
9	Mill Pond	130	76	0.556	0.91	504	0.90	64.3
10	Nauset Heights	65	149	0.281	0.50	989	3.52	251.3
TOTAL		1518	1529	6.176	7.87	10,148	1.65	117.8

Notes:

1. Nitrogen load (kg/year) is houses x 2.5 persons/house x 208 liters per capita per day x nitrogen concentration of 35 mg/l.
2. Groundwater discharge (m^3/yr) is area x 41 cm/year (based on Cape Cod Commision Water Resources Office Technical Bulletin. No. 91-001, Dec.91).
3. Average shoreline discharge per day ($\text{m}^3/\text{m}/\text{day}$) is discharge/shoreline distance.
4. Average shoreline concentration (mg/l) is load/groundwater discharge.
5. * Visitors' Center "house equivalent" is 670,000 persons/year /365/2.5 x 1/8.

Overall conclusions are as follows:

1. The distribution of fresh groundwater outflow varies greatly along the shoreline depending on the heterogeneous nature of beach sand hydraulic conductivity. Further, the groundwater outflow occurs in a relatively narrow seepage zone only during low tide episodes.
2. The vertical movement of the bay water due to the tidal fluctuation causes major groundwater flow direction changes in the beach during the tidal cycle, effectively creating a hydraulic dam during high tide periods which blocks groundwater discharge.
3. The horizontal shoreward movement of the salty bay water during a flood tide causes a layer of salt water to infiltrate in the beach and overlay the outward flowing fresh water.
4. The concentration of anthropogenic nitrogen in the flowing groundwater tends to vary directly as the freshness of the groundwater, provided there is no denitrification.
5. The timing, location and magnitudes of the groundwater outflow during the tidal cycle can be determined by analysis of the piezometric heads along the beach face during the tidal cycle.
6. The location and magnitudes of the groundwater discharge during the tidal cycle are largely determined by the topography and geology of the beach face.

5. RECOMMENDATIONS FOR ADDITIONAL STUDY

Recommendations for additional study are:

1. Conduct further water quality sampling at major groundwater discharge areas identified in the low tide shoreline surveys. This would include more, and different, discharge zones than that included at the five sites.
2. Accomplish detailed vertical and horizontal water quality surveys at the Salt Pond Site beach to locate and define the on-site sewage disposal leachate discharge from the National Park Service Visitors' Center.
3. Relate the groundwater discharge and surface water runoff quality at Salt Pond to the Salt Pond water quality and flushing characteristics to evaluate the potential for eutrophication.
4. Accomplish additional comprehensive tide related piezometric and water quality measurements in the beach zone, similar to those done at the Salt Pond and Eldredge Sites, to obtain a better understanding of the dynamics of the groundwater discharge phenomena.

ACKNOWLEDGMENTS

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APPENDIX A

BEACH SOIL SAMPLE ANALYSIS

COEFFICIENT OF PERMEABILITY

Project Falling Head Test
Location of Project Environmental Lab
Description of Soil SP #1
Tested by Sang W. Lee
Date of Testing 3/29/97

Mass of Sample, W_s 319.6 g
 Area 16.66 cm^2
 L 10.50 cm
 Total Volume, V_T 174.93 cm^3
 Specific density, ρ_s 2.65 g/cm^3

Porosity, n

$$V_s = W_s / \rho_s = \underline{120.60 \text{ cm}^3}$$

$$V_v = V_T / V_s = \underline{54.33 \text{ cm}^3}$$

$$n = V_v / V_T = \underline{0.311}$$

Area standpipe, a 9.65 cm^2

Test Number	h_1 cm	h_2 cm	time sec	T $^{\circ}C$	K_T cm/sec	α η_T / η_{20}	K_{20} αK_T
1	13	10	393.17	15	0.004	1.0010	0.004
2	13	10	266.59	15	0.006	1.0010	0.006
3	13	10	264.24	15	0.006	1.0010	0.006

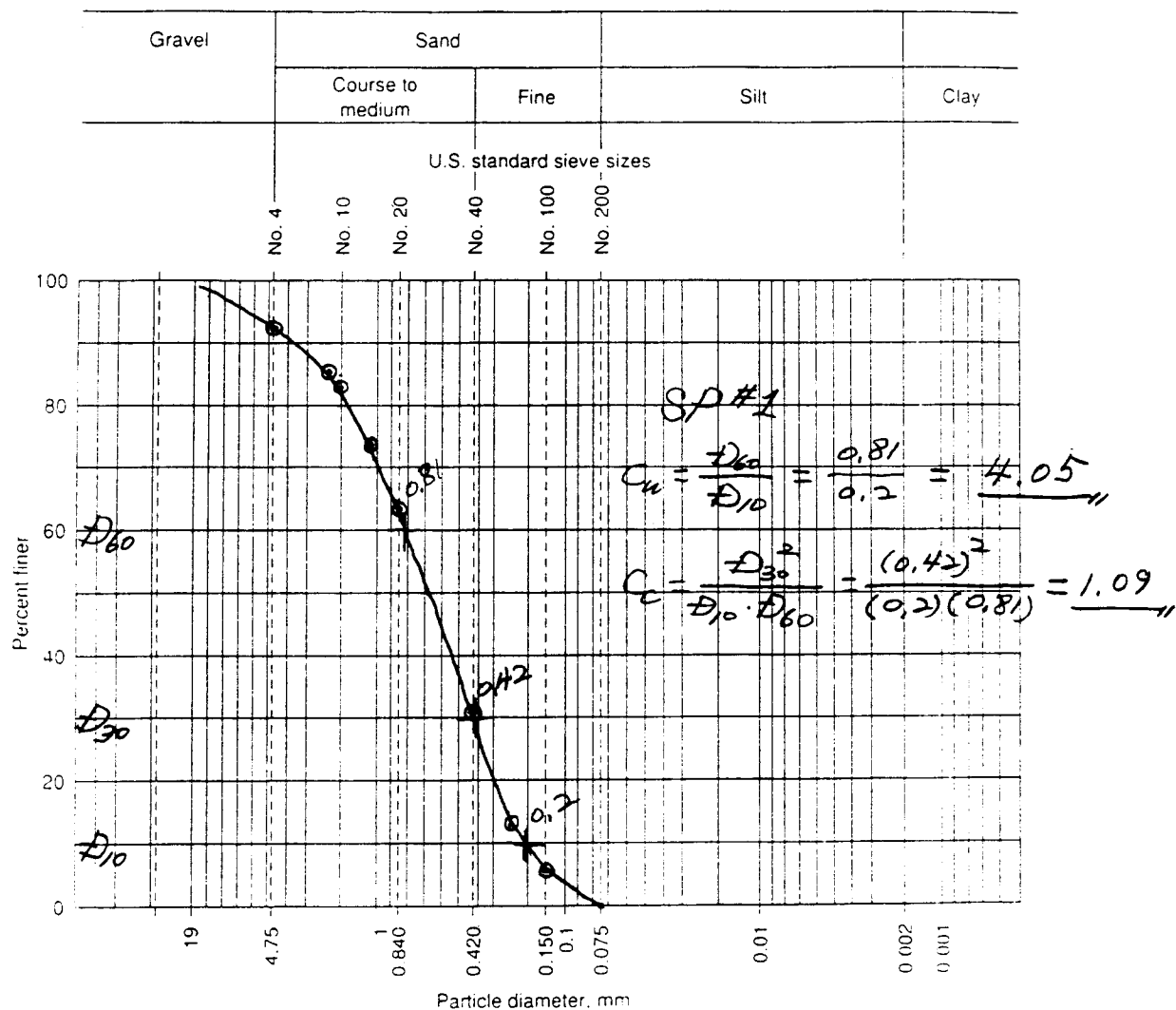
$$\text{Average } K_T = \underline{0.005 \text{ cm/sec}}$$

$$\text{Average } K_{20} = \underline{0.005 \text{ cm/sec}}$$

$$K_T = \frac{aL}{At} \ln \frac{h_1}{h_2}$$

GRAIN SIZE DISTRIBUTION

Data Sheet 5b

Project Sieve for SP #1 Job No. _____Location of Project Soil Lab Boring No. _____ Sample No. _____Tested By Sang W. Lee Date of Testing 3/21/97

Visual soil description _____

Soil classification _____

System _____

COEFFICIENT OF PERMEABILITY

Project Falling Head Test
Location of Project Environmental Lab
Description of Soil SP2 Top
Tested by Sang W. Lee
Date of Testing 3/29/97

Mass of Sample, W_s 347.12 g
 Area 16.66 cm²
 L 12.00 cm
 Total Volume, V_T 199.92 cm³
 Specific density, ρ_s 2.65 g/cm³

Porosity, n

$$V_s = W_s / \rho_s = \underline{130.99 \text{ cm}^3}$$

$$V_v = V_T / V_s = \underline{68.93 \text{ cm}^3}$$

$$n = V_v / V_T = \underline{0.345}$$

Area standpipe, a 9.65 cm²

Test Number	h_1 cm	h_2 cm	time sec	T °C	K_T cm/sec	α η_T / η_{20}	K_{20} αK_T
1	12	11	217.21	16	0.00278	1.0008	0.00279
2	11	10	254.73	15	0.00260	1.0010	0.00260
3	11	10	258.16	15	0.00257	1.0010	0.00257

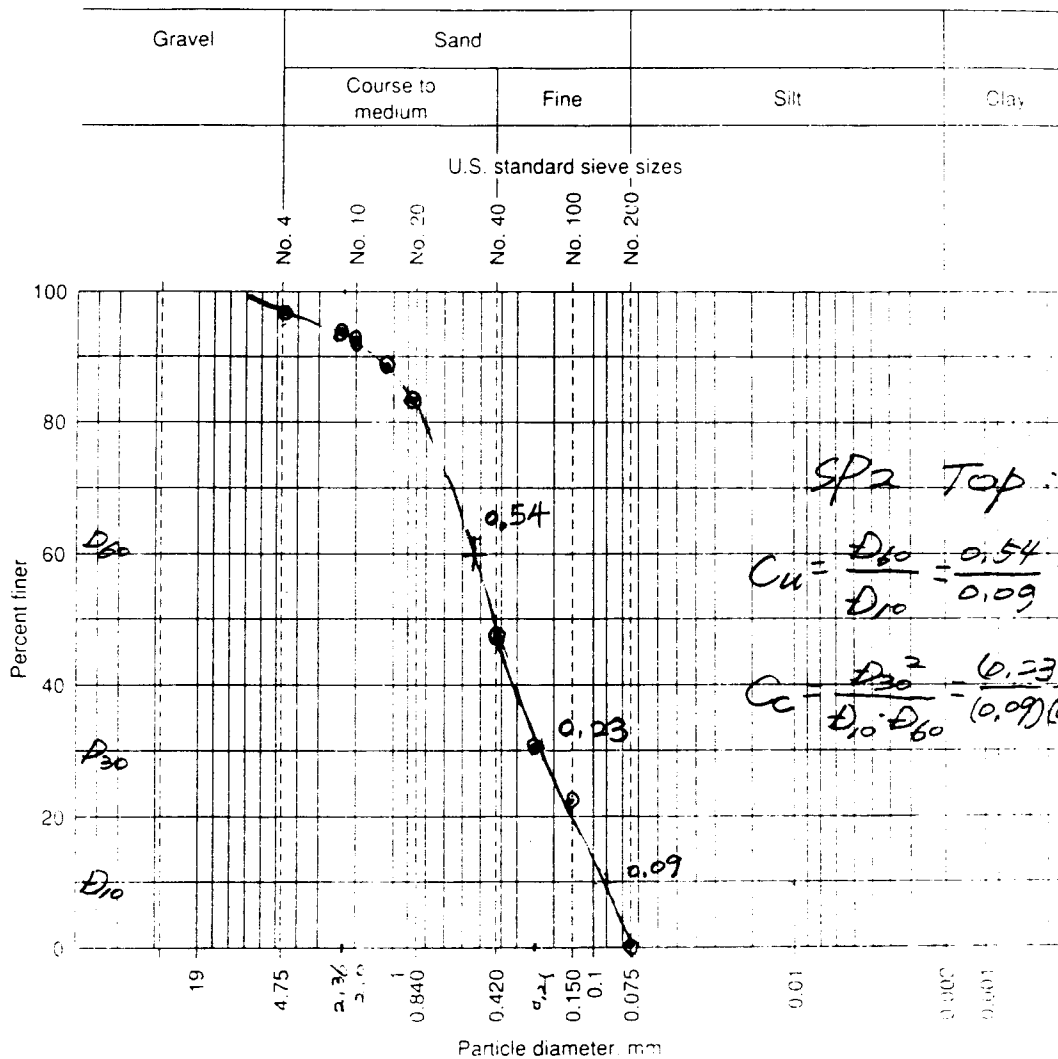
$$\text{Average } K_T = \underline{0.0027 \text{ cm/sec}}$$

$$\text{Average } K_{20} = \underline{0.0027 \text{ cm/sec}}$$

$$K_T = \frac{aL}{At} \ln \frac{h_1}{h_2}$$

GRAIN SIZE DISTRIBUTION

Data Sheet 5b

Project Sieve for SP2 Top Job No. _____Location of Project Soil Lab. Boring No. _____ Sample No. _____Tested By Sang W. Lee Date of Testing 3/21/97

Visual soil description _____

Soil classification _____

System _____

COEFFICIENT OF PERMEABILITY

<i>Project</i>	<u>Falling Head Test</u>
<i>Location of Project</i>	<u>Environmental Lab</u>
<i>Description of Soil</i>	<u>SPB</u>
<i>Tested by</i>	<u>Sang W. Lee</u>
<i>Date of Testing</i>	<u>3/29/97</u>

Mass of Sample, W_s	<u>341.7 g</u>
Area	<u>16.66 cm²</u>
L	<u>11.50 cm</u>
Total Volume, V_T	<u>191.59 cm³</u>
Specific density, ρ_s	<u>2.65 g / cm³</u>

Porosity, n

$$V_s = W_s / \rho_s = \underline{128.94 \text{ cm}^3}$$

$$V_v = V_T / V_s = \underline{62.65 \text{ cm}^3}$$

$$n = V_v / V_T = \underline{0.327}$$

Area standpipe, a	<u>9.65 cm²</u>
---------------------	----------------------------

Test Number	h_1 cm	h_2 cm	time sec	T °C	K_T cm/sec	α η_T / η_{20}	K_{20} αK_T
1	11	9	139.57	15	0.00958	1.0010	0.00959
2	11	9	163.58	15	0.00817	1.0010	0.00818
3	12	10	120.81	15	0.01005	1.0010	0.01006

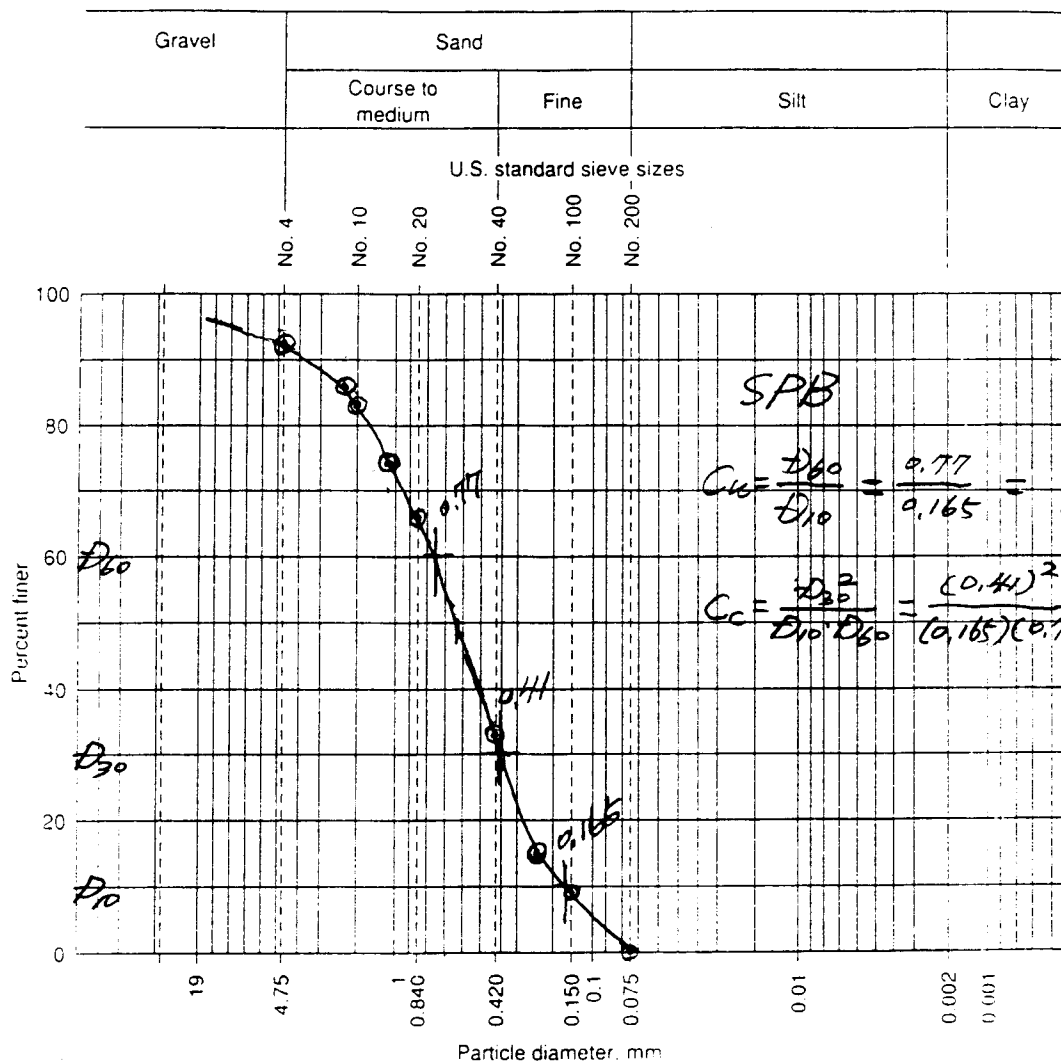
Average $K_T = \underline{0.0093 \text{ cm/sec}}$

Average $K_{20} = \underline{0.0093 \text{ cm/sec}}$

$$K_T = \frac{aL}{At} \ln \frac{h_1}{h_2}$$

GRAIN SIZE DISTRIBUTION

Data Sheet 5b

Project Sieve for SPB Job No. _____Location of Project Soil Lab Boring No. _____ Sample No. _____Tested By Sang W. Lee Date of Testing 3 / 21 / 97

Visual soil description _____

Soil classification _____

System _____

COEFFICIENT OF PERMEABILITY

Project Falling Head Test
Location of Project Environmental Lab
Description of Soil SG1
Tested by Sang W. Lee
Date of Testing 3/29/97

Mass of Sample, W_s 330.62 g
 Area 16.66 cm²
 L 10.70 cm
 Total Volume, V_T 178.262 cm³
 Specific density, ρ_s 2.65 g / cm³

Porosity, n

$$V_s = W_s / \rho_s = \underline{124.76 \text{ cm}^3}$$

$$V_v = V_T / V_s = \underline{53.50 \text{ cm}^3}$$

$$n = V_v / V_T = \underline{0.300}$$

Area standpipe, a 9.65 cm²

Test Number	h_1 cm	h_2 cm	time sec	T °C	K_T cm/sec	α η_T / η_{20}	K_{20} αK_T
1	12	9	82.23	16	0.022	1.0008	0.022
2	13	10	80.84	16	0.020	1.0008	0.020
3	12	9	83.28	16	0.021	1.0008	0.021

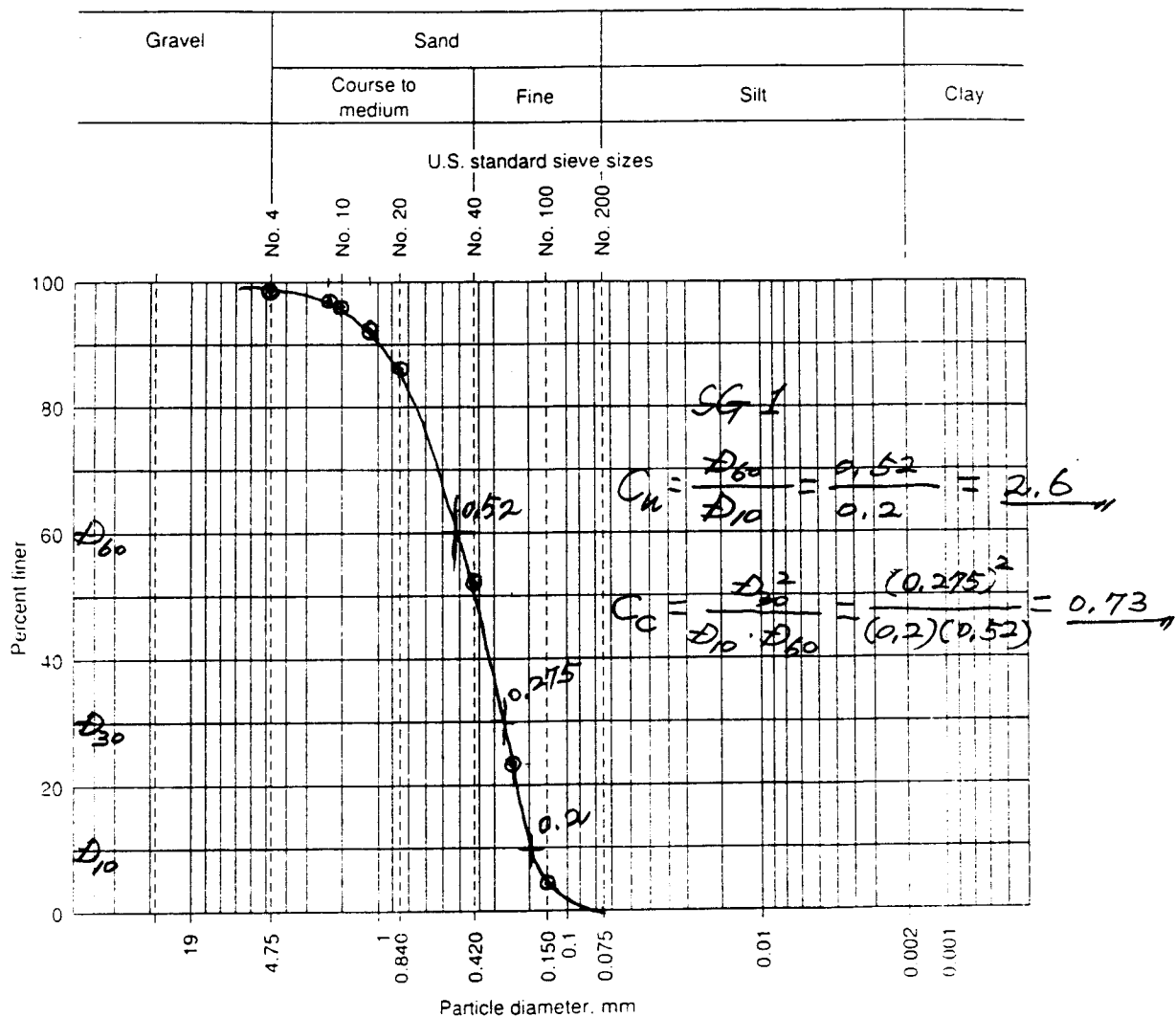
Average $K_T = \underline{0.021 \text{ cm/sec}}$

Average $K_{20} = \underline{0.021 \text{ cm/sec}}$

$$K_T = \frac{aL}{At} \ln \frac{h_1}{h_2}$$

GRAIN SIZE DISTRIBUTION

Data Sheet 5b

Project Sieve for SG 1 Job No. _____Location of Project Soil Lab Boring No. _____ Sample No. _____Tested By Sang W. Lee Date of Testing 3/21/97

Visual soil description _____

Soil classification _____

System _____

COEFFICIENT OF PERMEABILITY

<i>Project</i>	<u>Falling Head Test</u>
<i>Location of Project</i>	<u>Environmental Lab</u>
<i>Description of Soil</i>	<u>SG2</u>
<i>Tested by</i>	<u>Sang W. Lee</u>
<i>Date of Testing</i>	<u>3/29/97</u>

Mass of Sample, W_s	<u>308.72 g</u>
Area	<u>16.66 cm²</u>
L	<u>10.80 cm</u>
Total Volume, V_T	<u>179.928 cm³</u>
Specific density, ρ_s	<u>2.65 g/cm³</u>

Porosity, n

$$V_s = W_s / \rho_s = \underline{116.50 \text{ cm}^3}$$

$$V_v = V_T / V_s = \underline{63.43 \text{ cm}^3}$$

$$n = V_v / V_T = \underline{0.353}$$

Area standpipe, a	<u>9.65 cm²</u>
---------------------	----------------------------

Test Number	h_1 cm	h_2 cm	time sec	T °C	K_T cm/sec	α η_T / η_{20}	K_{20} αK_T
1	13	12	946.3	15	0.00053	1.0010	0.00053
2	12	11	937.15	15	0.00058	1.0010	0.00058
3	12	11	941.26	15	0.00058	1.0010	0.00058

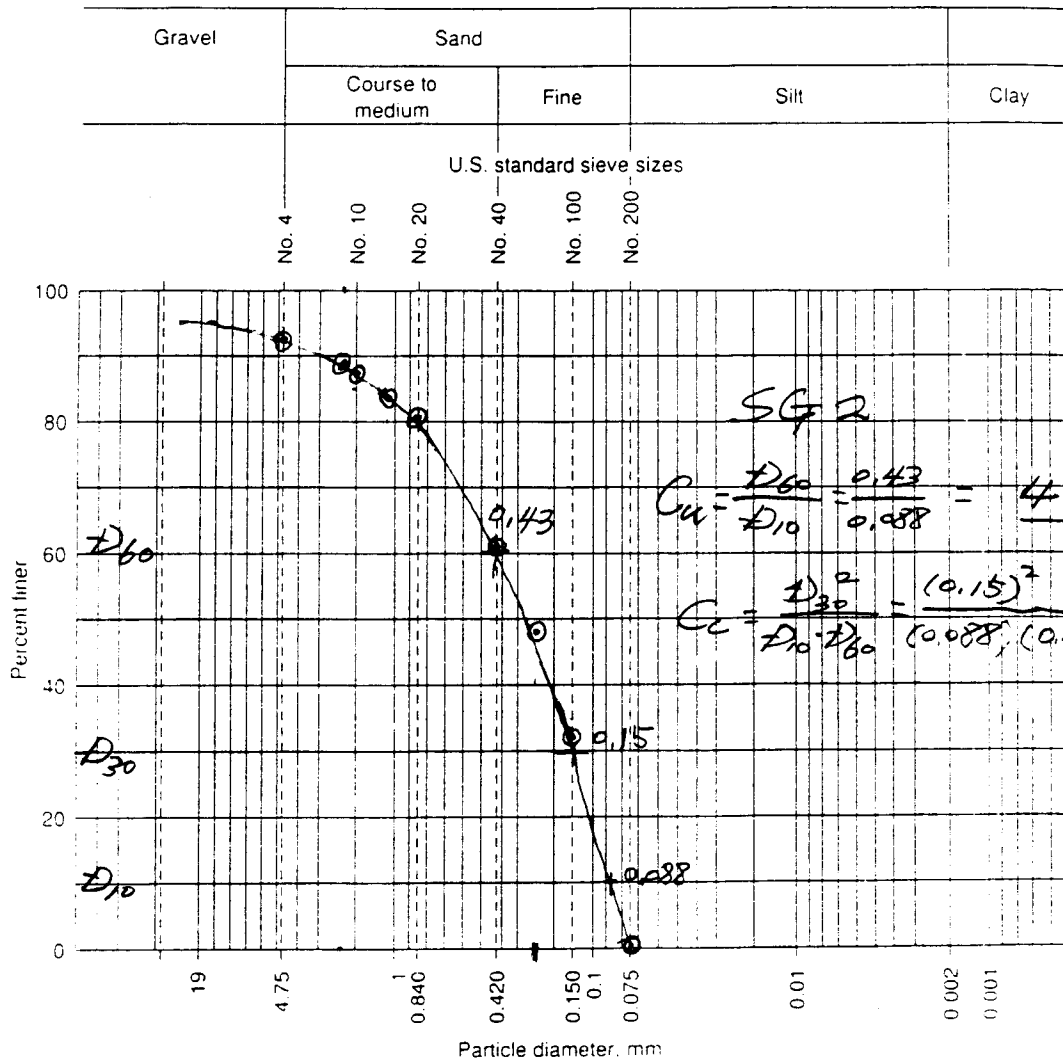
Average $K_T = \underline{0.0006 \text{ cm/sec}}$

Average $K_{20} = \underline{0.0006 \text{ cm/sec}}$

$$K_T = \frac{aL}{At} \ln \frac{h_1}{h_2}$$

GRAIN SIZE DISTRIBUTION

Data Sheet 5b

Project Sieve for SG 2 Job No. _____Location of Project Soil Lab Boring No. _____ Sample No. _____Tested By Sang W. Lee Date of Testing 3/21/97

Visual soil description _____

Soil classification _____

System _____

COEFFICIENT OF PERMEABILITY

Project Falling Head Test
Location of Project Environmental Lab
Description of Soil Navseset-Eldridge Beach SP #1 (Cape Cod)
Tested by Sang W. Lee
Date of Testing 3/29/97

Mass of Sample, W_s 317.45 g
 Area 16.66 cm²
 L 10.3 cm
 Total Volume, V_T 171.598 cm³
 Specific density, ρ_s 2.65 g / cm³

Porosity, n

$$V_s = W_s / \rho_s = 119.79 \text{ cm}^3$$

$$V_v = V_T / V_s = 51.81 \text{ cm}^3$$

$$n = V_v / V_T = 0.302$$

Area standpipe, a 9.65 cm²

Test Number	h_1 cm	h_2 cm	time sec	T °C	K_T cm/sec	α η_T / η_{20}	K_{20} αK_T
1	11	5	40.45	15	0.116	1.0010	0.116
2	13	10	20.31	16	0.077	1.0008	0.077
3	12	9	20.24	15	0.085	1.0010	0.085

Average $K_T = 0.093 \text{ cm/sec}$

Average $K_{20} = 0.093 \text{ cm/sec}$

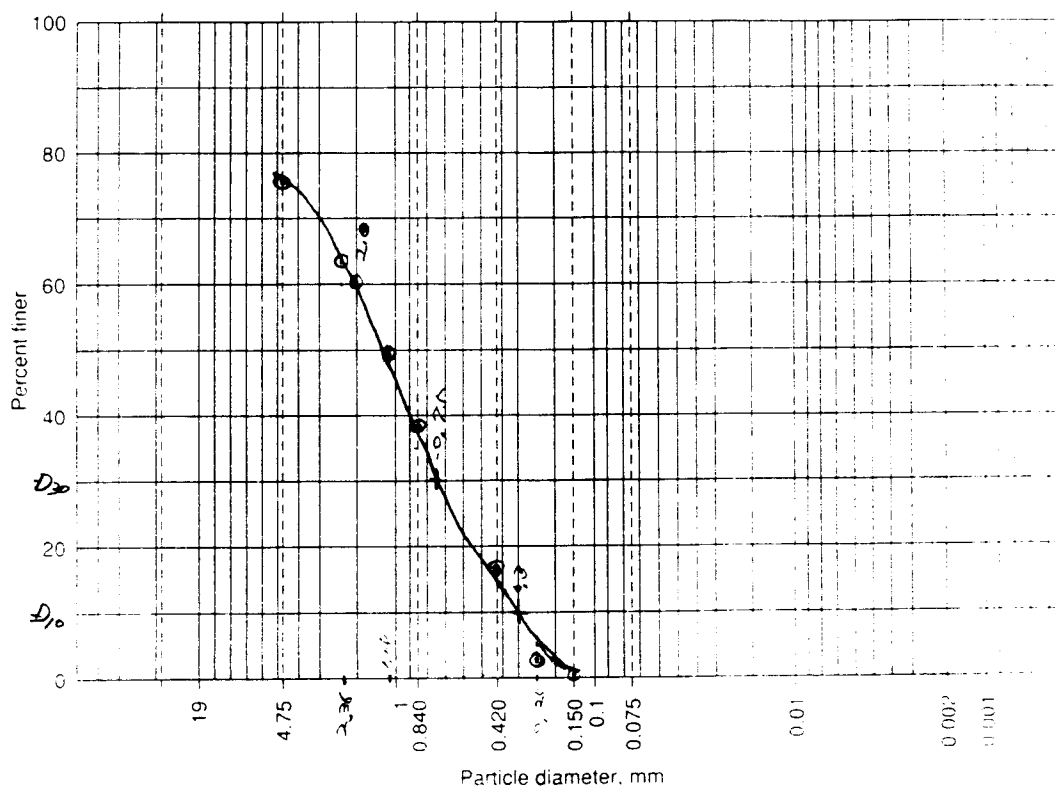
$$K_T = \frac{aL}{At} \ln \frac{h_1}{h_2}$$

GRAIN SIZE DISTRIBUTION

Data Sheet 5b

Project Nauvoo Job No. _____Location of Project E101 Boring No. Sp1 Sample No. SP#1Tested By Sang W. Lee Date of Testing 11/1/96

Gravel	Sand		Silt	Clay	
	Course to medium	Fine			
U.S. standard sieve sizes					
No. 4	No. 10	No. 20	No. 40	No. 100	No. 200



Visual soil description _____

Soil classification _____

System _____

$$C_u = \frac{D_{60}}{D_{10}} = \frac{2.0}{0.3} = 6.67$$

$$C_c = \frac{D_{30}^2}{D_{10} D_{60}} = \frac{0.75^2}{0.3(2.0)} = 0.94$$

COEFFICIENT OF PERMEABILITY

Project Falling Head Test
Location of Project Environmental Lab
Description of Soil Navseset-Eldridge Beach SP #2 (Cape Cod, Aug, 95)
Tested by Sang W. Lee
Date of Testing 3/29/97

Mass of Sample, W_s 321.87 g
 Area 16.66 cm²
 L 10.5 cm
 Total Volume, V_T 174.94 cm³
 Specific density, ρ_s 2.65 g / cm³

Porosity, n

$$V_s = W_s / \rho_s = 121.46 \text{ cm}^3$$

$$V_v = V_T / V_s = 53.48 \text{ cm}^3$$

$$n = V_v / V_T = 0.306$$

Area standpipe, a 9.65 cm²

Test Number	h_1 cm	h_2 cm	time sec	T °C	K_T cm/sec	α η_T / η_{20}	K_{20} αK_T
1	10	7	36.33	16	0.060	1.0008	0.060
2	13	10	36.24	16	0.044	1.0008	0.044
3	12	9	37.01	15	0.047	1.0010	0.047

Average $K_T = 0.050 \text{ cm/sec}$

Average $K_{20} = 0.050 \text{ cm/sec}$

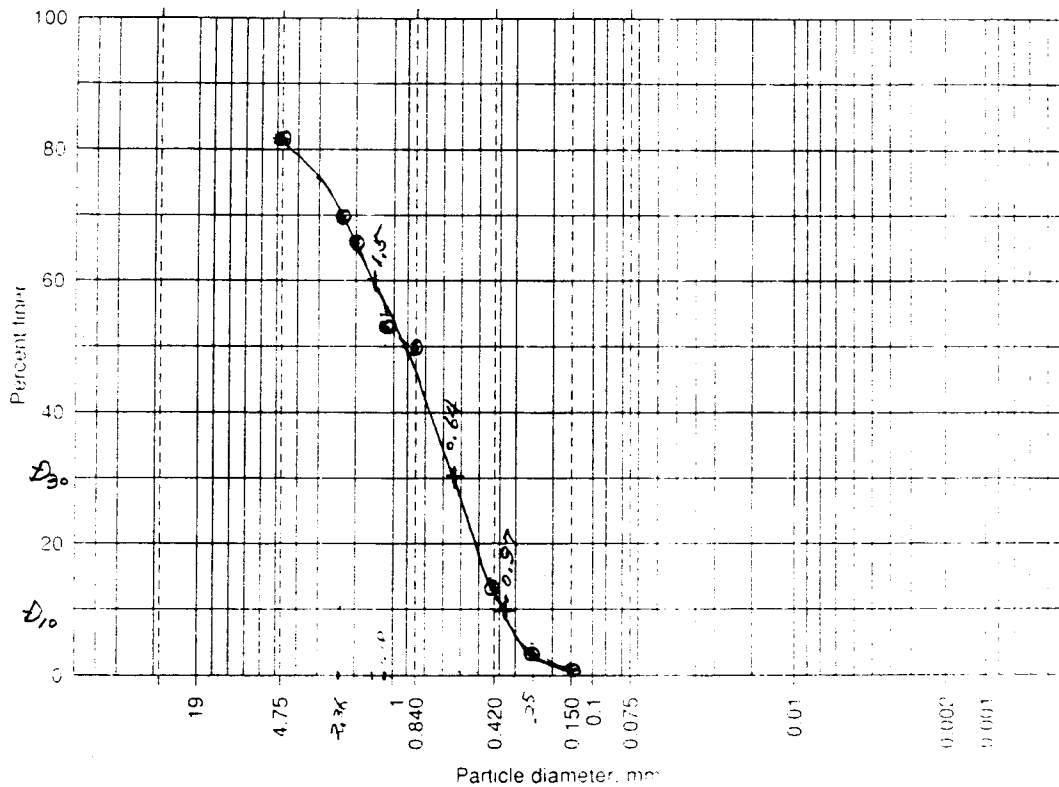
$$K_T = \frac{aL}{At} \ln \frac{h_1}{h_2}$$

GRAIN SIZE DISTRIBUTION

Data Sheet 5b

Project Siete Noiset Job No. _____
 Location of Project ETA Boring No. SP 2 Sample No. SP #2
 Tested By Sang W. Lee Date of Testing 11/1/96

Gravel	Sand		Silt	Clay	
	Course to medium	Fine			
U.S. standard sieve sizes					
No. 4	No. 10	No. 20	No. 40	No. 100	No. 200



Visual soil description _____

Soil classification _____

System _____

$$C_u = \frac{D_{60}}{D_{10}} = \frac{1.5}{0.37} = 4.05$$

$$C_c = \frac{D_{30}^2}{D_{10} D_{60}} = \frac{0.64^2}{1.5 (0.37)} = 0.74$$

COEFFICIENT OF PERMEABILITY

Project Falling Head Test
Location of Project Environmental Lab
Description of Soil Navseset-Eldridge Beach No Spring (Cape Cod)
Tested by Sang W. Lee
Date of Testing 3/29/97

Mass of Sample, W_s 332.36 g
 Area 16.66 cm^2
 L 11.00 cm
 Total Volume, V_T 183.26 cm^3
 Specific density, ρ_s 2.65 g / cm^3

Porosity, n

$$V_s = W_s / \rho_s = \underline{125.42 \text{ cm}^3}$$

$$V_v = V_T / V_s = \underline{57.84 \text{ cm}^3}$$

$$n = V_v / V_T = \underline{0.316}$$

Area standpipe, a 9.65 cm^2

Test Number	h_1 cm	h_2 cm	time sec	T $^{\circ}\text{C}$	K_T cm/sec	α η_T / η_{20}	K_{20} αK_T
1	11	8	39.42	16	0.051	1.0008	0.052
2	11	8	37.01	16	0.055	1.0008	0.055
3	11	8	40.16	15	0.051	1.0010	0.051

Average $K_T = \underline{0.052 \text{ cm/sec}}$

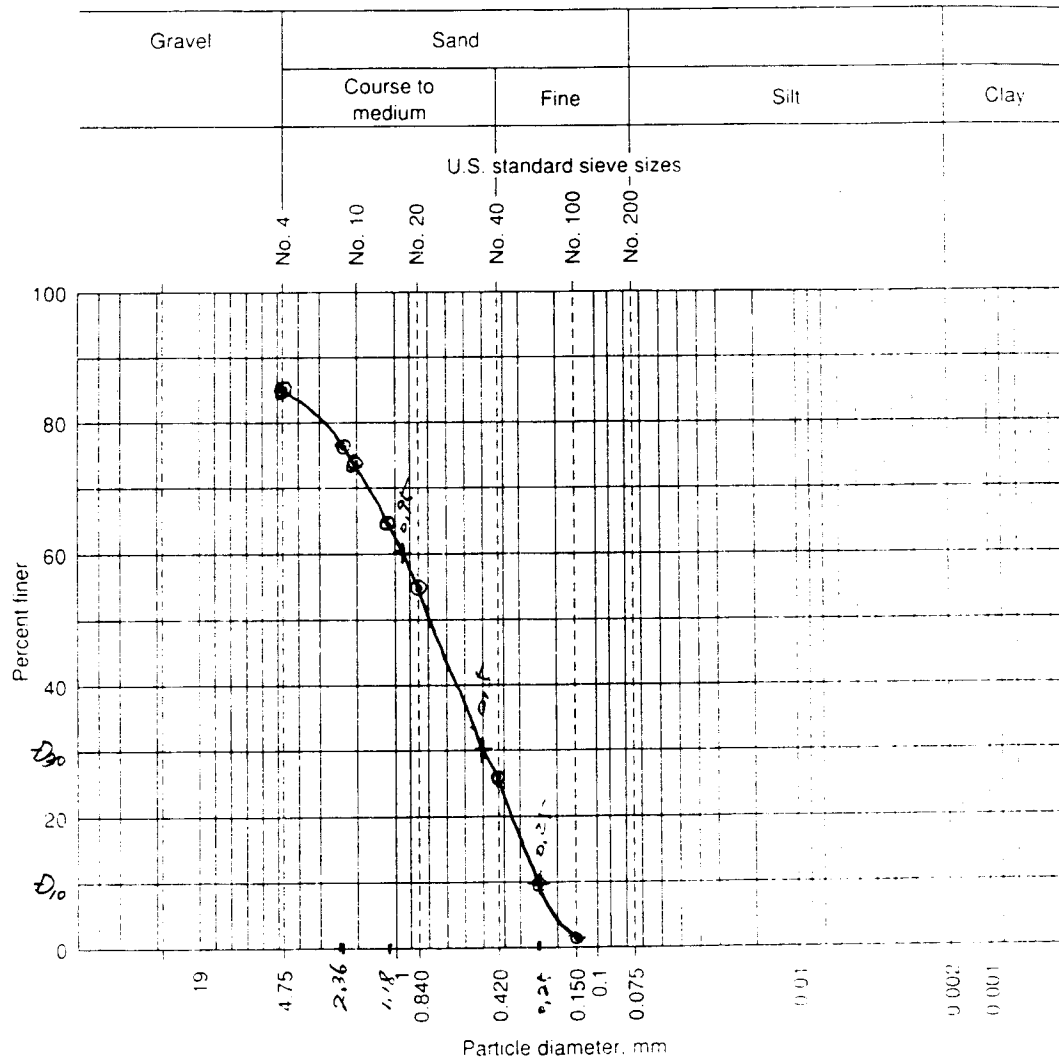
Average $K_{20} = \underline{0.052 \text{ cm/sec}}$

$$K_T = \frac{aL}{At} \ln \frac{h_1}{h_2}$$

GRAIN SIZE DISTRIBUTION

Data Sheet 5b

Project Naurex Job No. _____
 Location of Project Eld. Boring No. No Spring Sample No. No Spring
 Tested By Sang W. Lee Date of Testing 11/1/96



Visual soil description _____

Soil classification _____

System _____

$$C_u = \frac{D_{60}}{D_{10}} = \frac{0.95}{0.25} = 3.8$$

$$C_c = \frac{D_{30}^2}{D_{10} D_{60}} = \frac{0.52^2}{0.25(0.95)} = 1.05$$

COEFFICIENT OF PERMEABILITY

<i>Project</i>	<u>Falling Head Test</u>
<i>Location of Project</i>	<u>Environmental Lab</u>
<i>Description of Soil</i>	<u>ELD Monitor Well P4 (Cape Cod)</u>
<i>Tested by</i>	<u>Sang W. Lee</u>
<i>Date of Testing</i>	<u>3/29/97</u>

Mass of Sample, W_s	<u>307.93 g</u>
Area	<u>16.66 cm²</u>
L	<u>10.00 cm</u>
Total Volume, V_T	<u>166.6 cm³</u>
Specific density, ρ_s	<u>2.65 g / cm³</u>

Porosity, n

$$V_s = W_s / \rho_s = \underline{116.20 \text{ cm}^3}$$

$$V_v = V_T / V_s = \underline{50.40 \text{ cm}^3}$$

$$n = V_v / V_T = \underline{\boxed{0.303}}$$

Area standpipe, a	<u>9.65 cm²</u>
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Test Number	h_1 cm	h_2 cm	time sec	T °C	K_T cm/sec	α η_T / η_{20}	K_{20} αK_T
1	13	10	39.42	16	0.039	1.0008	0.039
2	13.5	10.5	37.01	15	0.039	1.0010	0.039
3	13	10	40.16	15	0.038	1.0010	0.038

Average $K_T = \underline{0.039 \text{ cm/sec}}$

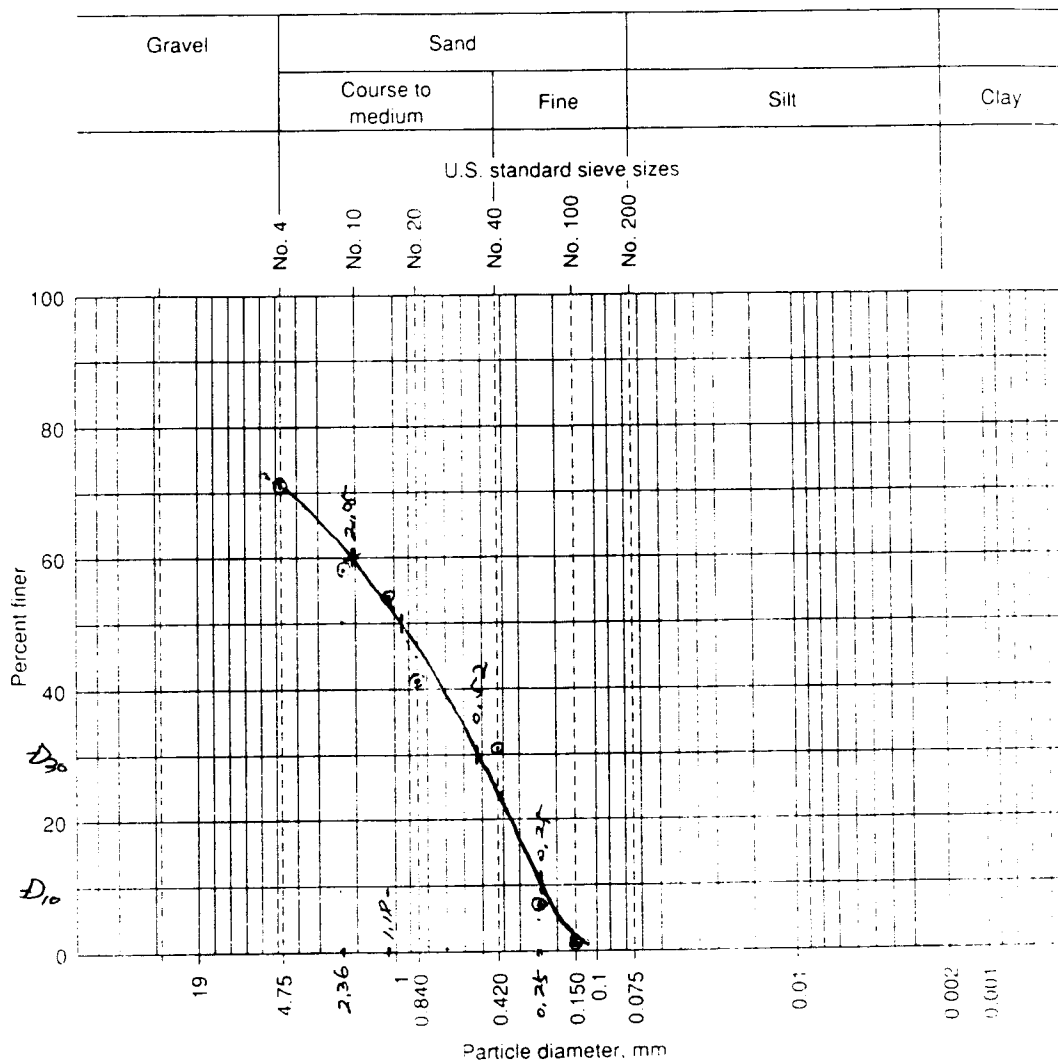
Average $K_{20} = \underline{0.039 \text{ cm/sec}}$

$$K_T = \frac{aL}{At} \ln \frac{h_1}{h_2}$$

GRAIN SIZE DISTRIBUTION

Data Sheet 5b

Project Nauaset Job No. _____
 Location of Project El Estero Boring No. MW P4 Sample No. P4
 Tested By Sang W. Lee Date of Testing 11/1/96



Visual soil description _____

Soil classification _____

System _____

$$C_u = \frac{D_{60}}{D_{10}} = \frac{2.05}{0.25} = 8.2$$

$$C_s = \frac{D_{30}^2}{D_{10} D_{60}} = \frac{0.52^2}{0.25(2.05)} = 0.53$$

COEFFICIENT OF PERMEABILITY

<i>Project</i>	<u>Falling Head Test</u>
<i>Location of Project</i>	<u>Environmental Lab</u>
<i>Description of Soil</i>	<u>W1</u>
<i>Tested by</i>	<u>Sang W. Lee</u>
<i>Date of Testing</i>	<u>3/29/97</u>

Mass of Sample, W_s	<u>222.82 g</u>
Area	<u>16.66 cm²</u>
L	<u>6.70 cm</u>
Total Volume, V_T	<u>111.622 cm³</u>
Specific density, ρ_s	<u>2.65 g / cm³</u>

Porosity, n

$$V_s = W_s / \rho_s = \underline{84.08 \text{ cm}^3}$$

$$V_v = V_T / V_s = \underline{27.54 \text{ cm}^3}$$

$$n = V_v / V_T = \underline{0.247}$$

Area standpipe, a	<u>9.65 cm²</u>
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Test Number	h_1 cm	h_2 cm	time sec	T °C	K_T cm/sec	α η_T / η_{20}	K_{20} αK_T
1	14	11	18.66	16	0.050	1.0008	0.050
2	11	7	27.95	15	0.063	1.0010	0.063
3	11	8	16.67	15	0.074	1.0010	0.074

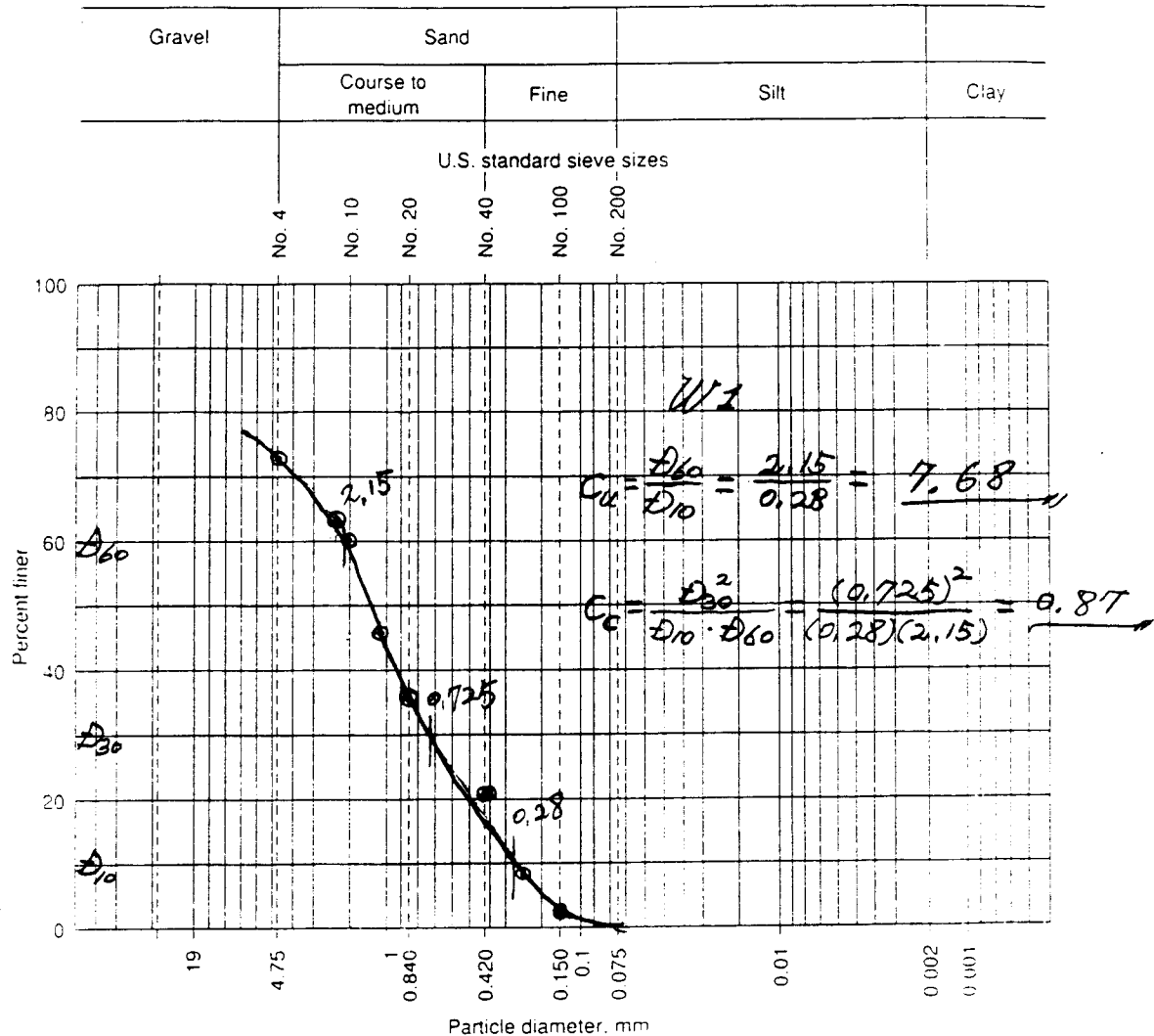
Average $K_T = \underline{0.062 \text{ cm/sec}}$

Average $K_{20} = \underline{0.062 \text{ cm/sec}}$

$$K_T = \frac{aL}{At} \ln \frac{h_1}{h_2}$$

GRAIN SIZE DISTRIBUTION

Data Sheet 5b

Project Sieve for W1 Job No. _____Location of Project Soil Lab Boring No. _____ Sample No. _____Tested By Sang W. Lee Date of Testing 3/21/97

Visual soil description _____

Soil classification _____

System _____

COEFFICIENT OF PERMEABILITY

<i>Project</i>	<u>Falling Head Test</u>
<i>Location of Project</i>	<u>Environmental Lab</u>
<i>Description of Soil</i>	<u>W2</u>
<i>Tested by</i>	<u>Sang W. Lee</u>
<i>Date of Testing</i>	<u>3/29/97</u>

Mass of Sample, W_s	<u>333.1 g</u>
Area	<u>16.66 cm²</u>
L	<u>11.00 cm</u>
Total Volume, V_T	<u>183.26 cm³</u>
Specific density, ρ_s	<u>2.65 g/cm³</u>

Porosity, n

$$V_s = W_s / \rho_s = \underline{125.70 \text{ cm}^3}$$

$$V_v = V_T / V_s = \underline{57.56 \text{ cm}^3}$$

$$n = V_v / V_T = \underline{\boxed{0.314}}$$

Area standpipe, a	<u>9.65 cm²</u>
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Test Number	h_1 cm	h_2 cm	time sec	T °C	K_T cm/sec	α η_T / η_{20}	K_{20} αK_T
1	13	10	471.78	16	0.004	1.0008	0.004
2	14	11	371.12	15	0.004	1.0010	0.004
3	13	10	398.32	15	0.004	1.0010	0.004

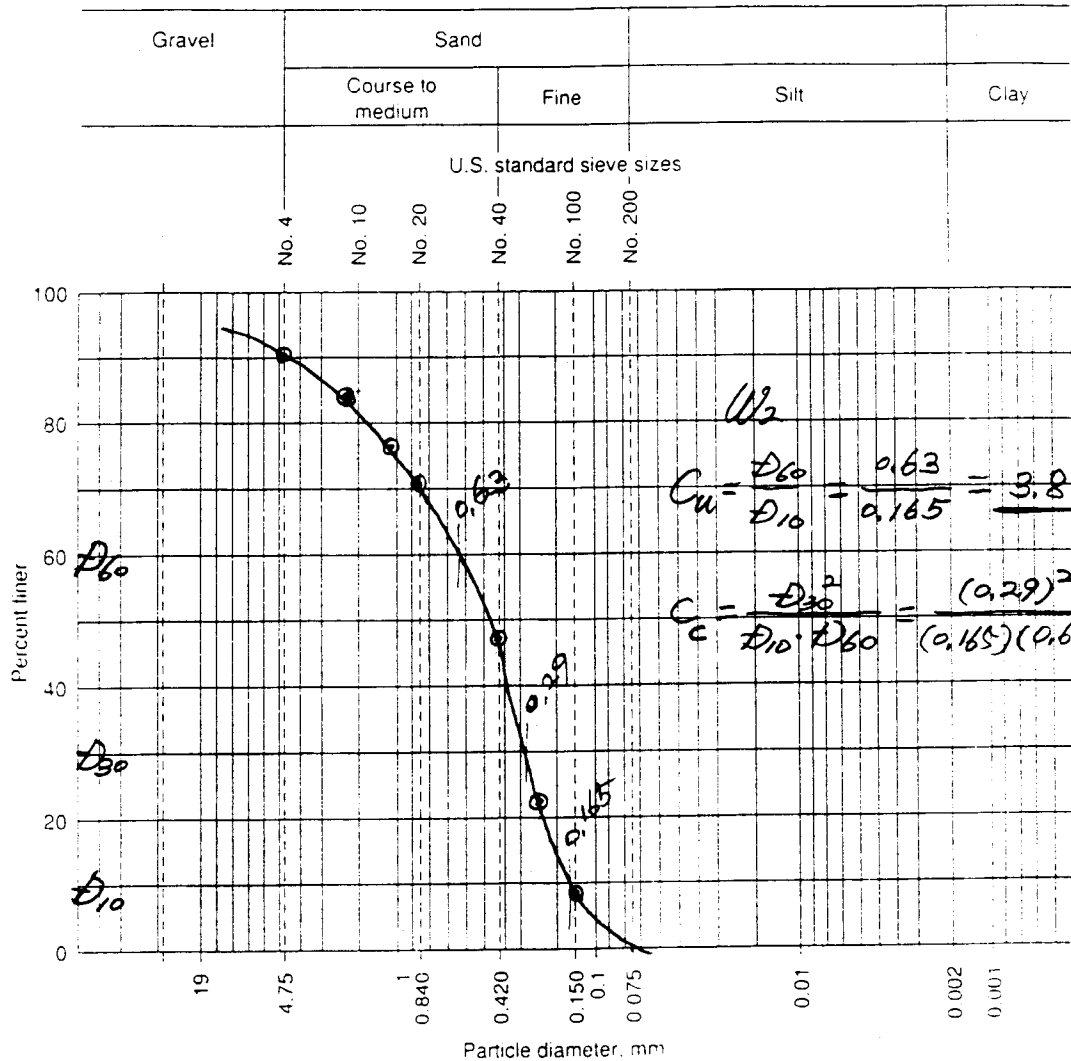
Average $K_T = \underline{0.004 \text{ cm/sec}}$

Average $K_{20} = \underline{0.004 \text{ cm/sec}}$

$$K_T = \frac{aL}{At} \ln \frac{h_1}{h_2}$$

GRAIN SIZE DISTRIBUTION

Data Sheet 5b

Project Sieve for W2 Job No. _____Location of Project Soil Lab Boring No. _____ Sample No. _____Tested By Sang W. Lee Date of Testing 3/21/97

Visual soil description _____

Soil classification _____

System _____

APPENDIX B

THERMAL INFRARED AIR PHOTOS

A: SALT POND

A



B SALT POND BAY

B



C TOWN COVE (NORTH)



4
D TOWN COVE (SOUTH)



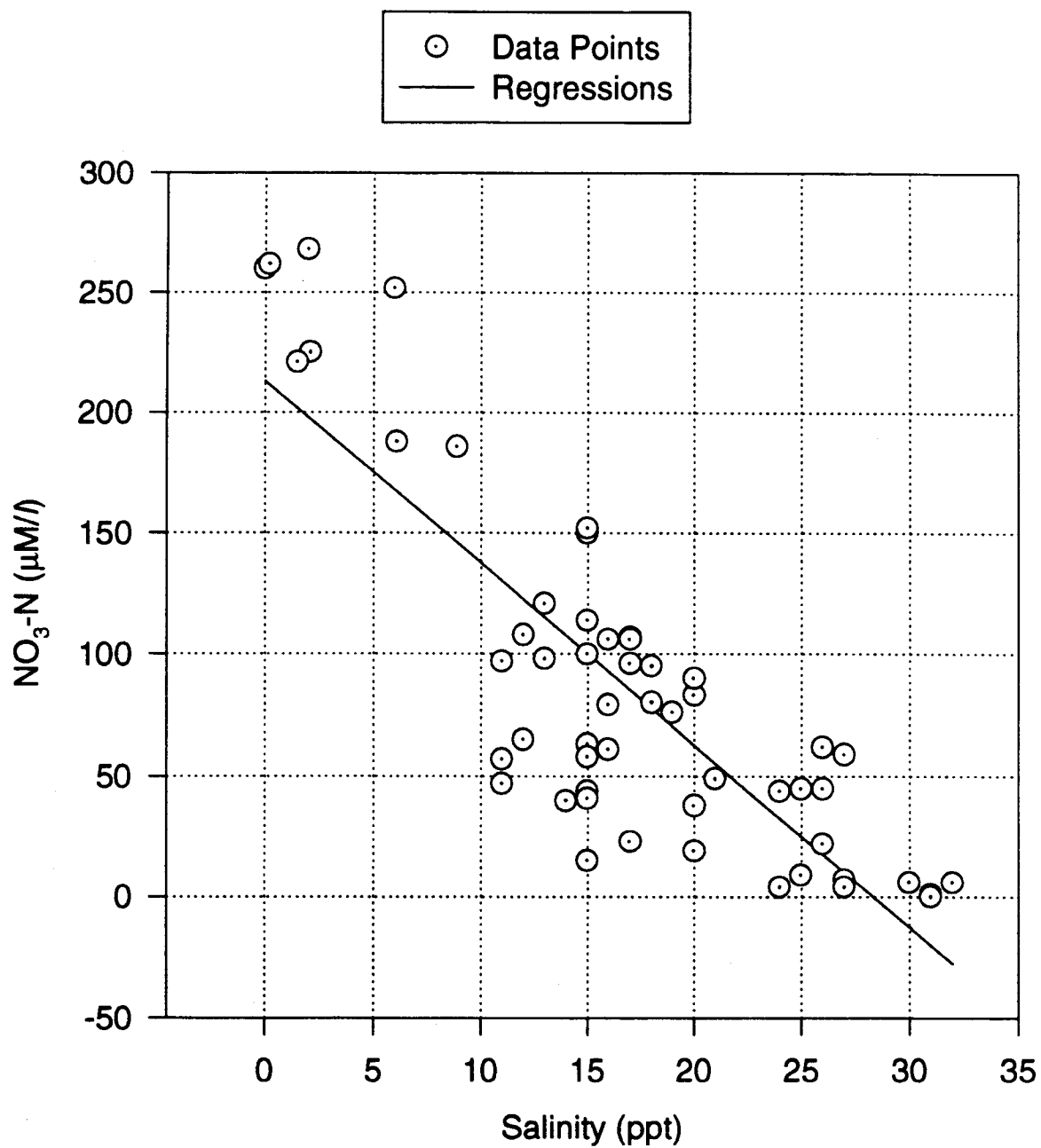
E WEESET

E

APPENDIX C

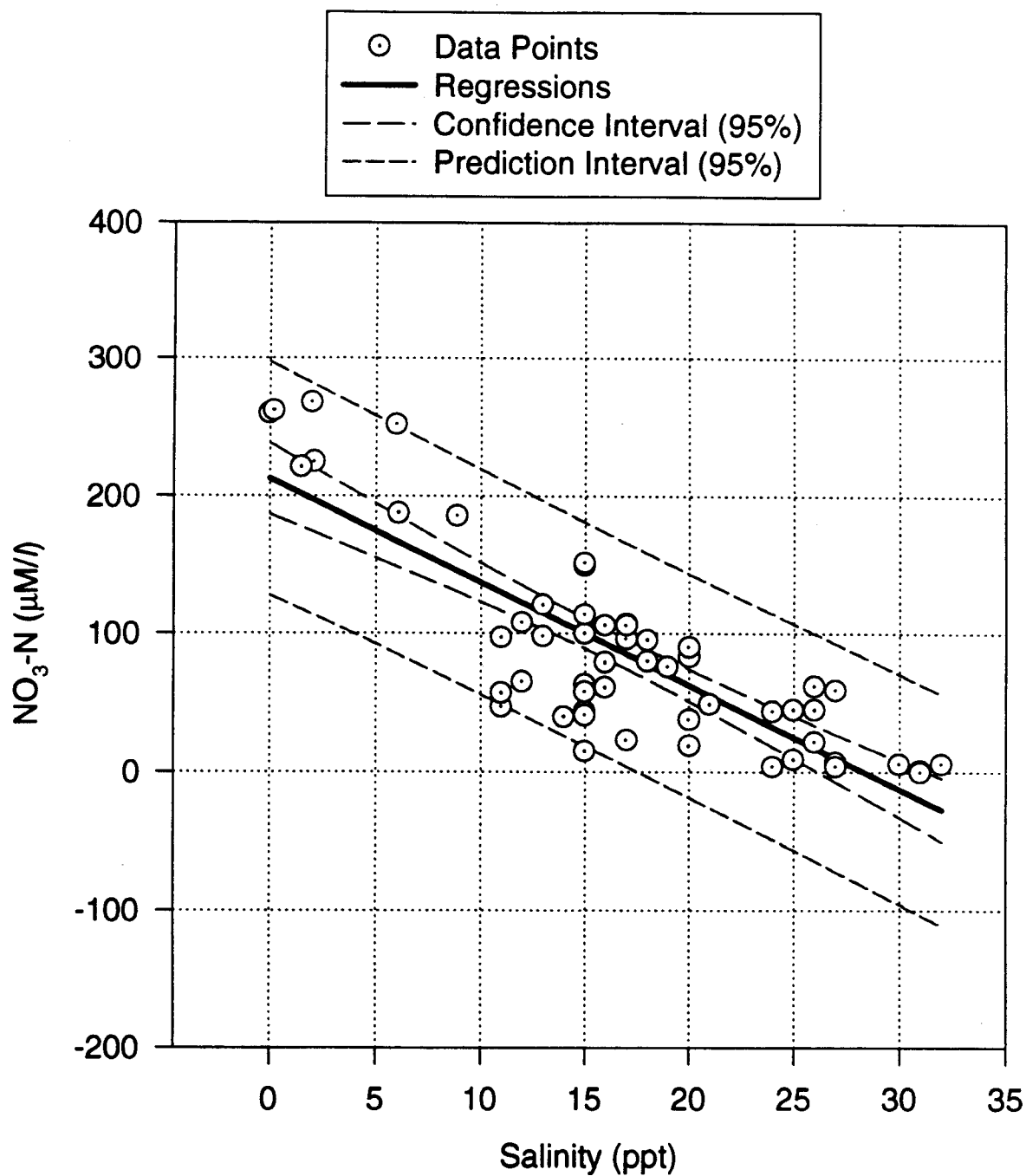
SALINITY AND NITROGEN STATISTICAL ANALYSIS

Salt Pond Site, Salinity and $\text{NO}_3\text{-N}$ Relationship



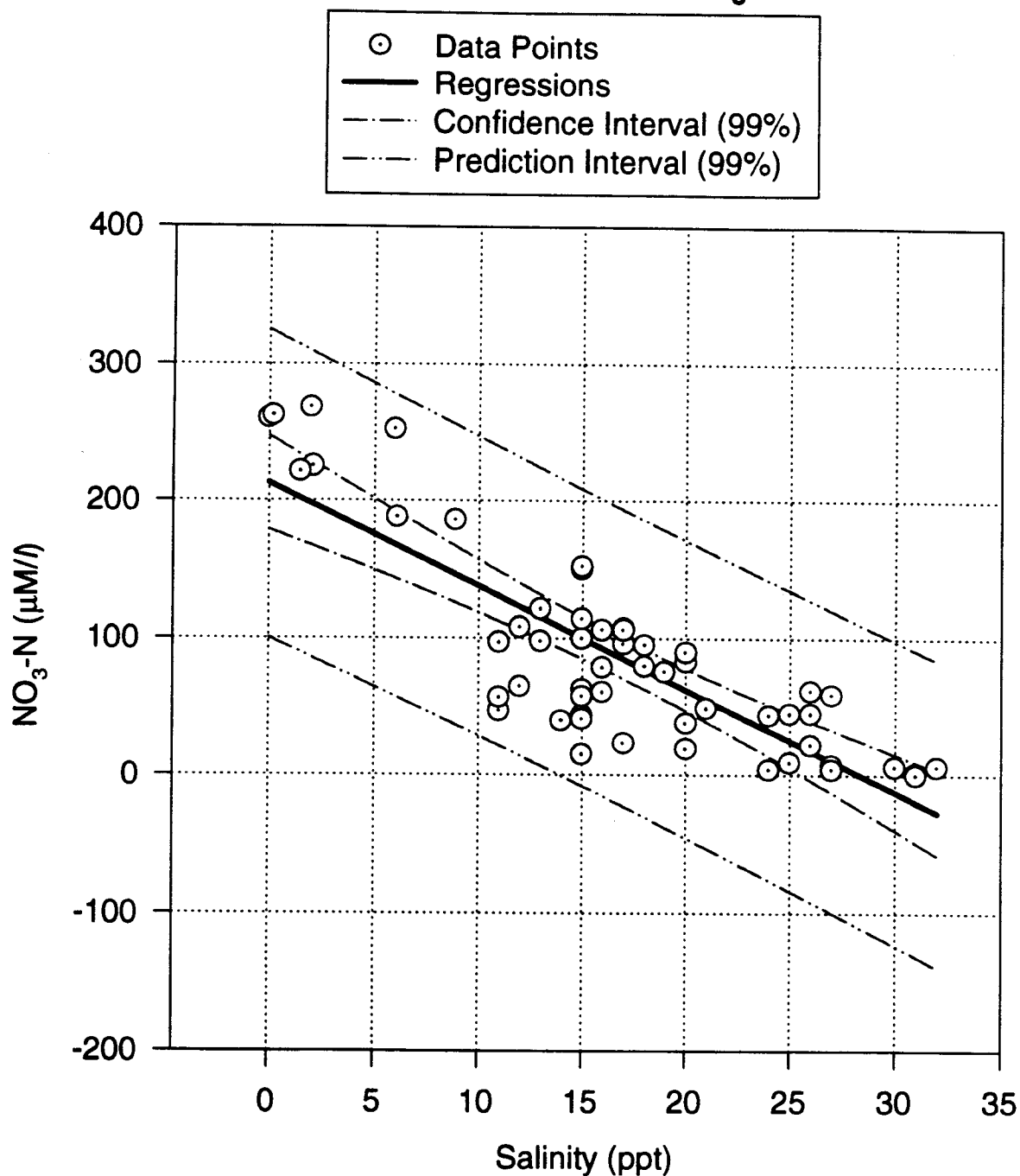
$b[0]=212.8943792817$, $b[1]=-7.5168820737$, $r^2=0.6900398494$

Salt Pond Site, Salinity and $\text{NO}_3\text{-N}$ Relationship



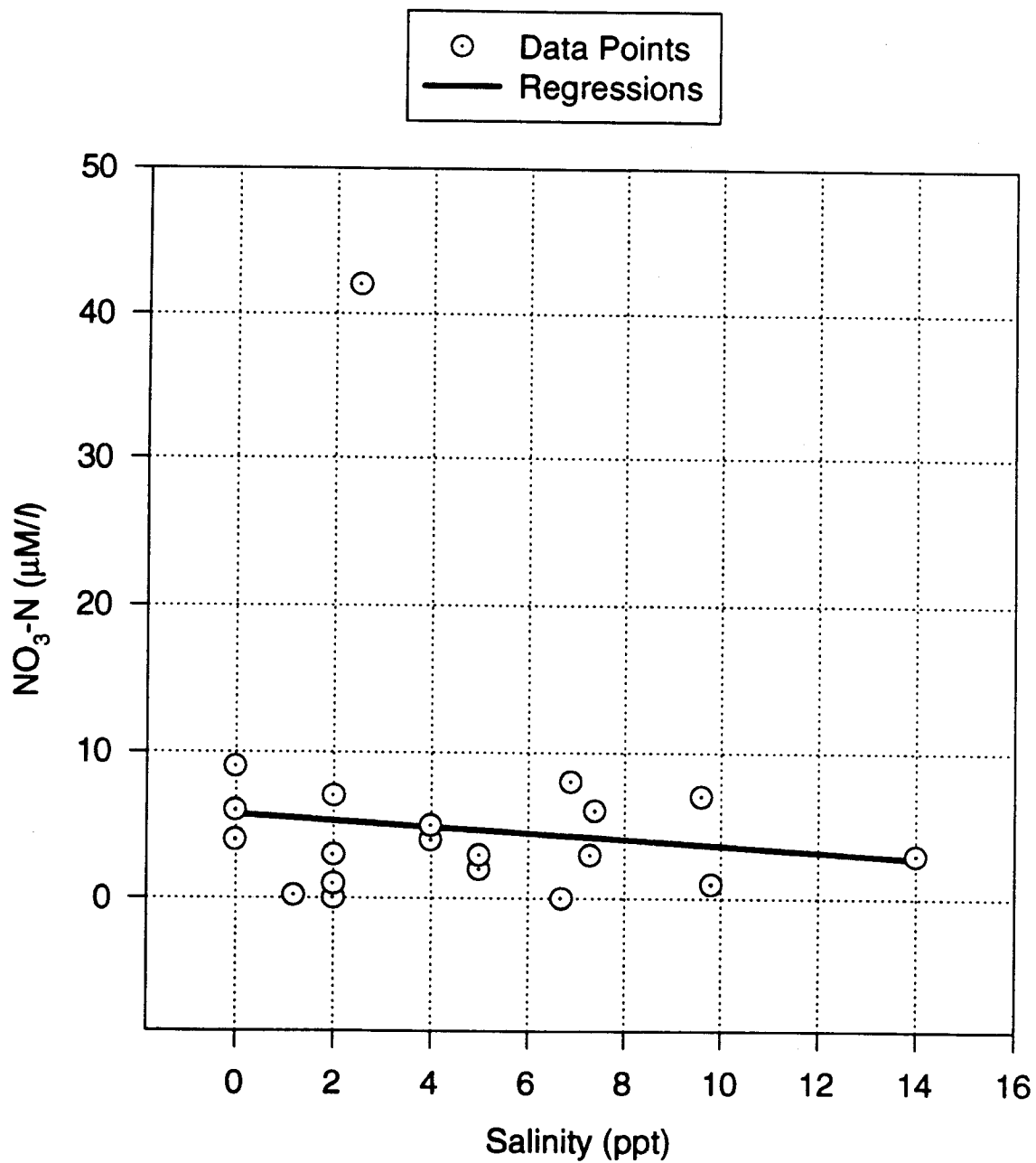
$b[0]=212.8943792817$, $b[1]=-7.5168820737$, $r^2=0.6900398494$

Salt Pond Site, Salinity and $\text{NO}_3\text{-N}$ Relationship



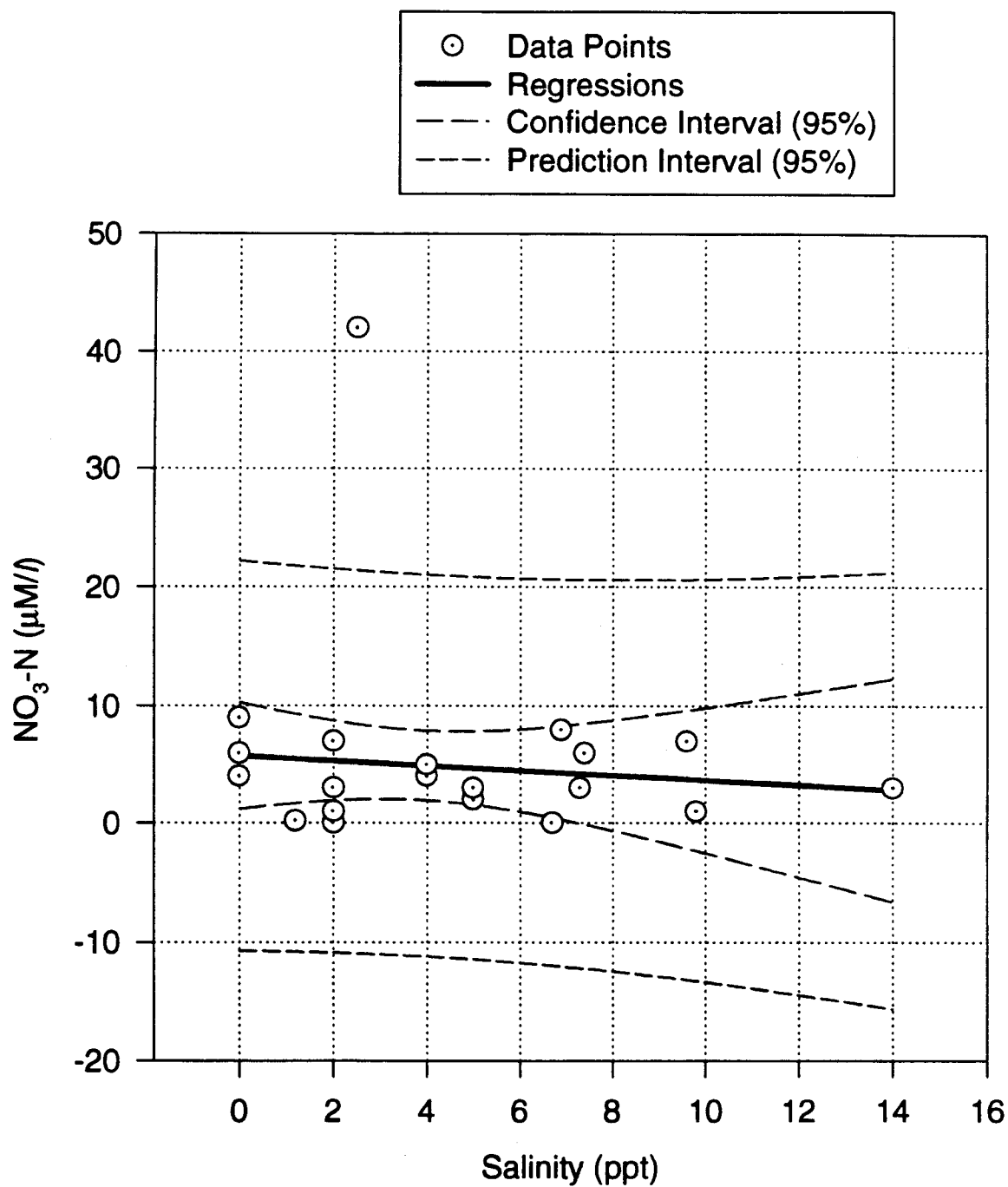
$b[0]=212.8943792817$, $b[1]=-7.5168820737$, $r^2=0.6900398494$

Salt Pond Bay, Salinity and $\text{NO}_3\text{-N}$ Relationship



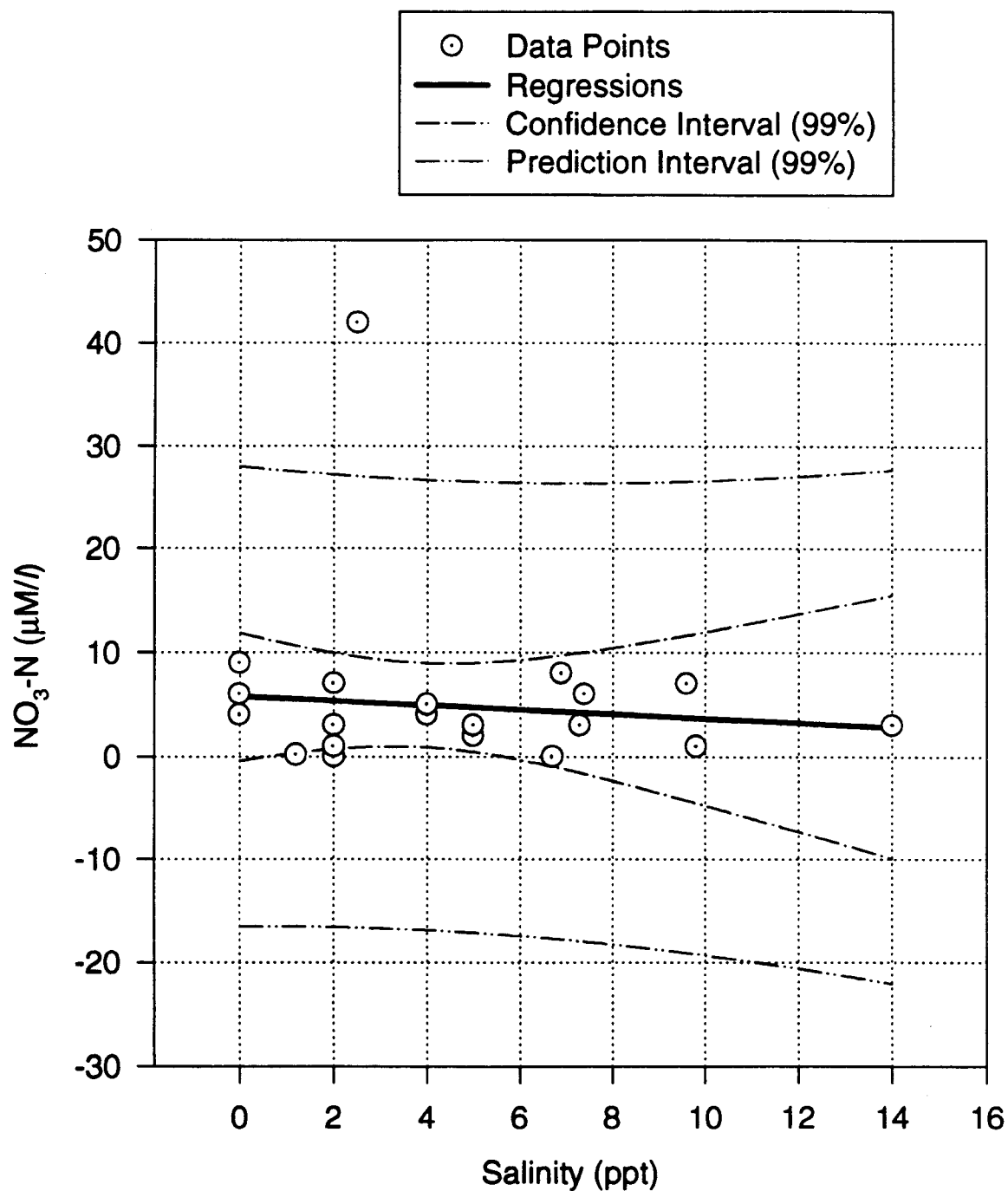
$b[0]=5.7503877701$, $b[1]=-0.2104322653$, $r^2=8.7629648719\text{e-}3$

Salt Pond Bay, Salinity and $\text{NO}_3\text{-N}$ Relationship



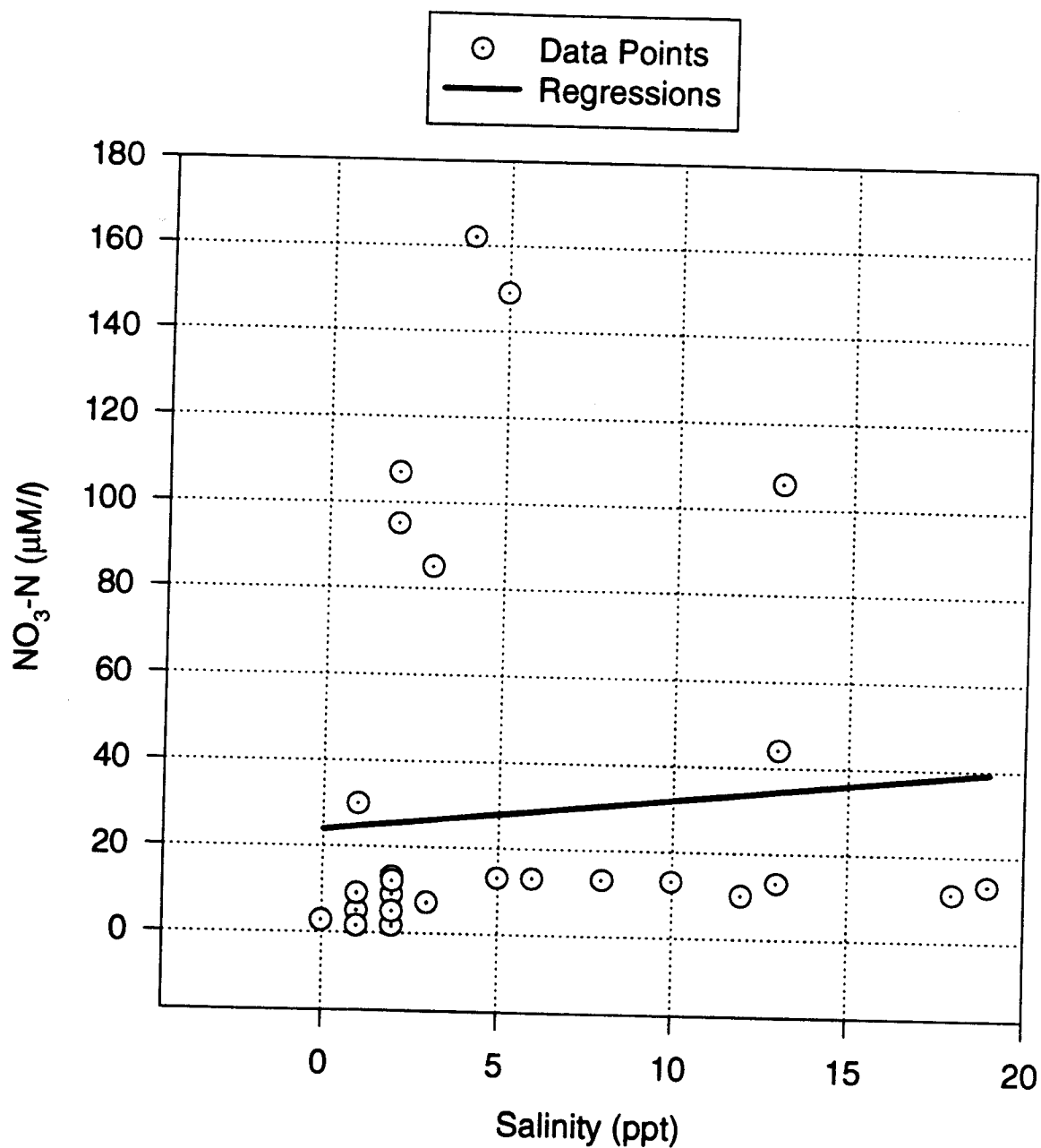
$b[0]=5.7503877701$, $b[1]=-0.2104322653$, $r^2=8.7629648719\text{e-}3$

Salt Pond Bay, Salinity and $\text{NO}_3\text{-N}$ Relationship



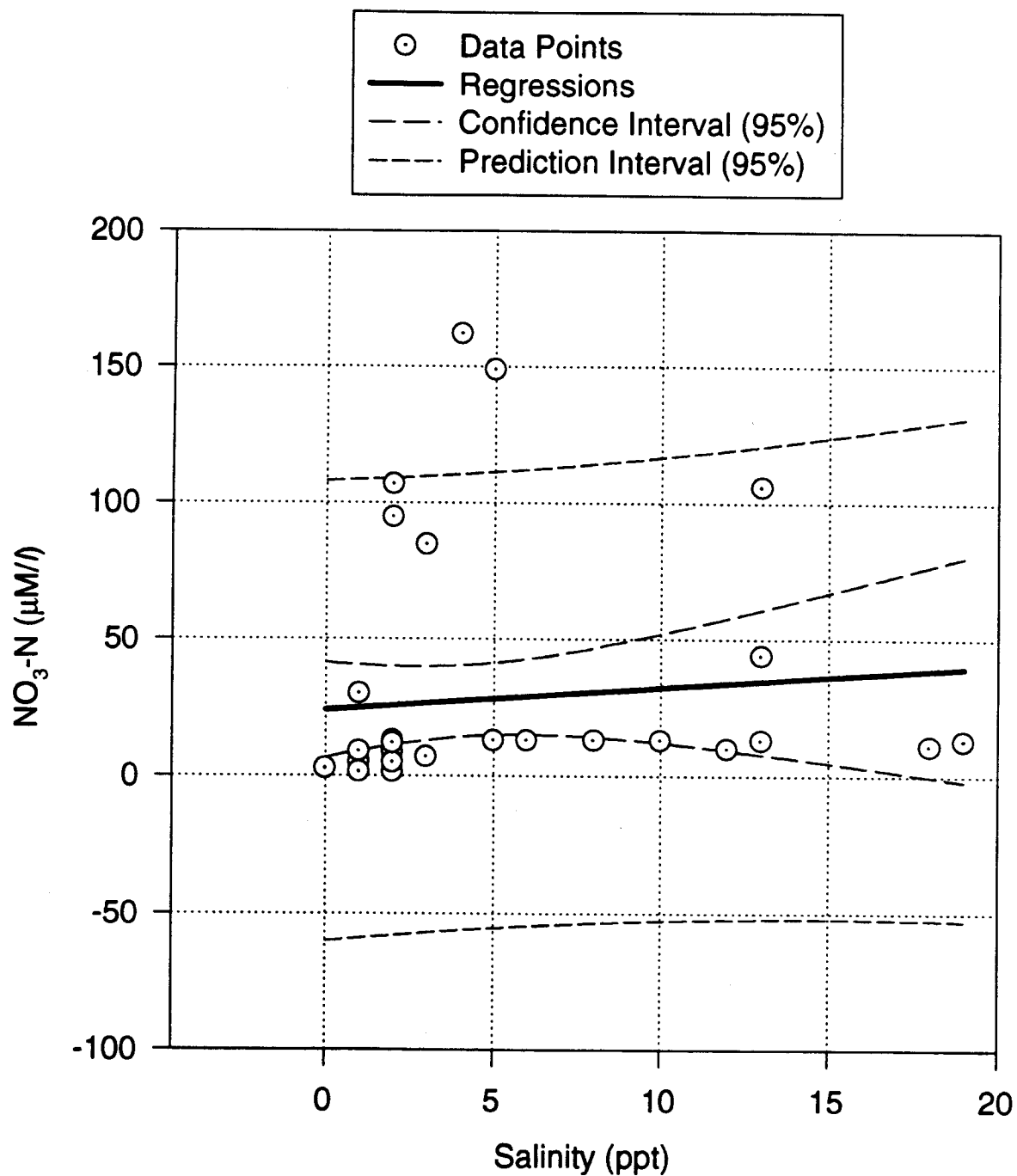
$b[0]=5.7503877701$, $b[1]=-0.2104322653$, $r^2=8.7629648719\text{e-}3$

Shore Garden, Salinity and $\text{NO}_3\text{-N}$ Relationship



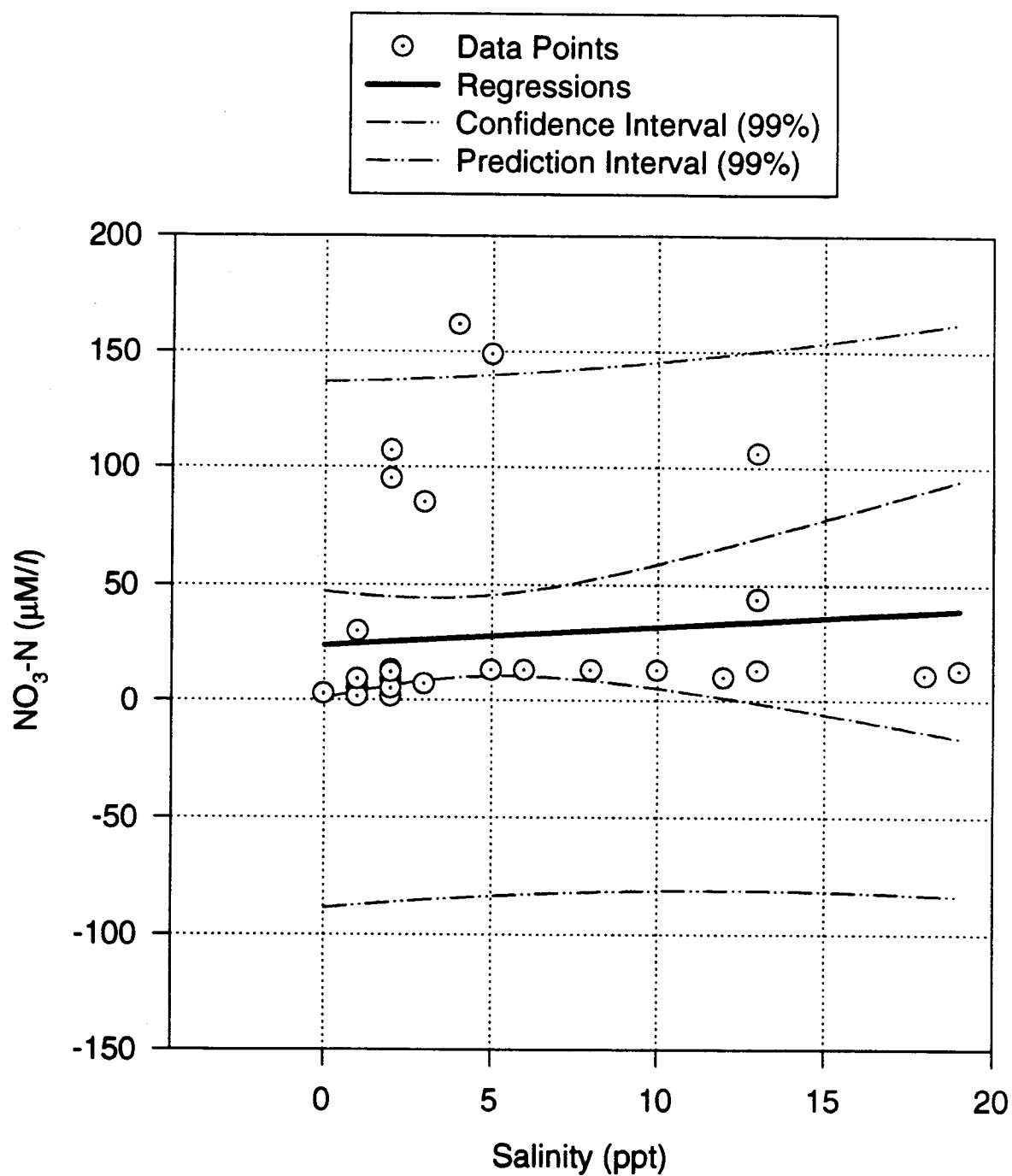
$b[0]=23.9081642751$, $b[1]=0.8121253158$, $r^2=9.7093121482\text{e-}3$

Shore Garden, Salinity and $\text{NO}_3\text{-N}$ Relationship



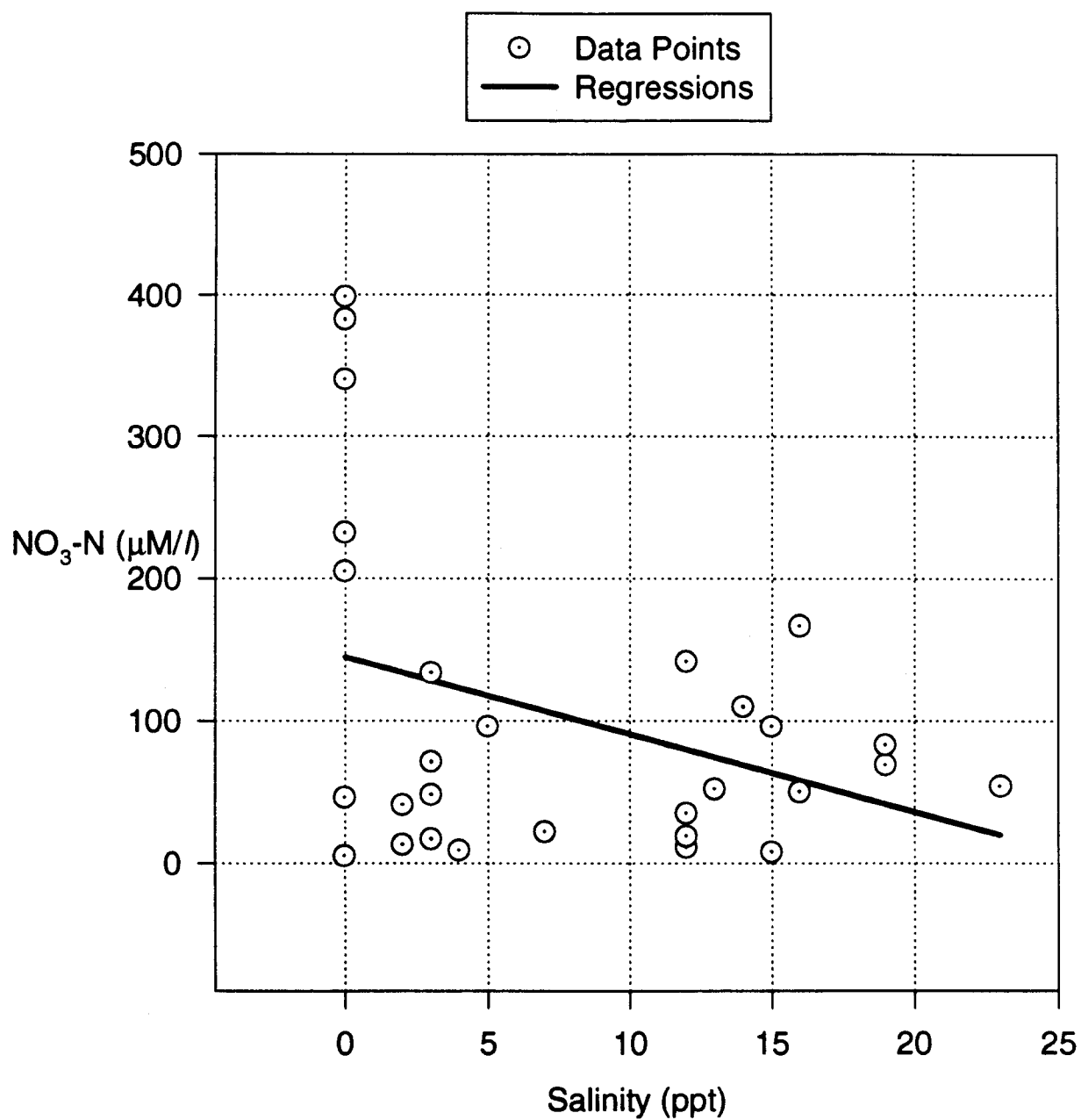
$b[0]=23.9081642751$, $b[1]=0.8121253158$, $r^2=9.7093121482\text{e-}3$

Shore Garden, Salinity and $\text{NO}_3\text{-N}$ Relationship



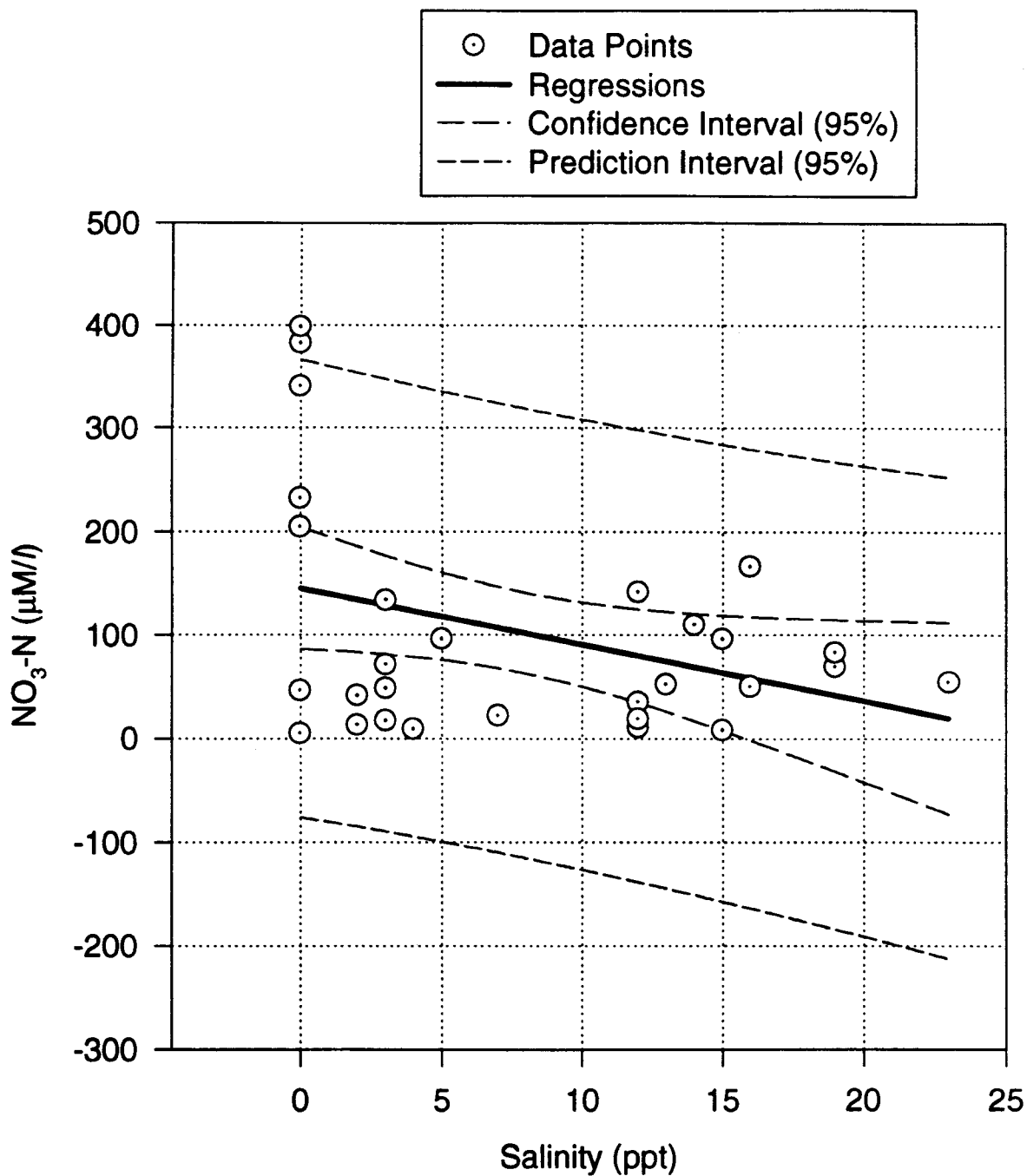
$b[0]=23.9081642751$, $b[1]=0.8121253158$, $r^2=9.7093121482\text{e-}3$

Eldredge Site Salinity and NO₃-N Relationship



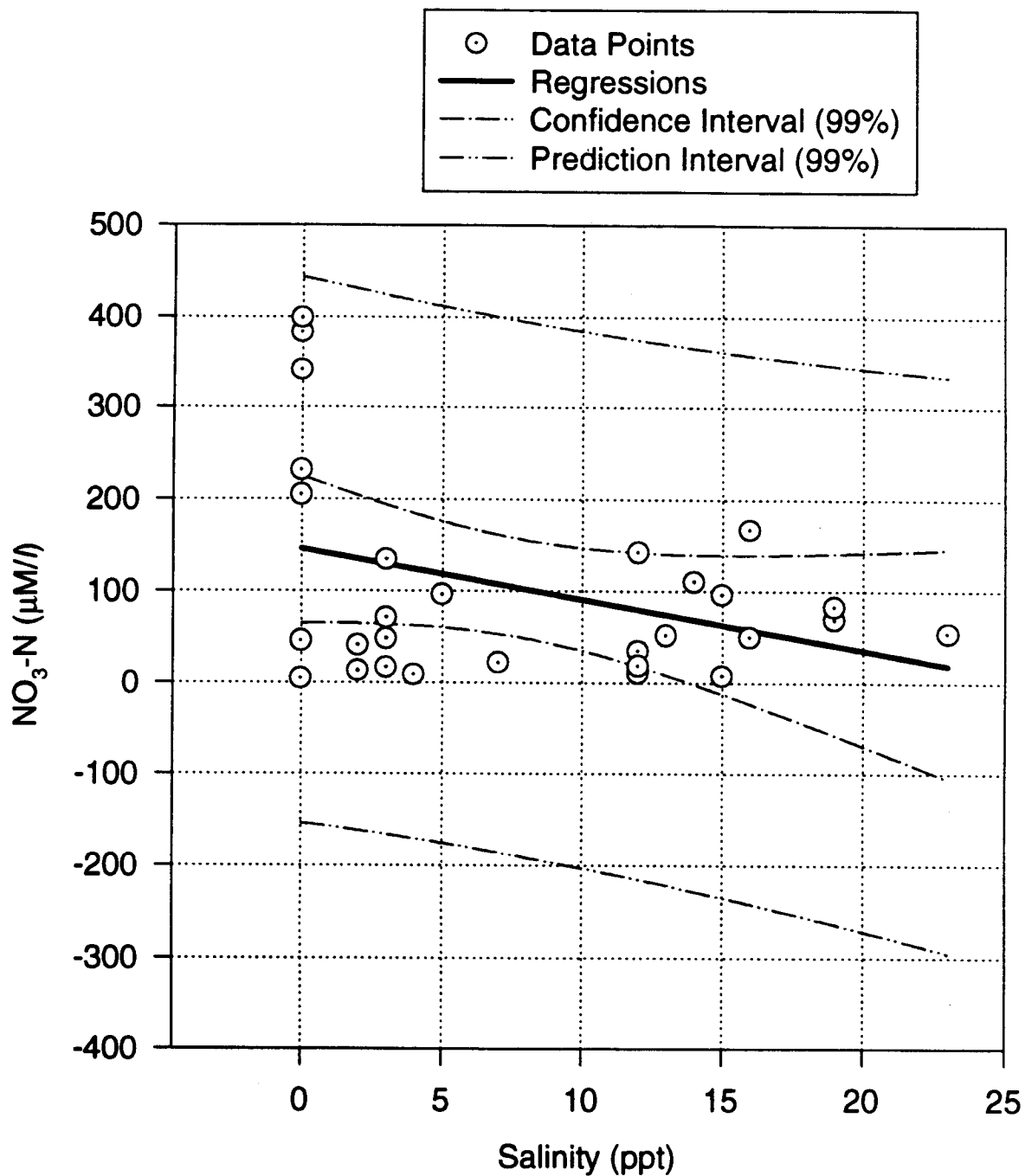
$b[0]=145.3972486573$, $b[1]=-5.4718270046$, $r^2=0.1264638472$

Eldredge Site, Salinity and $\text{NO}_3\text{-N}$ Relationship



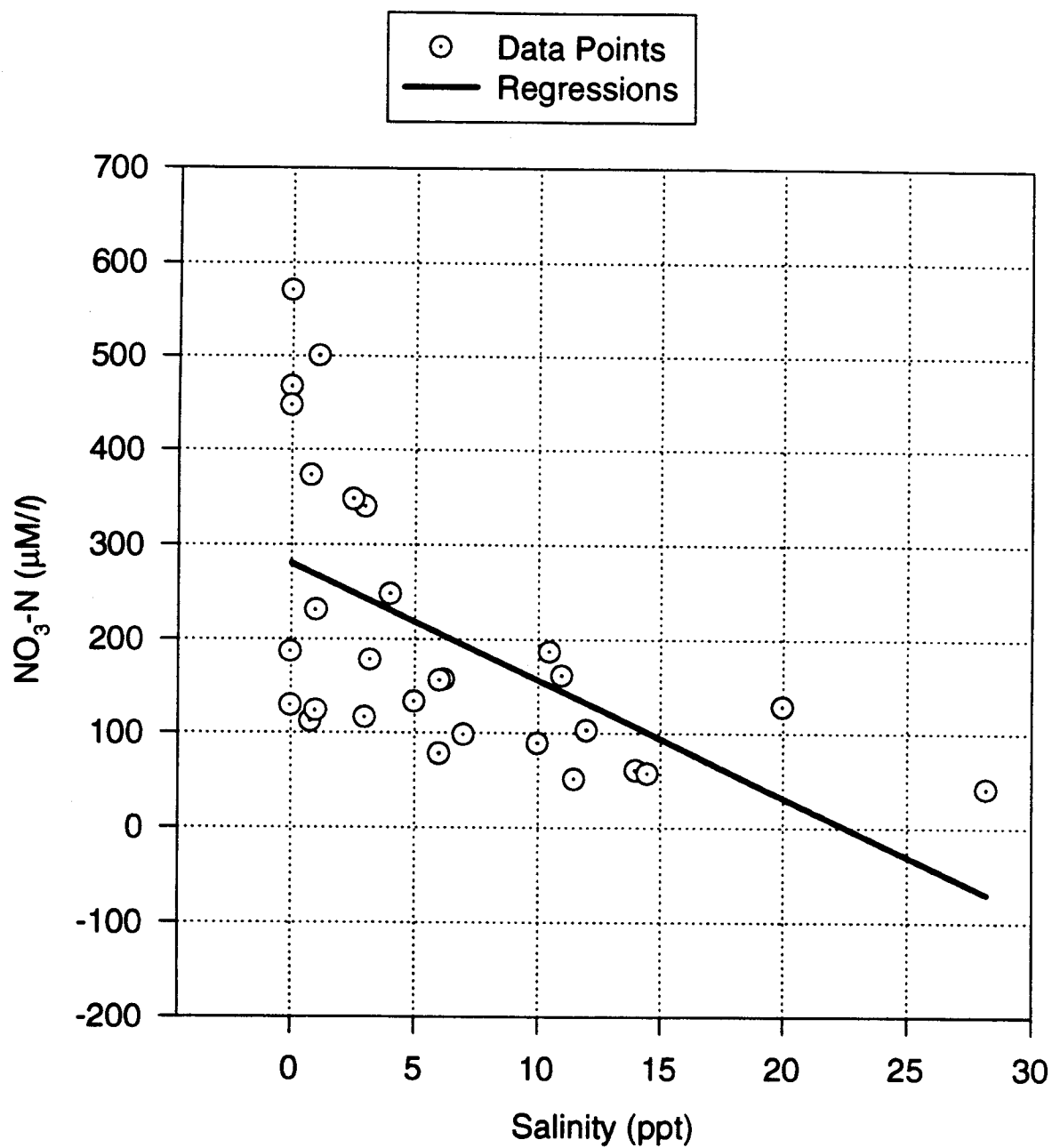
$b[0]=145.3972486573$, $b[1]=-5.4718270046$, $r^2=0.1264638472$

Eldredge Site, Salinity and $\text{NO}_3\text{-N}$ Relationship



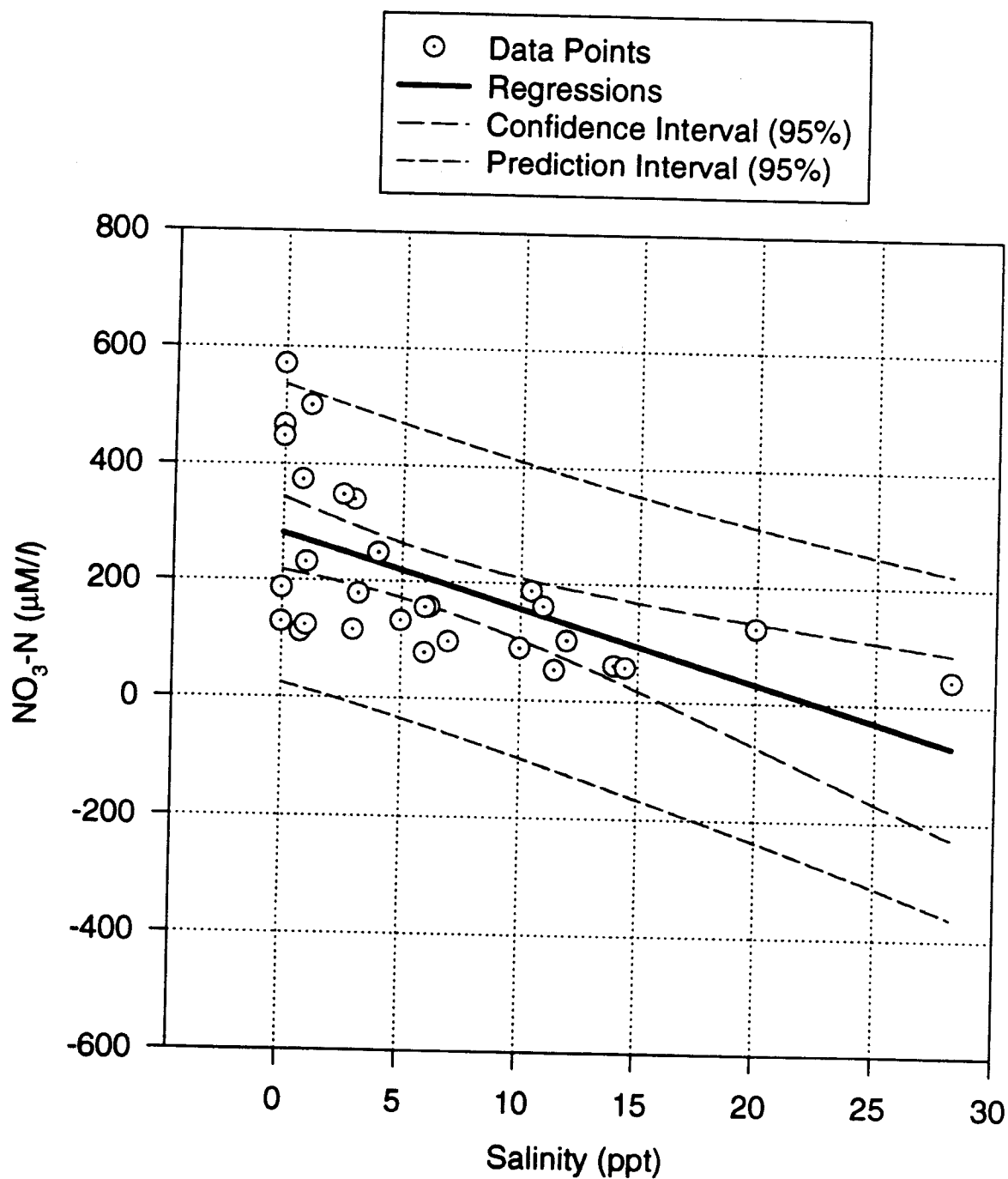
$b[0]=145.3972486573$, $b[1]=-5.4718270046$, $r^2=0.1264638472$

Weeset Site, Salinity and NO₃-N Relationship



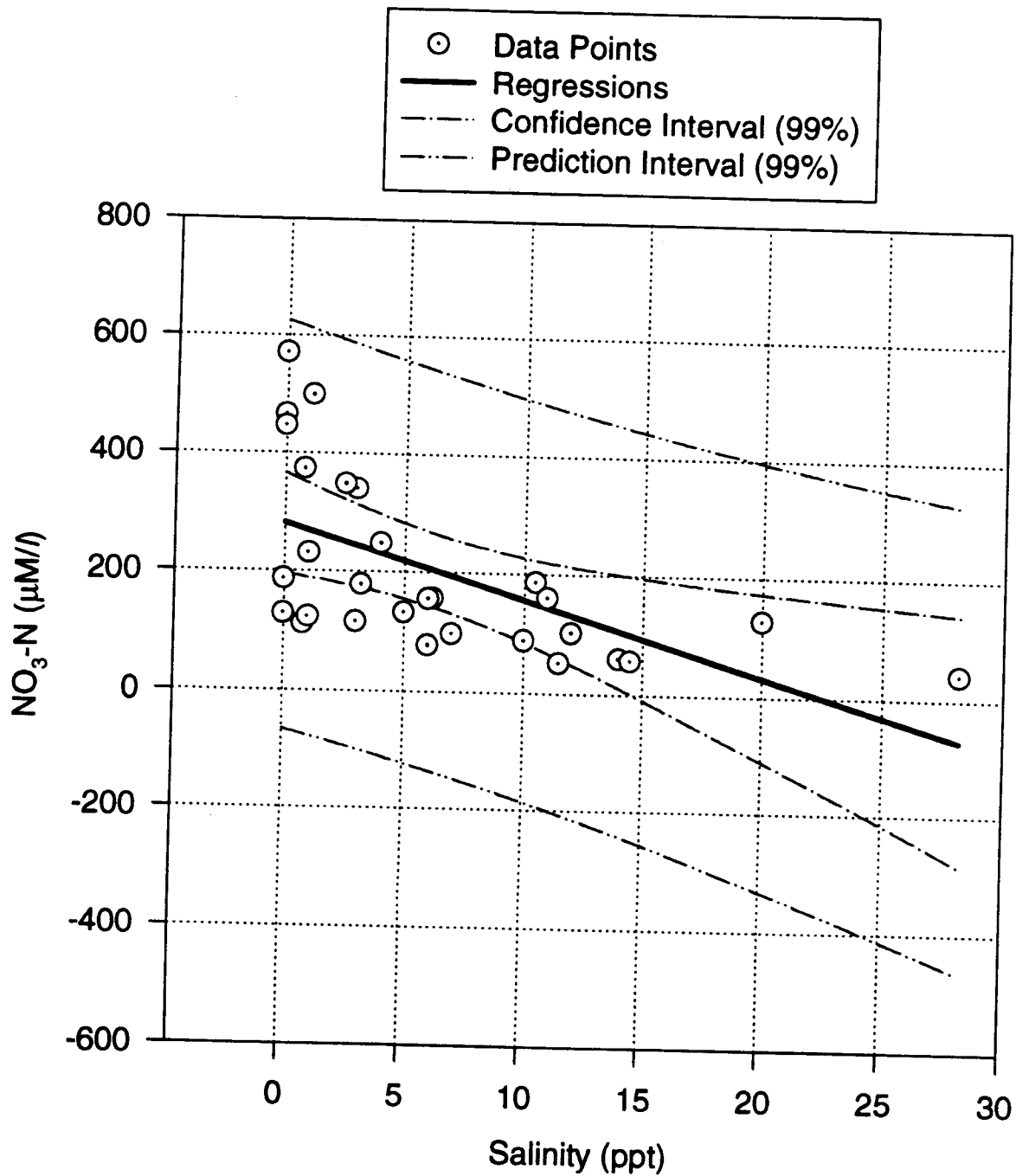
$b[0]=280.7114199933$, $b[1]=-12.4390081174$, $r^2=0.3306955339$

Weeset Site, Salinity and NO₃-N Relationship



$b[0]=280.7114199933$, $b[1]=-12.4390081174$, $r^2=0.3306955339$

Weeset Site, Salinity and $\text{NO}_3\text{-N}$ Relationship



$b[0]=280.7114199933$, $b[1]=-12.4390081174$, $r^2=0.3306955339$