SALT MARSH RESTORATION AT HERRING RIVER:
An Assessment of Potential Salt Water Intrusion in Areas Adjacent to Herring River and Mill Creek, Cape Cod National Seashore

Larry Martin

Technical Report NPS/NRWRD/NRTR-2004/319

WATER RESOURCES DIVISION

National Park Service - Department of the Interior
Fort Collins - Denver - Washington

United States Department of the Interior • National Park Service

The National Park Service Water Resources Division is responsible for providing water resources management policy and guidelines, planning, technical assistance, training, and operational support to units of the national park system. Program areas include water rights, water resources planning, regulatory guidance and review, hydrology, water quality, watershed management, watershed studies, and aquatic ecology.

Technical Reports

The National Park Service disseminates the results of biological, physical, and social research through the Natural Resources Technical Report Series. Natural resources inventories and monitoring activities, scientific literature reviews, bibliographies, and proceedings of technical workshops and conferences are also disseminated through this series.

Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the National Park Service.

Copies of this report are available from the following:

National Park Service (970) 225-3500
Water Resources Division
1201 Oak Ridge Drive, Suite 250
Fort Collins, CO 80525

National Park Service (303) 969-2130
Technical Information Center
Denver Service Center
P.O. Box 25287
Denver, CO 80225-0287

SALT MARSH RESTORATION AT HERRING RIVER:
An Assessment of Potential Salt Water Intrusion in Areas Adjacent to Herring River and Mill Creek, Cape Cod National Seashore

Larry Martin
Hydrogeologist

National Park Service
Water Resources Division
Fort Collins Colorado

Technical Report NPS/NRWRD/NRTR-2004/319

March, 2004

United States Department of the Interior
National Park Service

CONTENTS

LIST OF FIGURES

VERTICAL DATUM

NGVD29: Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 – a geodetic datum derived from a general adjustment of the first order nets of the United States and Canada, formerly referred to as the Sea Level Datum of 1929

Executive Summary

There is considerable interest in restoring estuarine salt marsh habitat in the lower reaches of the Herring River. This would be accomplished by some combination of opening or removing the tide gates or completely removing the dike that was constructed in 1908 at the mouth of Herring River. There is some concern that restoration of tidal flow into the Herring River and Mill Creek drainage basins might allow saltwater intrusion into the groundwater system in areas where private, domestic water supply wells are located adjacent to the restored estuarine system. This report addresses those concerns by evaluating the potential for saltwater intrusion and comparing hydrogeologic conditions in the area of concern with other, similar areas that are adjacent to saltwater bodies and tidal estuaries.

Evaluation of the problem included computer modeling of the local groundwater flow system using the probable hydrologic conditions that would result from various alternatives of opening or removing the existing tidal control structures. This modeling indicated that the thickness of the freshwater aquifer might become thinner for certain simulated conditions. Analytical modeling showed that any change in the thickness of the freshwater aquifer would be restricted to an area underlying and immediately adjacent to the newly created tidal estuaries. The thickness of the freshwater aquifer increases quickly inland from ocean shorelines.

Comparison of the Herring River estuary with similar nearby areas shows that the freshwater aquifer should remain a viable source of water for private domestic wells in upland areas adjacent to the restored estuary. In general, it was determined that wells constructed less than about 200 feet from the ocean and/or screened near the bottom of the freshwater aquifer are susceptible to saltwater intrusion. Wells located more than about 200 feet from ocean shorelines and having their screened interval a significant distance above the bottom of the freshwater zone in the aquifer generally

produce good quality water. While the planned restoration of tidal flow in the Herring River estuary will change the dynamics of the fresh/salt groundwater interface underlying the river valley, that change is not expected to propagate any significant distance inland under the upland areas where the private, domestic wells are located.

A monitoring plan will be developed with park staff to provide data regarding current water quality from private, domestic wells in areas adjacent to the planned restoration. Although water quality in these well is not expected to be affected, the data will provide a basis for evaluating any future claims of water quality degradation following restoration of tidal flow in the Herring River system.

Introduction

The National Park Service, along with numerous local, state, and federal partners is interested in restoring estuarine salt marsh habitat in the lower reaches of the Herring River. This would be accomplished by some combination of opening or removing the hydrologic control structures in the dike or completely removing the dike at the mouth of Herring River.

There is concern that restoration of tidal flow into the Herring River and Mill Creek drainage basins might allow saltwater intrusion into the groundwater system in areas where private, domestic water supply wells are located. The purpose of this report is to address those concerns; evaluate the potential for saltwater intrusion and make recommendations for a monitoring program to document changes that occur if tidal flow is restored to these riverine systems.

A dike was constructed across the mouth of the Herring River and the associated salt marsh system near Wellfleet, Massachusetts in 1909. The dike has three box culverts which allow water to flow between the river and adjacent Wellfleet Harbor. Two of the culverts have flapper tide gates which allow fresh water to flow out of the river system, but restrict the tidal inflow of salt water from the harbor. The third culvert has an adjustable sluice gate. The restriction of tidal flow imposed by these hydraulic control structures has caused the conversion of hundreds of acres of inter-tidal salt marsh to freshwater wetlands and upland vegetation. This conversion has eliminated habitat for estuarine plants and animals, including fish and shellfish. In addition it has resulted in adverse water quality changes including acidification of fresh water in the river (Soukup and Portnoy, 1986), leaching of metals from the sediments, and oxygen depletion (Portnoy, 19917).

Beginning in the early 1980's, the National Park Service conducted studies of the Herring River estuary to develop a plan for salt marsh restoration consistent with current social and economic uses of the floodplain (Roman, 1987). Research has been completed to:

1. Predict the physical and biological effects of opening the existing dike (Roman, 1987).
2. Assess water quality changes after seawater reintroduction (Portnoy and Giblin, 1997a & 1997b).
3. Describe the flood protection needed for portions of the golf course within the floodplain (Nuttle, 1990).
4. Assess the potential for saltwater intrusion into adjacent groundwater supplies following increased seawater flow in the estuary (Fitterman and Dennehy, 1991 and Masterson, 2004).
5. Produce a hydrodynamic model of the estuary that predicts tide heights and salinities throughout the system for various dike-opening or removal scenarios (Spaulding and Grilli, 2001)

These studies have been conducted to help develop a restoration plan that meets the approval of local, state, and federal authorities, and the affected private property owners.

Recently there has been additional interest in restoring former salt marsh areas now occupied by several of the fairways of the golf course in the Mill Creek floodplain. The fairways are outside the park boundary but within the area that could be affected by tidal restoration. There are plans to relocate some of the low-lying fairways in the floodplain of Mill Creek to higher ground farther west on Chequesset Neck. Some of the low-lying areas on the golf course would then also be available for salt marsh restoration.

A map of the general area showing locations of dikes, the golf course, and potential areas of salt marsh restoration is shown on figure 1.

Conceptual Hydrogeology

The groundwater system underlying Cape Cod is recharged by infiltration of rainfall through the sandy soils. Masterson (2004) estimates the average recharge on Cape Cod at 24 inches/year. Infiltration of rainfall and resistance to groundwater flow causes the buildup of groundwater mounds beneath land masses. For example, the major part of the Lower Cape in the vicinity of Wellfleet is underlain by the Chequesset groundwater lens (Masterson, 2004). Smaller land masses, such as Griffin Island, Bound Brook Island, Great Island, and Wellfleet Center and Chequesset Neck are underlain by smaller, local groundwater mounds (Michaud and Cambareri, 2003) that are formed by infiltration of precipitation. Groundwater flows radially from the center of the land masses toward discharge areas at the shore of the ocean or bay, or along the larger creeks and rivers that dissect the land masses as shown in figure 2.

Under existing conditions, tidal flow into the Herring River drainage basin is restricted by the dike at the mouth of the river. Water levels in the Herring River system are lower than they would be without the tidal restriction because the dike effectively prevents high tides from entering the basin. During high tide, the water level on the downstream side of the dike is about 5 feet higher than on the upstream side (Spaulding and Grilli, 2001). Also during high tide, freshwater builds up on the upstream side of the dike, and is released through the dike at low tide. The source of the fresh water in the Herring River upstream of the dike is groundwater discharge, as depicted in figure 3. The net hydrologic result of the dike at the mouth of the Herring River is lower average water levels throughout the river basin because the inflow of high tides has been eliminated (or greatly reduced), but water is still allowed to flow out the flapper valves at low tide.

Several private, domestic wells have been constructed in proximity to the Herring River floodplain in areas where tidal flow of saltwater may be restored. There has been some concern that restoration of tidal flow of saltwater may affect the water quality in these wells by causing a shift in the location of the transition zone between the fresh/salt groundwater as shown in figure 4. If the shift in the location of the transition zone is less than shown in figure 4, it is probable that restoring tidal flow to Herring River and Mill Creek will not adversely affect water quality in wells adjacent to the restored areas. The potential for these impacts is addressed by review of previous investigations, computer modeling, and comparison with areas having similar hydrologic conditions. Additionally, several monitoring wells have been constructed that can provide information regarding any changes in the location of the fresh/salt groundwater interface in the areas of concern (figure 5).

Predicted Hydrologic and Salinity Changes – Surface Water

Spaulding and Grilli (2001) conducted a series of hydrodynamic computer simulations for various dike-opening scenarios to determine the impact of tidal restoration on the flow, salinity, and sediment transport in the river. Spaulding and Grilli's report (2001) contains a complete discussion of model development, data collection, and model results for the various tidal-restoration options. Animated results for several of the model scenarios are available for viewing at the website; "www.nps.gov/caco/resources/Herring_River_Scenarios_Animated/Default.htm" The model showed that the tidal range, maximum and minimum water levels, salt penetration distance, and flushing time all increase as the effective cross sectional area of the opening in the dike increases. This is directly attributable to the increased tidal exchange volume with increased opening size.

An example of the predicted salinity distribution in the Herring River basin at mean tide is shown in figure 6. Figure 6 shows the salinity distribution at mean tide for existing conditions (Spaulding and Grilli, 2001; Case 2, Basin Configuration 0). In this case, the sluice gate is open 24 inches and both tidal flapper gates are operational, blocking seawater inflow during high tide and allowing water to flow out of the Herring River basin during low tide. Also in this case, tidal flow upstream of High Toss Road is restricted by the small amount of culvert openings under the road. Under this scenario, the mean water elevation in the Herring River basin is 0.7 feet NGVD29.

One possibility for reintroducing tidal flow into the Herring River basin would be to open the sluice gate to its maximum (51 inches), remove the tide gates, and install additional culverts under High Toss Road (Spaulding and Grilli, 2001; Case 5, Basin configuration B1). The predicted salinity distribution at mean tide for this scenario is shown in figure 7. The model results shown in figure 7 assume that a dike was constructed across the mouth of Mill Creek to prevent flooding on the golf course. Under this scenario, the predicted mean water elevation in the Herring River basin is 2.5 feet NGVD29.

Spaulding and Grilli (2001) conducted additional modeling to show the effect of removing the tidal control structures including removing the dike. Their modeling showed that tidal flow was not restricted for inlet openings larger than 30 meters. Predicted elevations of high and low tides did not change appreciably for inlet openings between 30 and 200 meters. The predicted mean water elevation in the Herring River basin with unrestricted tidal flow is 1.5 feet NGVD29.

Model results were used to identify the range of conditions (average water levels and salinity distribution) that could be expected for restoration of tidal flow through the dike at the mouth of the Herring River. In general, the suite of simulations showed that the tidal range and water levels in the river asymptotically approached those in the bay as the effective size of the opening increased.

Assessment of Potential Changes to the Fresh Groundwater System

Restoring tidal flow of saltwater into the Herring River basin could change the balance between fresh and saline groundwater underlying the basin. If restoration of tidal flow caused the fresh/salt groundwater interface to rise, there could be adverse impacts to private, domestic wells bordering the Herring River floodplain. The potential for impacting private, domestic wells was evaluated by computer and analytical modeling of the groundwater flow system and by comparison with previous investigations in similar hydrogeologic environments.

USGS Groundwater Model -- The USGS conducted computer modeling of the groundwater flow system in the vicinity of the Herring River to assess the potential changes in the fresh/salt groundwater interface that might be expected due to restoration of tidal flow in the Herring River basin (Masterson, 2004). Four scenarios were simulated to assess the potential impacts of restoring tidal flow on the fresh/salt groundwater interface in the vicinity of the Herring River. These simulations were made for a period of 300 years to allow enough time for the groundwater flow system to reach a new equilibrium with respect to changes in the position of the fresh/salt groundwater interface.

The four scenarios simulated in the computer model were for combinations of increasing the mean water elevation and changing the salinity distribution in the Herring Basin. Mean water elevation was simulated as being either 2.5 or 1.5 feet NGVD29, corresponding with maximum opening of the existing tide gates and complete removal of the tidal control structure and dike. The salinity distribution was simulated as either full-strength seawater upstream to High Toss Road or a gradational change from full-strength seawater at the mouth of Herring River to fresher water at High Toss Road (Masterson, 2004). The results of the four simulations show that changing the salinity distribution and mean water elevation by modifying the operation of the tidal gates or removal of the tide control structure can affect the simulated position of the fresh/salt groundwater interface.

The results of simulations with the mean water elevation 2.5 feet NGVD29 (tide control structure remaining in place, but with tide gates at their maximum opening) indicate that the position of the fresh/salt groundwater interface is very sensitive to the specified salinity distribution. When the salt concentration was specified to equal the concentration of seawater throughout the basin, the fresh/salt groundwater interface rose causing the freshwater lens in the vicinity of the Herring River to become thinner compared to current conditions. When it was assumed that the salt concentration decreased upstream of the tide-control structure, the altitude of the fresh/salt groundwater interface decreased causing the freshwater lens in the vicinity of the Herring River to become thicker compared to current conditions (Masterson, 2004).

In the third and fourth simulations, the mean water elevation in the Herring River Basin was set at 1.5 feet NGVD29, the current mean water elevation measured on the seaward side of the tide-control structure. In these simulations it was assumed that the entire tide-control structure, including the dike, was removed so there was no restriction to tidal flow into the basin. The salt concentrations were simulated as either a uniform concentration of seawater from the dike to High Toss Road (simulation 3) or the concentration gradient predicted by Spaulding and Grilli (2001) (simulation 4). In both of these simulations, the depth to the fresh/salt groundwater interface decreased (the freshwater aquifer became thinner) by less than 10 feet relative to its position under current conditions (Masterson, 2004).

The results of the four model simulations show that introducing tidal flow of salt water into the Herring River basin can change the simulated thickness of the freshwater lens in the vicinity of the Herring River. How that thickness changes is dependent on the conditions specified for mean water elevation and salinity distribution in the Herring River basin (Masterson, 2004).

Analytical Modeling -- At coastal locations, the fresh groundwater beneath the land mixes with saline groundwater and discharges across the shore face. The depth to the fresh/salt groundwater interface increases rapidly in the landward direction. Because of the difference in densities of fresh and salty groundwater, the fresh water floats on top of the salty water in a lens shape where the thickness of the freshwater lens below sea level is approximately equal to 40 times the height of the water table above sea level (figure 8). This relationship is referred to as the Ghyben-Herzberg principle. The zone of mixing between the fresh and saline water is generally thin in comparison to the overall thickness of the freshwater lens (Fetter, 2001).

The cross sections shown in figure 8 are for homogeneous, isotropic conditions. In areas where there is heterogeneity, for example layering in the sediments, the relationship between fresh and saline groundwater, and the location of the zone of transition between fresh and saline groundwater can vary as shown by LeBlanc (1986). Conditions shown in figure 8 are probably a reasonable representation of conditions in the Wellfleet and Herring River areas.

Figure 8 shows the relationship between fresh and saline groundwater that would be expected to occur at the ocean shoreline. This cross section is representative of hydrogeologic conditions at homes on the outer part of Chequesset Neck and adjacent to Wellfleet Harbor (or any other comparable location adjacent to a saltwater body). The relationship between the height of the water table and depth to the interface near the shoreline is governed by the rate of recharge to the groundwater system, the size of the land mass where recharge occurs, and the permeability of sediments making up the land mass. In general, greater recharge rates and lower permeability will cause the water table to rise to higher elevations, causing the interface to be deeper. Conversely, areas where recharge rates are low, or areas where the permeability is large and the groundwater can rapidly flow to discharge areas, will have lower water table elevations and therefore a shallow depth to the interface. Equations to allow calculations of the water table elevation and depth to the interface are succinctly described in Fetter (2001, pp. 332-337)

The outer part of Chequesset Neck (that area beyond the golf course) can be described in hydrological terms as approximating an island. The groundwater system underlying this area is probably derived mainly from local recharge forming a small mound with groundwater flow toward discharge areas along Mill Creek, Herring River, and Wellfleet Bay (figure 2). Equations from Fetter (2001) can be used to predict the resultant shape of the water table and the fresh/salt groundwater interface underlying the area, as if it were an oceanic island. If there is any additional inflow of groundwater from the main part of the aquifer (northeast of Chequesset Neck) to the Chequesset Neck peninsula, the predicted interface will be deeper and further seaward.

For Chequesset Neck (or any infinite-strip island), having a width of 2a, the height of the water table above sea level, h, at any distance, x, from the shoreline can be calculated from;

$$h^2 = \frac{w\left[a^2 - (a-x)^2\right]}{K(1+G)}$$ from Fetter, 2001, pp 335

where;

w is the recharge rate to the aquifer (L/T)

K is the hydraulic conductivity (L/T)

a is the radius of the "island"

G is a ratio of the density of fresh to salty water, $\frac{\rho_w}{\rho_s - \rho_w} = 40$

ρ_w is the density of fresh water, 1.000 gm/cm^3

ρ_s is the density of salty groundwater, 1.025 gm/cm^3

For average conditions on Chequesset Neck, we can assume that;

w = 2 ft/yr

K = 100 ft/d = 36500 ft/yr

a = 1000 ft

Then the elevation of the water table above mean sea level and the depth to the interface below mean sea level for any distance from the shoreline can be computed as follows;

Distance from shore, feet	Water Table Elevation, feet above sea level	Depth to Interface, feet below sea level
0	0.00	0.00
25	0.26	10.28
50	0.36	14.44
75	0.44	17.57
100	0.50	20.16
200	0.69	27.75
300	0.83	33.02
400	0.92	36.99
500	1.00	40.05

Graphically, this relationship is shown on figure 9. Figure 9 is a simplified representation of conditions in the near-shore area in that it does not account for the vertical component of groundwater flow. A more exact analytical solution including a vertical component of groundwater flow in the near-shore area would show the formation of a groundwater outflow face, a higher water table and a greater depth to the fresh/salt groundwater interface. Analytical results for either method of computation produce essentially the same results away from the coastal zone (Fetter, 2001).

The important thing to note in figures 8 and 9 is that the depth of the fresh/salt groundwater interface increases rather quickly with increasing distance from the shoreline. Thus, we would expect that there would be ample thickness of the freshwater aquifer to supply good quality water to low-volume domestic wells unless the wells are screened too deeply in the aquifer (near the interface).

The thickness of the fresh groundwater lens underlying Chequesset Neck is not expected to change significantly regardless of whether tidal flow is restored in the Herring River and Mill Creek drainage basins. The size and shape of the freshwater lens is controlled by recharge (local infiltration of precipitation) and the permeability of sediments underlying the area. There may be some thinning of the freshwater lens where the upland areas meet the river valley if the groundwater underlying the valley becomes predominantly salty. However, a short distance inland (100-200 feet) the freshwater lens should remain thick enough to provide water for private domestic wells.

Geophysical logging of the new monitoring well (WNW-133) at the golf course in September 2003 showed that the freshwater lens was about 35 feet thick. The monitoring well is about 700 feet from Wellfleet Harbor. Calculations using the analytical solution (Fetter, 2001) predict that the freshwater lens should be about 45 feet thick at this distance from the ocean. The difference between the predicted and observed thickness of freshwater at this location may be due to groundwater flow toward and discharge to Mill Creek in the area of the golf course. The analytical solution assumes that groundwater flow is entirely toward the ocean. The proximity of an alternative groundwater discharge area compromises the results predicted by the analytical solution.

Related Studies

Several investigations have been conducted on or near Cape Cod, to evaluate the potential impacts of restoring tidal flow to streams or estuaries. These investigations generally use analytical equations (as opposed to computer models) to evaluate the extent of influence of tidal fluctuation in a stream on the water table elevation in the adjacent freshwater aquifer.

Fitterman and others (1989) conducted a geophysical survey of the highlands to the east of the Herring River. They determined that the thickness of the freshwater aquifer was at least 10 meters (30 feet) and that the thickness of the aquifer increased away from the river. They used an analytical equation to evaluate how increased tidal fluctuation in the river would affect the water table adjacent to the stream. They concluded that completely opening the tide gates would have no effect on wells in the highlands east of the river because the mean river level would not change and the area affected by water table fluctuations would be limited to a few tens of meters from the river.

In a subsequent study, Fitterman and Dennehy (1991) installed monitoring wells to verify the results of the geophysical investigation conducted in 1989. They found that the thickness of the freshwater aquifer at four monitor wells (figure 5) ranged from 18-22 meters (59-73 feet). At two monitor wells adjacent to the floodplain of the Herring River (WNW-115 & WNW-117), the thickness of the freshwater aquifer was determined to be approximately 65 and 59 feet respectively. Fitterman and Dennehy (1991) assumed that completely opening the tide gates would cause both static-water and high-tide levels in the Herring River to increase by less than 0.5 meter. They then concluded that such a small increase, compared to the large thickness of the freshwater aquifer, makes it unlikely that the thickness of the freshwater aquifer or the position of the fresh/salt groundwater interface would change at wells in the highlands east of the Herring River (although it is unclear how they reached this conclusion). They did acknowledge that wells in the lowland along the river road could potentially draw salty water due to infiltration of salt water from the surface or repositioning of the fresh/salt groundwater interface (Fitterman and Dennehy, 1991).

Eichner and others (1997) investigated a similar issue at the Pamet River in Truro. They investigated current hydrogeologic conditions in the upper Pamet River valley and assessed the potential for saltwater intrusion if tidal flow were restored to the upper part of the river (east of Highway 6). They concluded that restoration of tidal fluctuation (estimated at 2.4 feet at Highway 6 and 0.9 feet at Ballston Beach) would result in negligible water table fluctuation (less than 0.01 feet) at a distance of 500 feet from the river. The low permeability of the marsh peat underlying most of the valley dampens the tidal influence on groundwater levels. Upward groundwater gradients (i.e., freshwater discharge from the aquifer to the stream) further suggest that saltwater inflow into the adjacent aquifer would be minimized. Monitoring near Ballston Beach showed that although the tidal range at the beach exceeds 5 feet, most of the monitor wells within 500 feet of the ocean had fluctuations of less than 0.1 feet. Calculations using an analytical equation showed that the predicted tidal fluctuations in the Pamet River would be quickly dampened, such that water table fluctuations in the adjacent aquifer would be less than 0.01 feet at distances of 46-56 feet from the river. This dampening is, in large part, due to the low permeability of the marsh peat deposits.

Walter and others (1996) conducted a study of the hydrogeology and an analysis of the groundwater flow system near Sagamore Marsh in southeastern Massachusetts to determine whether restoration of tidal flow in the marsh would affect a nearby municipal supply well. They determined that the low permeability peat deposits in the marsh restricted tidal influences on water table elevations to within a few tens of feet of the surface water channels. They then assumed a worst-case scenario in which the surface water channels were in direct connection with the underlying sand and silt aquifer. Under those conditions, tidal fluctuations would affect water table elevations by 0.05 to 0.1 feet for distances of approximately 100-400 feet from the channels. A computer model of the marsh and adjacent groundwater flow system predicted that increased tidal flow in the marsh would have a negligible effect on local groundwater levels.

Niedoroda and April (1975) conducted an investigation of the fresh/salt water transition zone beneath coastal marshes. One of their field sites was the salt marsh on the northwest side of Great Island, an area called “The Gut” on topographic maps (figure 5). Fourteen shallow monitoring wells were placed along an 800-foot transect extending from approximately the highest high tide to the lowest low tide across the salt marsh and adjacent sandy intertidal area. At low tide, fresh groundwater from adjacent upland areas flows outward and upward beneath the salt marsh creating a net seaward transport of fresh and brackish groundwater beneath the tidal salt marsh. At high tide, there is a downward and landward flow of groundwater beneath the salt marsh. The salt water that infiltrates downward beneath the salt marsh during each high tide is incompletely flushed from the aquifer during low tide. The overall result is a widening of the transition zone between fresh/salt groundwater. Figure 10 (from Barlow, 2003) graphically shows this temporal pattern of shallow groundwater flow in the near-shore environment, similar to what might be expected in the Herring River basin if tidal flow were restored. While the presence or absence of a salt marsh adjacent to an ocean shoreline or in an estuary can have a large effect on the shape and location of the transition zone in the near-surface environment, it has no appreciable effect on the depth to the transition zone in the aquifer underlying the adjacent upland areas.

Comparison With Similar Hydrogeologic Environments

There are several nearby areas with hydrogeologic conditions that are similar to conditions that will be expected if tidal flow is restored to the Herring River and Mill Creek drainage basins. Current conditions in these areas may provide insight into what may occur in the Herring River drainage basin if tidal flow was restored. These areas include homes bordering Wellfleet Harbor along Chequesset Neck Road and the southern part of Indian Neck. These areas have a small size, so the groundwater recharge area is limited and they are adjacent to or nearly surrounded by salt water in Wellfleet Bay and tidal salt marsh. Michaud and Cambareri (2003) show that these areas have local groundwater flow cells that are largely independent of the regional aquifer.

Southern Indian Neck Area – Indian Neck is a peninsula that protrudes into the east side of Wellfleet Harbor. The south part of Indian Neck is topographically and hydrologically isolated from the north part of Indian Neck and the mainland (figure 11). A large salt marsh east of Indian Neck creates a hydrological separation from the mainland. A smaller salt marsh area separates the north and south parts of Indian Neck, both hydrologically and topographically. There is a narrow, low-lying connection between the north and south parts of Indian Neck, but it is not of sufficient size to be hydrologically significant.

The south part of Indian Neck ranges from about 800-1500 feet wide and is about 3500 feet long. The only source for groundwater underlying the area is infiltration of local recharge from precipitation. There is no inflow of groundwater from adjacent areas. Using the methods presented in Fetter (2001) and previously described in this report, the thickness of the fresh groundwater lens underlying the area is computed to be in the range of 15-25 feet. The fresh groundwater lens would be expected to be adequate to supply low-volume, private, domestic wells.

Well completion and water chemistry reports for the southern part of Indian Neck were obtained from the Wellfleet Board of Health. Basic water chemistry data were available for 24 wells in this area. Specific conductivity of water from these wells was evaluated as an indicator of overall water quality. Specific conductivity exceeded the recommended limit of 500 umhos/cm in 4 of the 24 samples. Two more samples were barely below the 500 umhos/cm limit. Four of the six samples in this group of high conductivity had values between 450-500 umhos/cm, at or near the recommended limit but not exceeding it. Only two of the samples would be classified as exceeding the recommended limit. These samples were 660 and 783 umhos/cm, but would still be classified as freshwater (Fetter, 2001). However, fresh groundwater from the Cape Cod aquifer (that is groundwater that is not influenced by intrusion of salt water) generally has a specific conductivity of less than 175 umhos/cm (Frimpter and Gay, 1979)

Examination of well construction and water quality data for the southern part of Indian Neck shows that even a relatively small, hydrologically isolated area will have sufficient groundwater recharge to form a freshwater lens of sufficient size and thickness to supply low-volume, private, domestic wells. Examination of the records shows that there are many wells located within 200-250 feet of Wellfleet Bay that supply excellent quality water for domestic use.

Chequesset Neck Area -- Well completion and water chemistry reports for several areas adjacent to Mill Creek and Herring River were obtained from the Wellfleet Board of Health. Examination of these records shows that some wells in the area already have water quality problems, primarily related to being drilled too deep and drawing groundwater from the transition zone between salty and fresh groundwater. As mentioned, there are many wells in close proximity to Wellfleet Harbor that are capable of providing adequate supplies of good quality water for private, domestic wells.

Well construction and water quality data were available for Lots 10 and 11, located on the north side of Mill Creek (figure 11). Examination of data for these wells illustrates a common problem that was seen in examining well records throughout the Chequesset Neck area: many of the wells are screened too deep in the aquifer and pump poor-quality groundwater from near the fresh/salt groundwater interface. Wells screened near the top of the aquifer generally produce better quality water (figure 12).

The well in Lot 10 is located at a land surface elevation about 11 feet above sea level. It is screened from 52-55 feet below ground surface, or about 41-44 feet below sea level. Water quality exceeds the recommended limits for conductance and sodium. The conductance is 683 umhos/cm and the sodium concentration is 115 mg/l.

A few hundred feet away, the well in Lot 11 is located at an elevation about 30 feet above sea level. It is screened from 30-35 feet below ground level, or about 0-5 feet below sea level. This well is constructed in a manner that causes it to draw water from just below the top of the water table, several tens of feet higher than the fresh/salt groundwater interface. Water quality from this well is much better, having a conductance of 130 umhos/cm and a sodium concentration of 13 mg/l.

Homes Southeast of Golf Course – Well construction and water quality records were obtained for 12 domestic wells at homes north of Chequesset Neck Road and southeast of the golf course. These homes are located along Powers Lane and Way 55 (figure 11). Wells in this area are 250-1000 feet from Wellfleet Harbor. Groundwater underlying the small hills where these homes are located is partly derived from local infiltration of precipitation and partly from inflow of groundwater from adjacent areas

Specific conductance of water from all of the wells in this area (for which records were available from the Wellfleet Board of Health) falls below the recommended level of 500 umhos/cm. However, almost all of the water samples exceeded the recommended limit for sodium of 20 mg/l. Sodium is not a regulated contaminant in drinking water supplies. It is routinely tested on Cape Cod as an indicator of saltwater intrusion and as an advisory for persons on low-sodium diets. Private well records across the Outer Cape show high sodium and chloride concentrations that are believed to be caused by deposition of salt spray from the ocean (Frimpter and Gay, 1979).

All of the wells in these areas are screened more than 10 feet below the water table. Better quality water might be obtained by screening wells higher in the aquifer, perhaps 4-7 feet below the water table. However, this might not allow enough saturated aquifer thickness to provide an adequate supply of water for the well. It is also quite possible that the total recharge in these relatively small areas is insufficient to support the level of development in this area and that groundwater quality has been locally compromised by overuse of the aquifer and intrusion of saltwater.

Homes along Chequesset Neck Road – Data were available for 12 private, domestic wells along Chequesset Neck Road between the golf course entrance and the Herring River dike (figure 11). Water quality from these wells is highly variable. Some wells that have very poor water quality are only a short distance from wells having acceptable water quality. In some cases, water quality tests for the same well range from acceptable to very poor. Closer examination of the data and well locations revealed that the wells having poor water quality were generally within about 100-150 feet of the bay, very close to the margin of the aquifer. At these locations, the freshwater lens is probably less than 20 feet thick and it would be quite easy to have the well screened in the transition zone between the salt and fresh groundwater. Pumping even small quantities of water from these wells for domestic uses may cause saltwater upconing into the screened section of the well.

The upland area southwest of the golf course should be of sufficient size to sustain a lens of freshwater sufficient to supply low-volume, private, domestic wells. However, homes located on the harbor side of Chequesset Neck Road may be too close to the edge of the freshwater lens to allow construction of water supply wells without penetrating the transition zone between the fresh and saline groundwater. This problem should not be affected in any way by reintroduction of tidal flow in Herring River and Mill Creek on the opposite side of the peninsula.

Monitoring the Fresh/Salt Groundwater Interface

Electromagnetic induction logging has proven to be an effective tool for locating the transition from fresh to saline groundwater. Electromagnetic induction logs measure the electrical conductivity of the aquifer material and water in a radial zone from about 0.5-4 feet from the vertical axis of the well. Conductivity of the aquifer is a function of rock lithology, porosity, moisture content, and the concentration of dissolved solids in the pore fluid. In the monitoring wells on this part of Cape Cod, where the sediment characteristics are fairly constant with depth, most of the response seen on the EM log is due to the concentration of dissolved solids in the groundwater; mostly an increase in salt concentration at the base of the fresh groundwater lens.

Fitterman and Dennehy (1991) constructed 4 monitoring wells on that part of Chequesset Neck north of Mill Creek in 1990 (Wells WNW-115, WNW-116, WNW-117, and WNW-118). Two additional wells were constructed in September 2003 to allow monitoring in other areas that might be affected by restoration of tidal flow in Herring River and Mill Creek (Wells WNW-133 and WNW-134). The location of these wells is shown on figure 5. These wells were constructed with PVC casing to facilitate geophysical logging in the wells. The wells were constructed deep enough to penetrate the interface between the fresh and salty groundwater.

The thickness of the freshwater lens at each of the monitoring wells north of Mill Creek and along the Herring River ranged from 59-69 feet in the area north of Mill Creek. Continued monitoring of these wells will allow detection of any change to the depth of the fresh/salt groundwater interface adjacent to the Herring River or on the north side of Mill Creek.

The one monitoring well south of Mill Creek (WNW-133) is near the maintenance shed at the golf course. This location is near the northeast margin of the freshwater lens underlying the Chequesset Neck peninsula. Continued monitoring at this location will allow detection of any change to the depth of the fresh/salt groundwater interface adjacent to that part of Mill Creek where tidal flow will be restored.

The electromagnetic induction logs for each of these monitoring wells are shown in figures 13 to 18. The thickness of the freshwater lens, as determined from interpretation of the EM logs is provided in the following table.

Well No.	Thickness of Freshwater Lens
115	65’
116	63’
117	59’
118	69’
133	37’
134	55’

Comparison of graphs for the electromagnetic induction logs from 1990 and 2003 (figures 14, 15, and 16) show that the depth to the fresh/salt groundwater interface (and therefore the thickness of the freshwater aquifer) did not change during that time span. These monitoring wells remain available to conduct future electromagnetic logging to determine if the position of the interface changes following restoration of tidal flow.

Well WNW-115 could not be located in 2003 due to incorrect location data on the site location map. Another map has been located that hopefully has the correct location data so that the well can be located for future monitoring.

Conclusions

The Herring River valley, like most estuaries on Cape Cod, is underlain by a significant thickness (2-4 meters) of low permeability peat. The peat limits movement of water between stream channels and the underlying aquifer. Water table fluctuations caused by tidal fluctuation are limited to a couple hundred feet from streams. Generally, stream valleys are groundwater discharge areas, having an upward gradient in the aquifer underlying the peat deposits (groundwater is flowing from upland areas toward discharge areas in stream valleys). This upward gradient further reduces the potential for saltwater intrusion. The large thickness of the freshwater aquifer, in comparison to the small range of water table fluctuations due to tidal effects, indicates that restoration of tidal flow in the Herring River will not affect private water supply wells at nearby homes.

Local infiltration of precipitation is sufficient to sustain lenses of fresh groundwater beneath small land masses in this area. Groundwater underlying these upland areas flows toward, and discharges to, adjacent creeks and rivers. The freshwater aquifers underlying those areas adjacent to Herring River and Mill Creek will continue to be replenished by recharge and should not be affected by restoration of tidal flow into river valleys at the margins of the aquifers. Anticipated changes in the location or depth of the transition zone between fresh and salt groundwater will mostly be limited to the margins of the freshwater lenses, in areas adjacent to the estuaries and salt marshes. There should be little, if any, change to the location of the fresh/salt groundwater interface beyond a few hundred feet inland from the areas affected by tidal flow. Although no changes are anticipated, a network of monitoring wells is in place to detect any changes to the depth or thickness of the interface and to provide an early warning system if changes should occur.

Numerous studies (Eichner and others, 1997; Fitterman and Dennehy, 1991; Walter and others, 1996) for this, and other areas on Cape Cod having similar hydrologic settings, have concluded that restoration of tidal flow in estuaries and salt marshes will not impact the supply of fresh groundwater for low-volume, domestic wells on adjacent upland areas. Restoration of tidal flow to former salt marsh areas will likely create a wider transition zone of mixed fresh/salt groundwater under the salt marshes, but it should not affect the availability of fresh groundwater underlying upland areas. The thickness of the fresh groundwater lens and the landward extent of the transition zone are primarily functions of the amount of groundwater recharge from infiltration of precipitation and the permeability of the underlying sediments. These parameters will not be changed by the presence or absence of tidal salt water in adjacent estuaries.

There are numerous low-volume, private, domestic wells in the Wellfleet area that are located adjacent to salt-water bodies. Some of these wells provide good quality water, others have poor quality water. It appears that those wells with poor quality water can be characterized as being located less than 100-150 feet from a salt-water body, where the thickness of the freshwater aquifer is marginal, and/or or having the screened area of the well deep enough below the water table to draw water from the transition zone between fresh and salty groundwater. Wells providing good quality groundwater can generally be characterized as being located more than 150 feet from a salt-water body and having the well screen located only a few feet below the water table, far above the transition zone.

The most likely scenario for change in the location of the transition zone between fresh and saline groundwater is shown in figure 19. Restoration of tidal flow of salt water in the streams will likely allow formation of a wedge of saline groundwater in a small area immediately underlying the stream channels. The depth and location of the transition zone beneath upland areas is unlikely to change as it is controlled by infiltration of precipitation to recharge the aquifer and the permeability of sediments in the aquifer, neither of which will be changed by restoration of tidal flow.

All indications are that restoration of tidal flow of salt water into the Herring River and Mill Creek drainage basins should not have an adverse effect on the supply of fresh water to low-volume, private, domestic wells in adjacent areas. However, wells with pre-existing water quality problems will continue to have problems.

References

Barlow, Paul M., 2003, Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast, USGS Circular 1262, 113 pp.

Cooper, H.H., 1964, A Hypothesis Concerning the Dynamic Balance of Fresh Water and Salt Water in a Coastal Aquifer, USGS Water Supply Paper 1613-C, pp. 1-12

Eichner, Eduard M., Thomas C. Cambareri, Kenneth Livingston, Bob Sobczak, and Ben Smith, 1997, Pamet River Investigation Groundwater Assessment Study, Truro, Massachusetts, Cape Cod Commission, 39 pp. plus appendices

Fetter, C.W., 2001, Applied Hydrogeology, 4th Ed., Prentice-Hall publisher, 598 pp.

Fitterman, David V., Glenn A. Brooks, and Stephen L. Snyder, 1989, Geophysical Investigation of Depth to Saltwater Near the Herring River, Cape Cod National Seashore, Wellfleet, Massachusetts, USGS Open-File Report 89-677, 69 pp.

Fitterman, David V., and Kevin Dennehy, 1991, Verification of Geophysically Determined Depths to Saltwater Near the Herring River, Cape Cod National Seashore, Wellfleet, Massachusetts, USGS Open-File Report 91-321, 47 pp.

Frimpter, Michael H. and Frederick B. Gay, 1979, Chemical Quality of Ground Water on Cape Cod, Massachusetts, USGS Water-Resources Investigations Report 79-65, 11 pp.

LeBlanc, Denis R., John H. Guswa, Michael H. Frimpter, and Clark J. Londquist, 1986, Ground-Water Resources of Cape Cod Massachusetts, USGS Hydrologic Investigations Atlas HA-692, 4 sheets

Masterson, John P., 2004, Simulated Interaction Between Freshwater and Saltwater and Effects of Ground-Water Pumping and Sea-level Change, Lower Cape Cod Aquifer System, Massachusetts, USGS Scientific Investigations Report 2004-5014, 70 pp.

Michaud, Scott, and Tom Cambareri, 2003,Hydrogeologic Investigation of the Pilgrim, Pamet, Chequesset, and Nauset Lenses Water Table Map of the Outer Cape: May 21-23, 2002. prepared by the Cape Cod Commission, November 17, 2003, 1 sheet

Niedoroda, Alan and Richard April, 1975, Report on Groundwater Flow Beneath Coastal Salt Marshes, unpublished report submitted to National Park Service, 49 pp.

Nuttle, W. K. 1990. Extreme values of discharge for Mill Creek and options to control flooding from the Herring River. Final report to National Park Service. 44 pp.

Portnoy, J.W., 1991, Summer oxygen depletion in a diked New England estuary. Estuaries, vol. 14, no. 2, pp. 122-129

Portnoy, J.W. and A.E. Giblin. 1997a. Effects of historic tidal restrictions on salt marsh sediment chemistry. Biogeochemistry 36:275-303.

Portnoy, J.W. and A.E. Giblin. 1997b. Biogeochemical effects of seawater restoration to diked salt marshes. Ecological Applications 7:1054-1063.

Portnoy, J. and M. Reynolds. 1997. Wellfleet's Herring River: The Case for Habitat Restoration. Environment Cape Cod 1:35-43.

Portnoy, J.W., B.L. Nowicki, C.T. Roman, and D.W. Urish, 1998, The discharge of nitrate-contaminated groundwater fromdeveloped shoreline to marsh-fringed estuary, Water Resources Research, v. 34, no. 11, pp. 3095-3104

Soukup, M.A., and J.W. Portnoy, 1986, Impacts from mosquito control induced-sulphur mobilization in a Cape Cod estuary, Environmental Conservation, vol. 13, no. 1, pp. 47-50

Spaulding, M. and A. Grilli. 2001. Hydrodynamic and salinity modeling for estuarine restoration at Herring River, Wellfleet, Massachusetts. Report to National Park Service. 94 pp.

Roman, C. T. 1987. An evaluation of alternatives for estuarine restoration management: The Herring River ecosystem (Cape Cod National Seashore). Report to National Park Service. 304 p.

Urish, D.W. and E.K. Qanbar, 1997, Hydrologic evaluation of groundwater discharge, Nauset Marsh, Cape Cod National Seashore, Massachusetts, U.S. National Park Service, New England System Support Office, Technical Report NPS/NESO-RNR/NRTR/97-07, 69 pp.

Walter, Donald A., John P. Masterson, and Paul M. Barlow, 1996, Hydrogeology and Analysis of Ground-Water-Flow System, Sagamore Wash Area, Southeastern Massachusetts, USGS Water Resources Investigations Report 96-4200, 41pp.

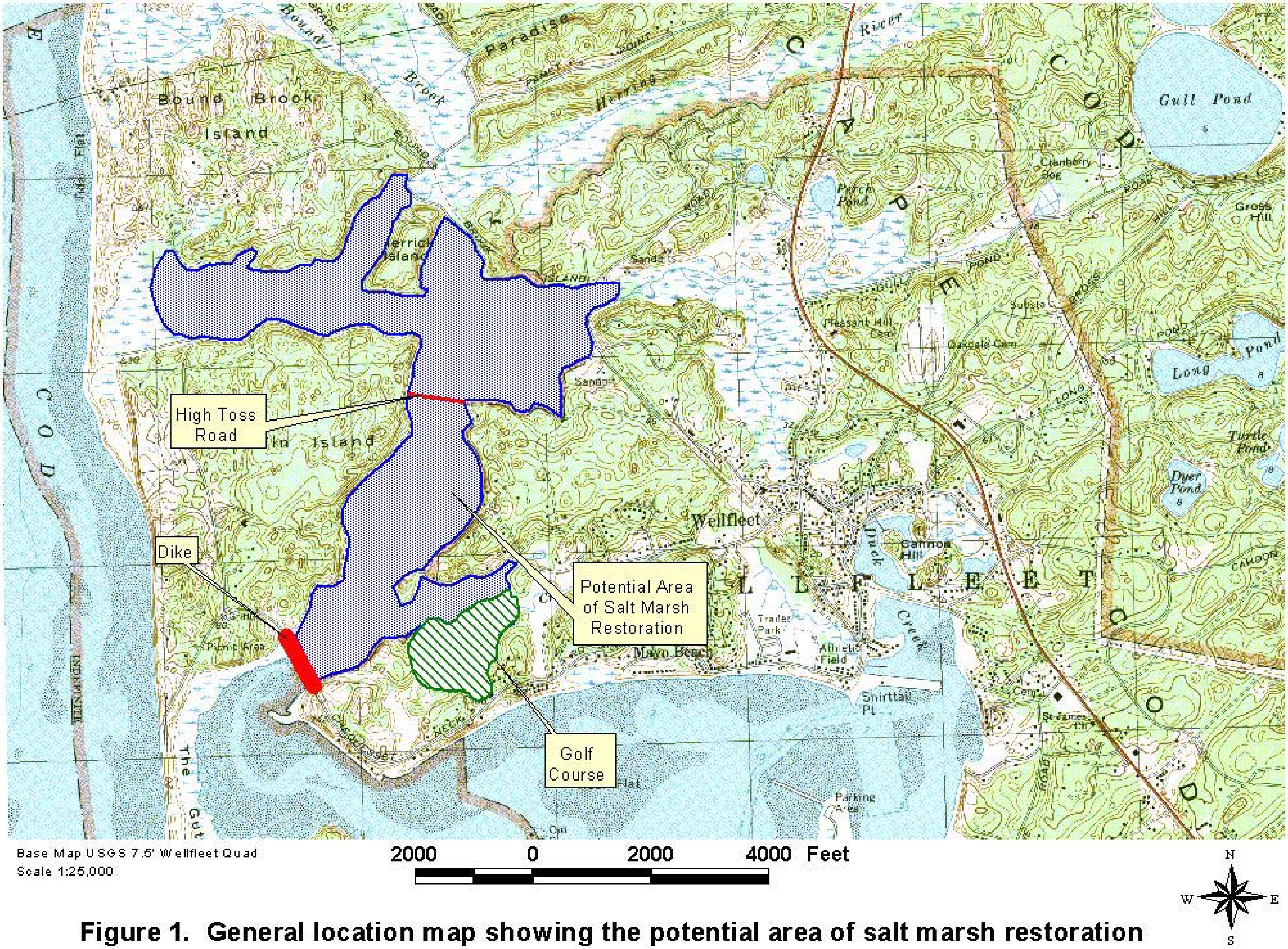


Figure 1. General location map showing the potential area of salt marsh restoration

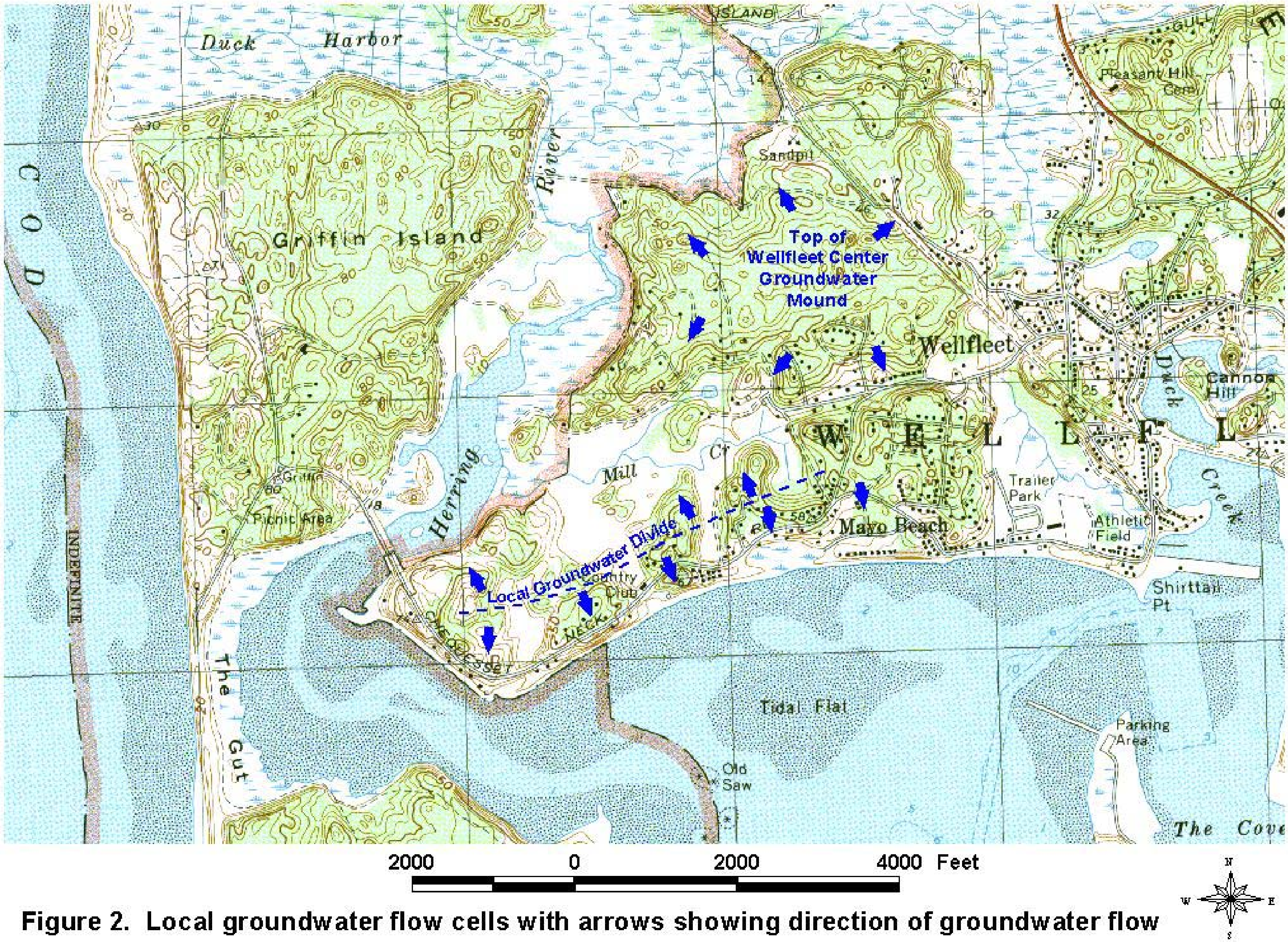


Figure 2. Local groundwater flow cells with arrows showing direction of groundwater flow

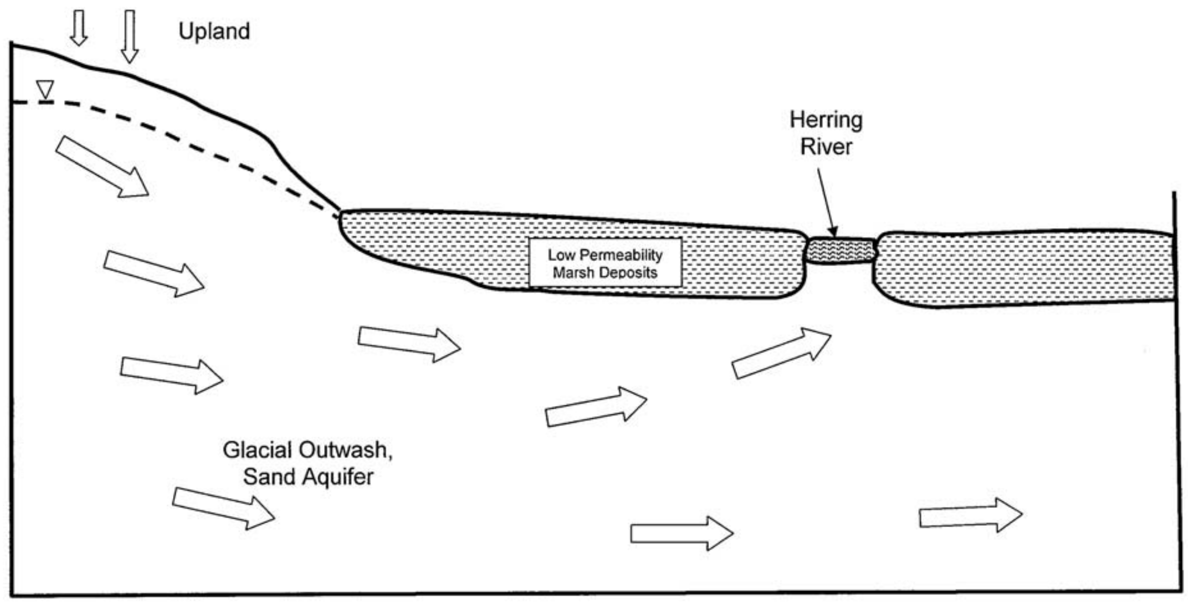


Figure 3. Cross section showing conceptual model of groundwater flow from recharge on upland areas, infiltration, and flow from upland areas to discharge into Mill Creek or Herring River.

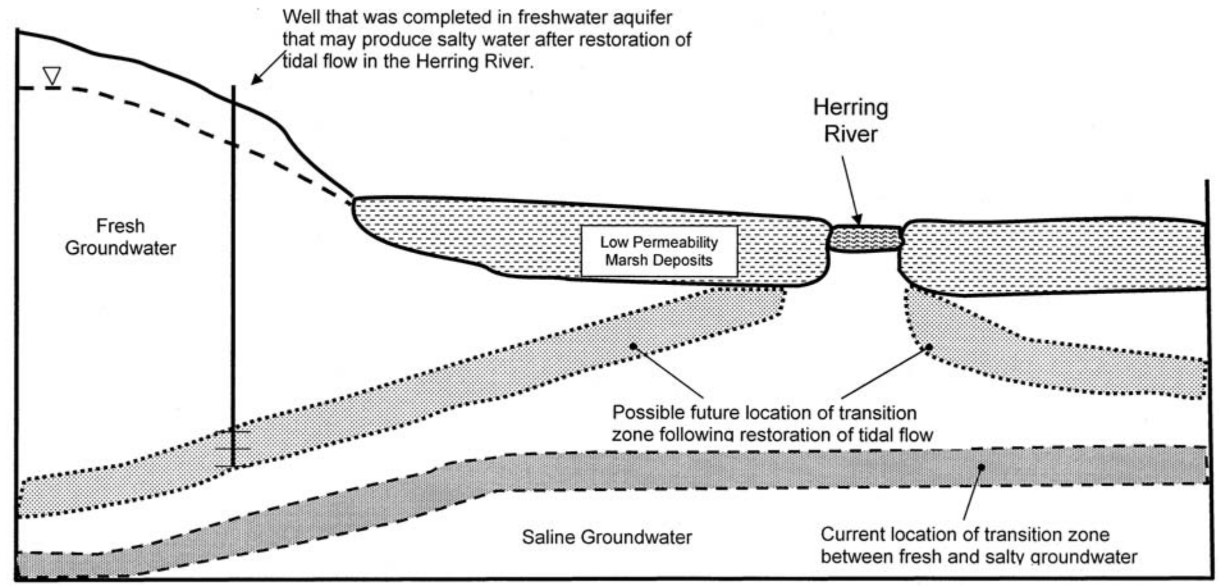


Figure 4. Cross section sketch showing a hypothetical upward or landward migration of the fresh/salt groundwater interface causing a well to pump salty water.

Figure 5. Locations of interface monitoring wells

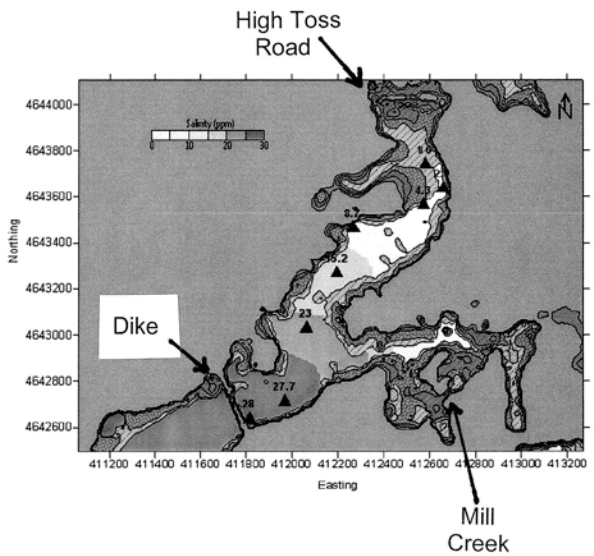


Figure 6. Salinity distribution (ppt) in the Herring River Basin at mean tide under existing conditions, two tide gates operative (i.e., closed at high tide) and one sluice gate open 61 cm (24 inches).
X and Y scales are feet.
Case C2, Basin B0. (from Spaulding and Grilli, 2001)

The area shown in this figure is the lower half of the area shown in figure 7.

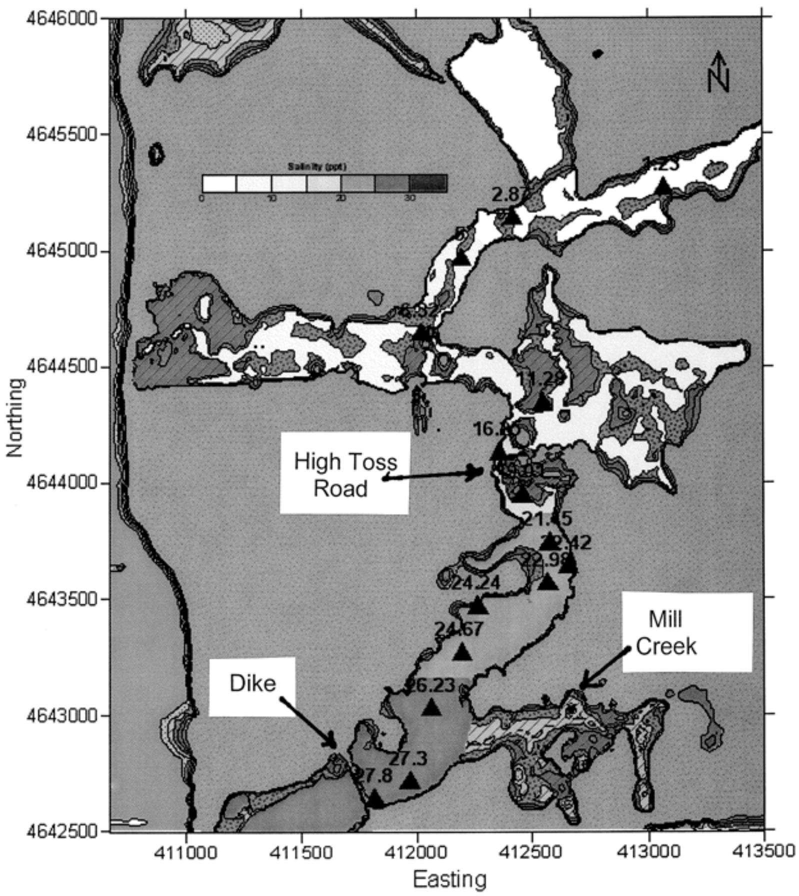
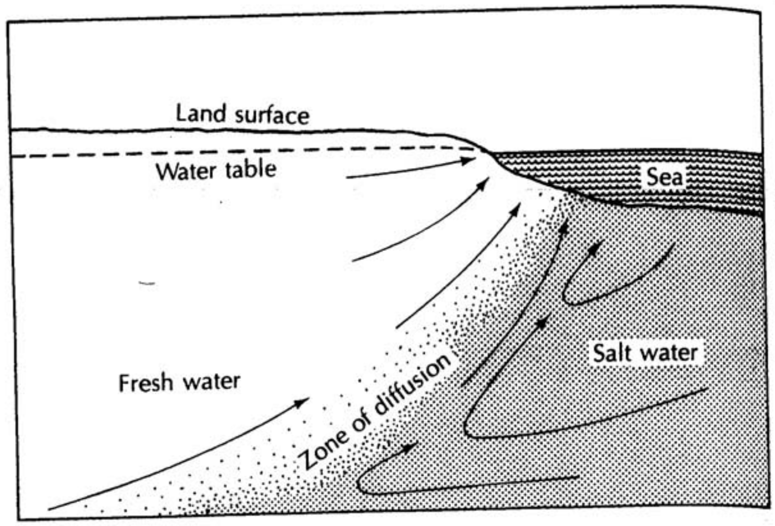


Figure 7. Predicted salinity distribution (ppt) in the Herring River Basin at mean tide with both tide gates removed and the sluice gate opened to its maximum 130 cm (51 inches). This scenario assumes that the dike at High Toss Road has been opened and a new dike constructed at the mouth of Mill Creek.
X and Y scales are feet.
Case C5, Basin B1. (from Spaulding and Grilli, 2001)

The area shown in figure 6 encompasses the bottom half of this figure.



Circulation of fresh and saline groundwater at a zone of diffusion in a coastal aquifer.
Source: H.H. Cooper, Jr., U.S. Geological Survey Circular 1613-C, 1964

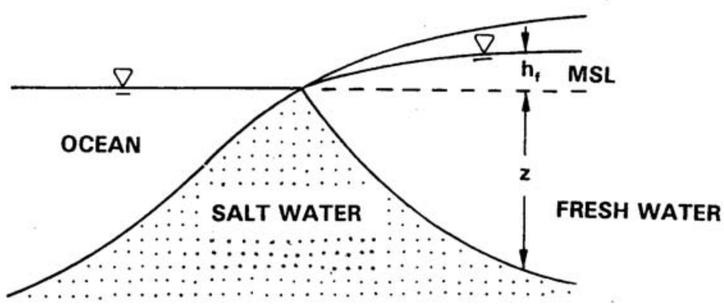


Figure 8. Relationship of fresh-water head and depth to salt-water interface in a coastal aquifer. h_f is the elevation of the water table above mean sea level and z is the depth below mean sea level to the salt-water interface. $Z=40(h_f)$

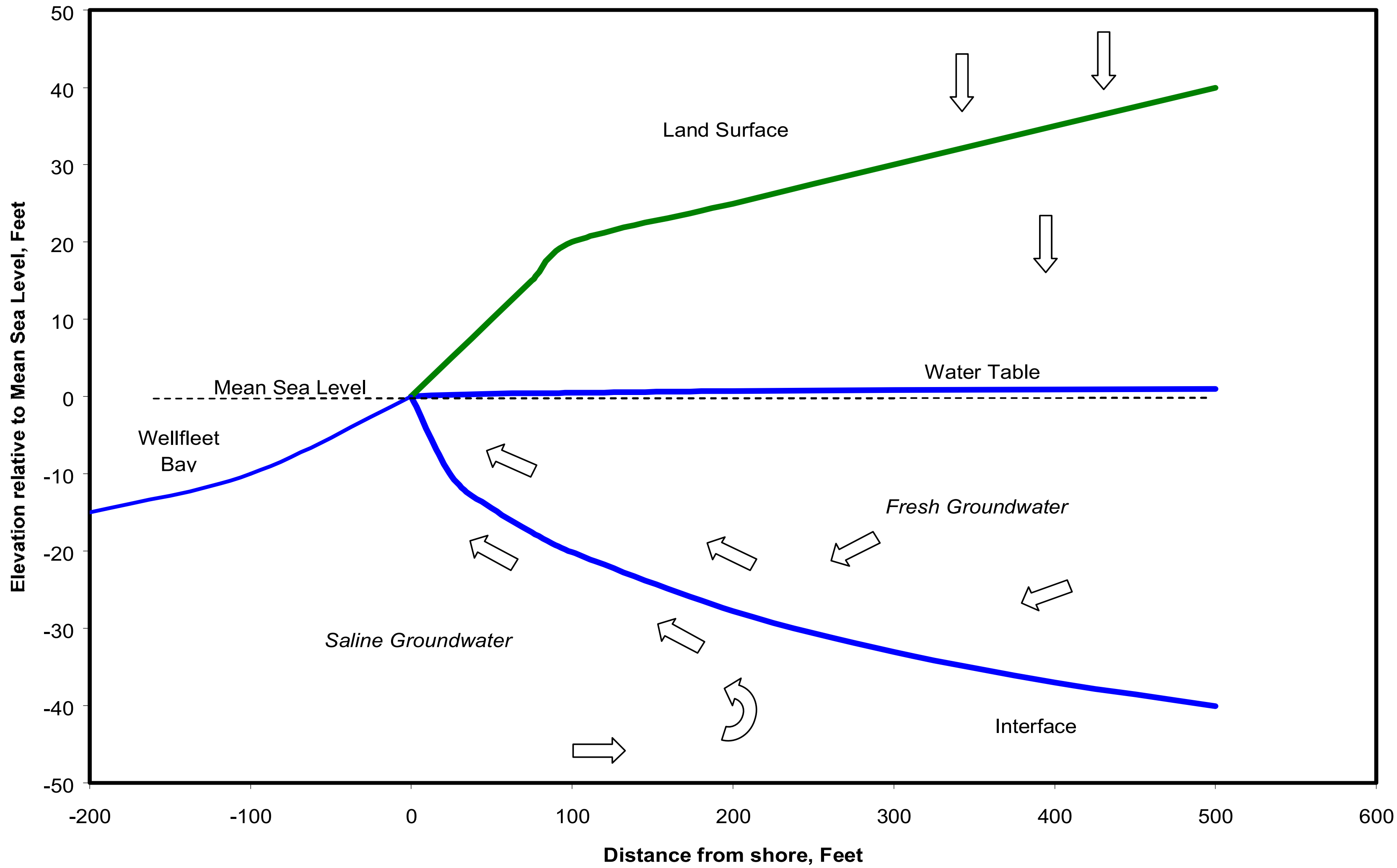


Figure 9. Estimated water table elevation and depth to salt-water interface from Wellfleet Bay inland on Chequesset Neck. This figure is based on solution of the Dupuit-Ghyben-Herzberg model. (equation 8.8, p. 335, Fetter 2001)

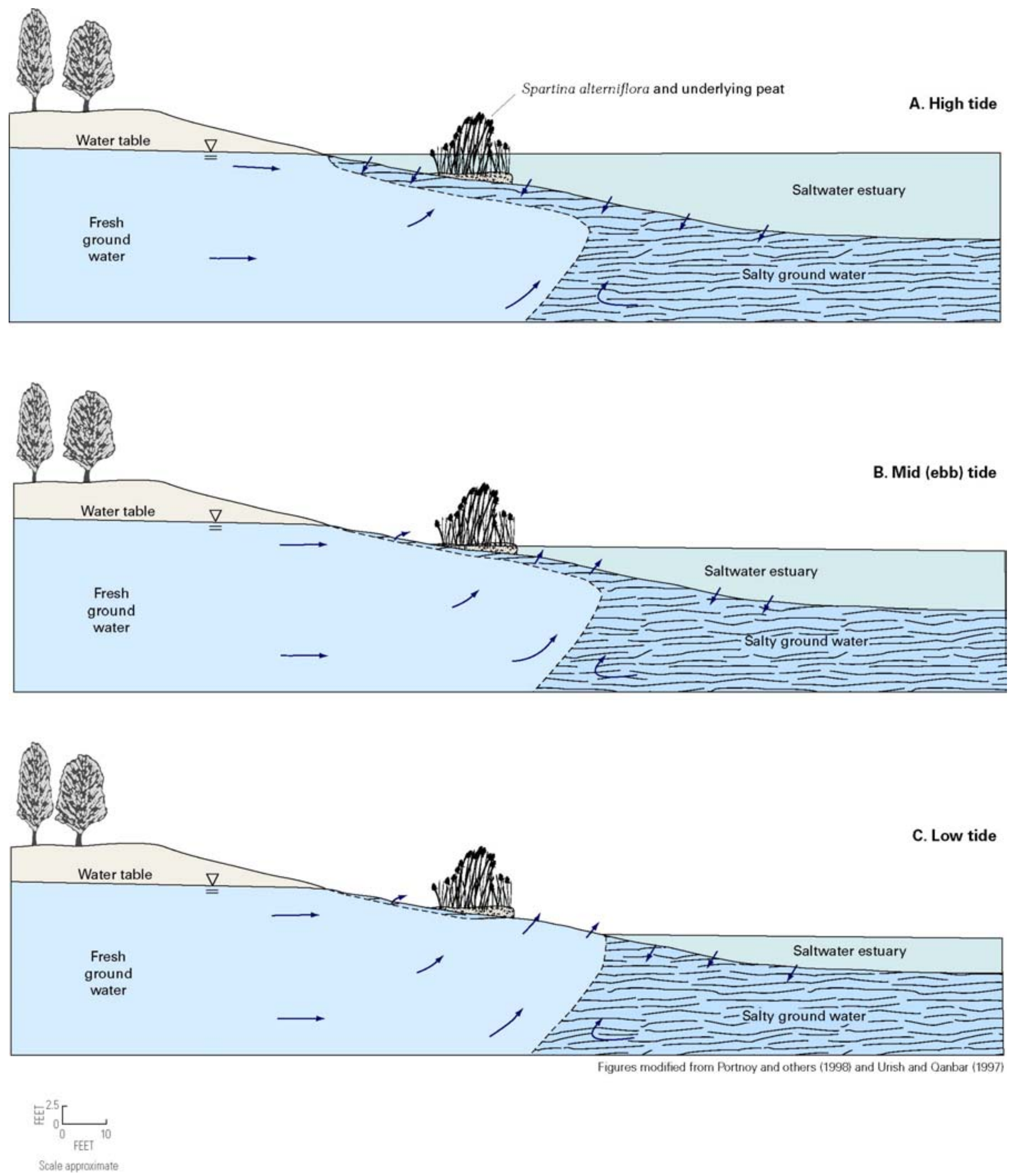


Figure 10. Groundwater discharge and saltwater infiltration at the aquifer-estuary boundary during a tidal cycle. (from Barlow, 2003)

Base Map USGS 7.5' Wellfleet Quad
Scale 1:25,000

2000 0 2000 4000 Feet

N W E S

Figure 11. Areas of comparable hydrogeologic conditions discussed in this report

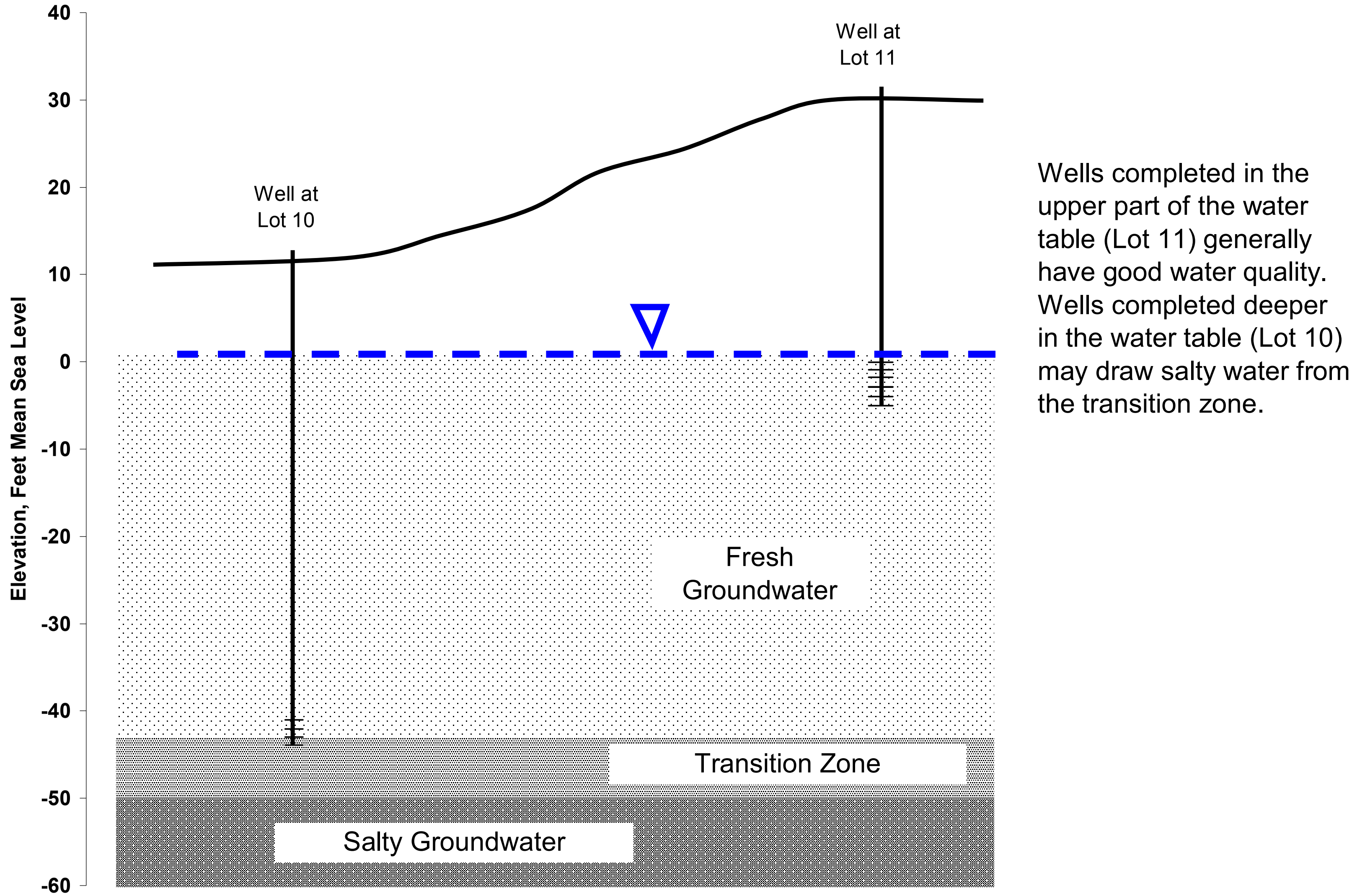


Figure 12. Schematic drawing of possible hydrogeologic setting of wells at Lots 10 and 11 north of Mill Creek

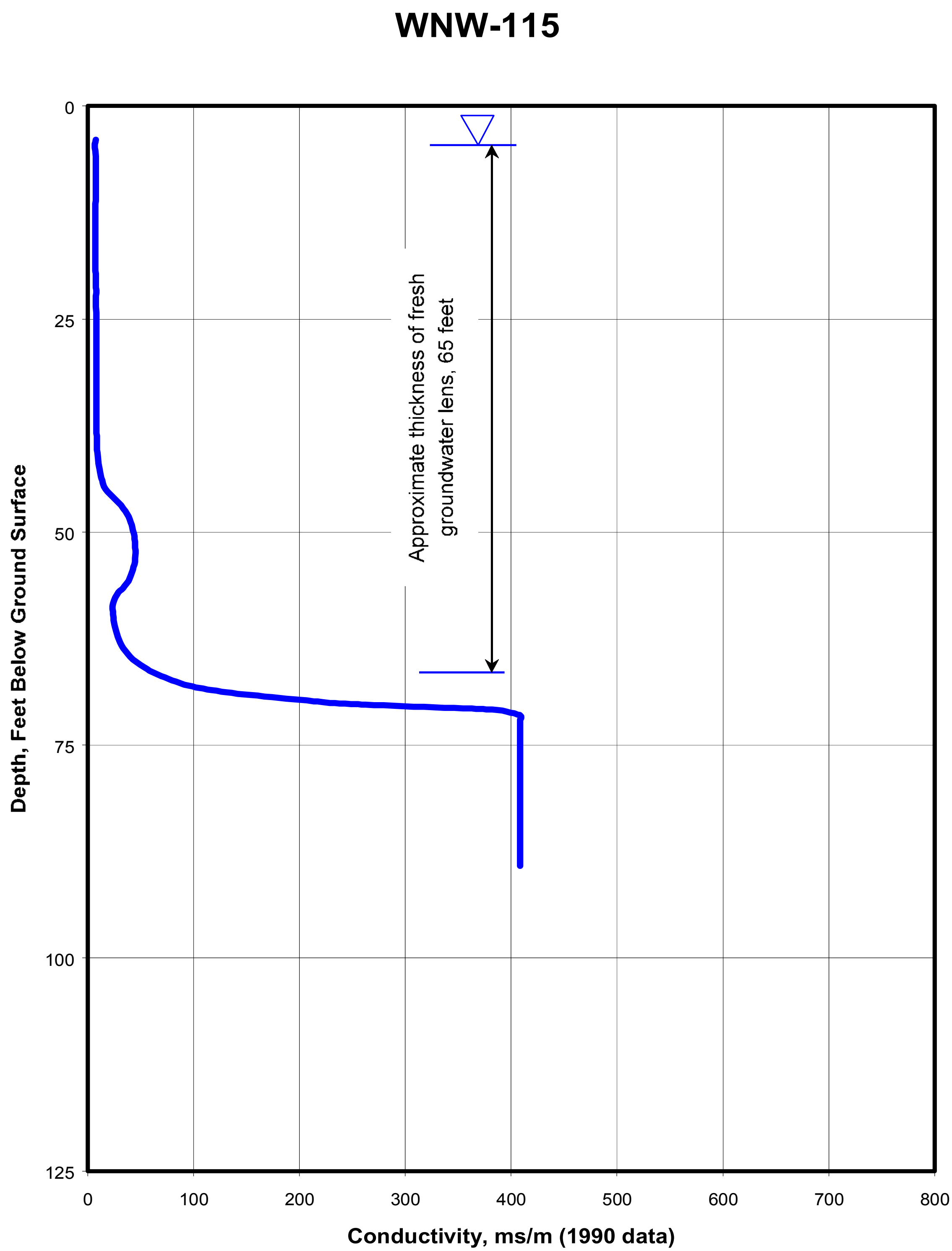


Figure 13. Electromagnetic Induction Log for Well WNW-115

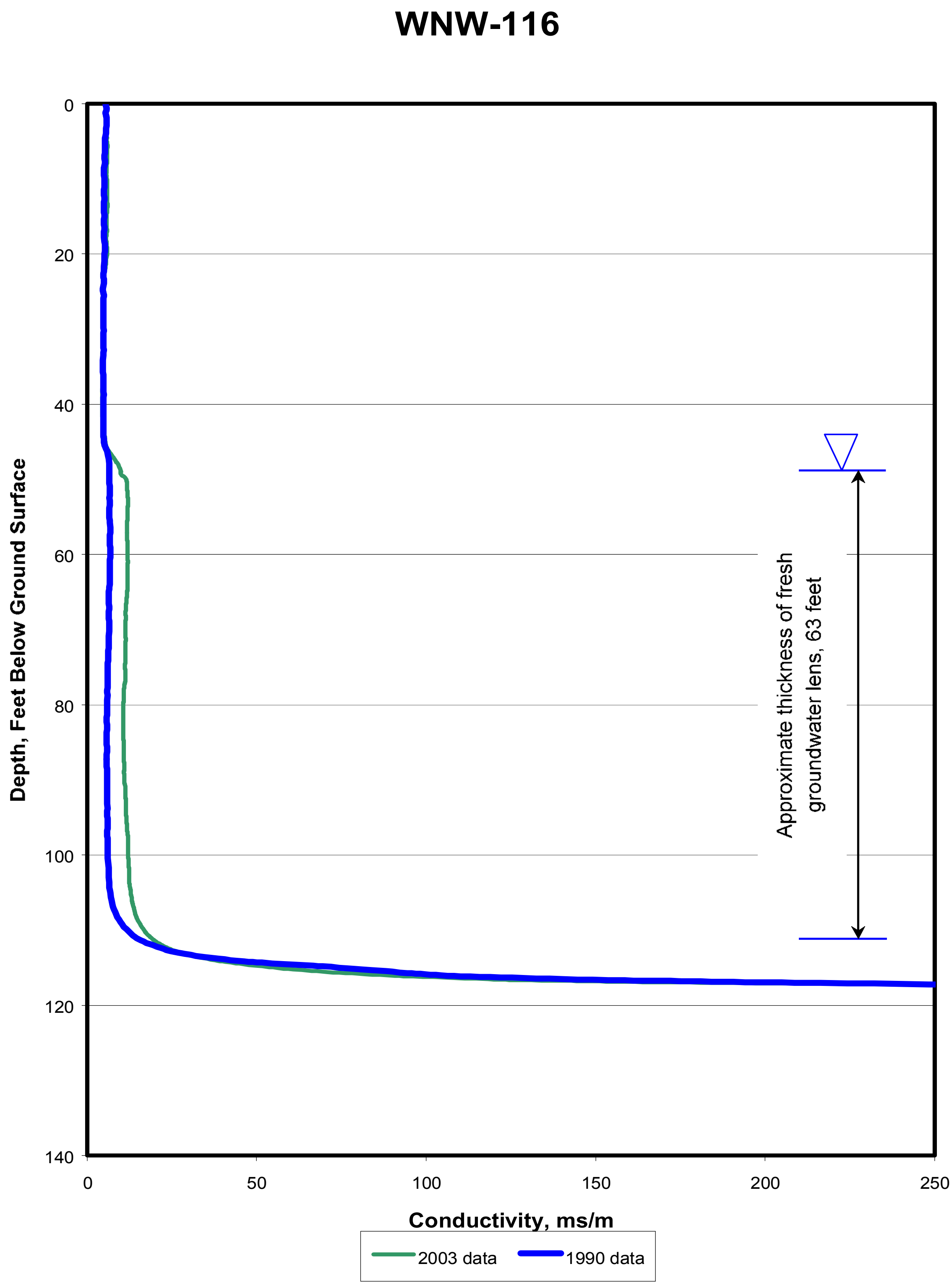


Figure 14. Electromagnetic Induction Logs for Well WNW-116

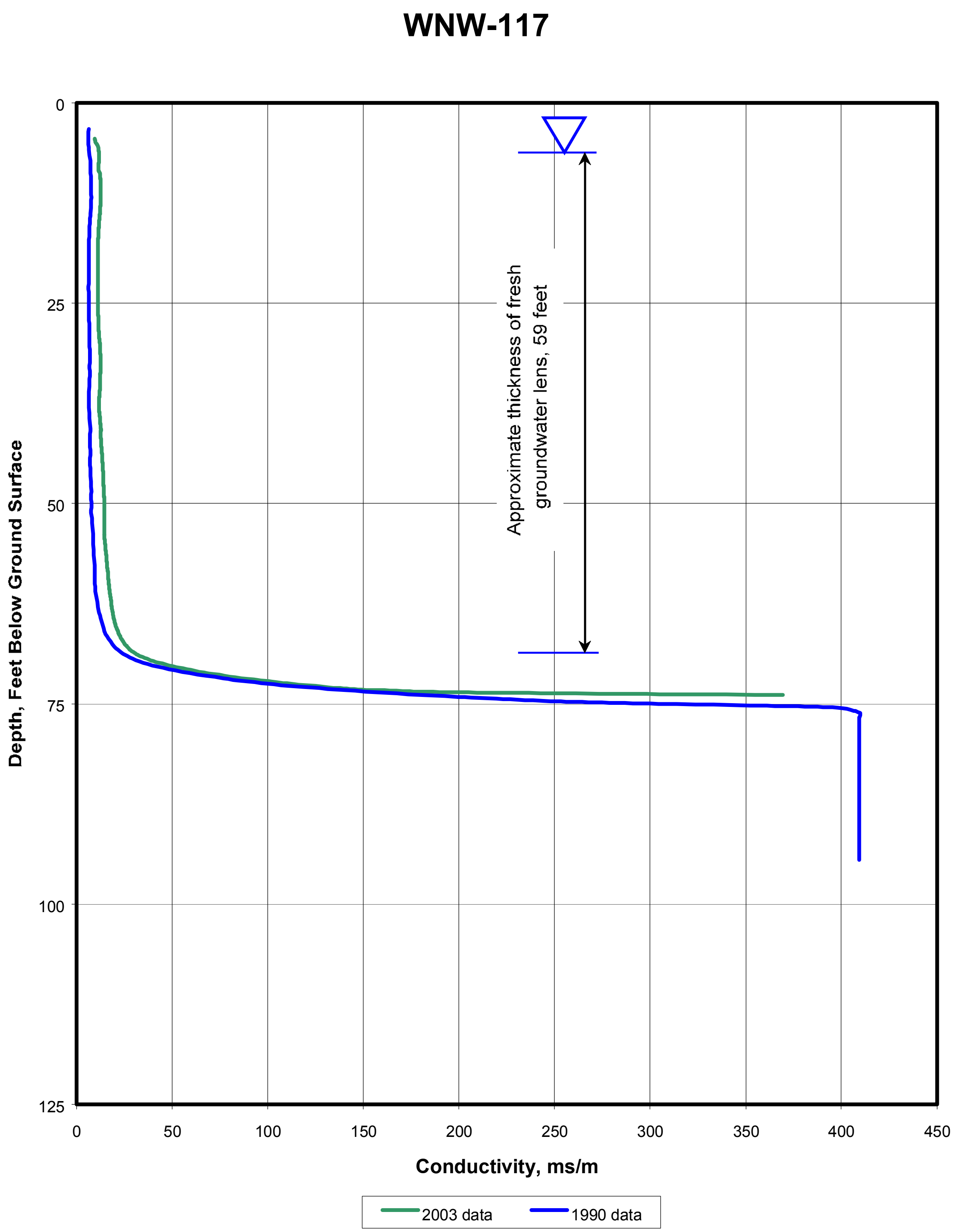


Figure 15. Electromagnetic Induction Logs for Well WNW-117

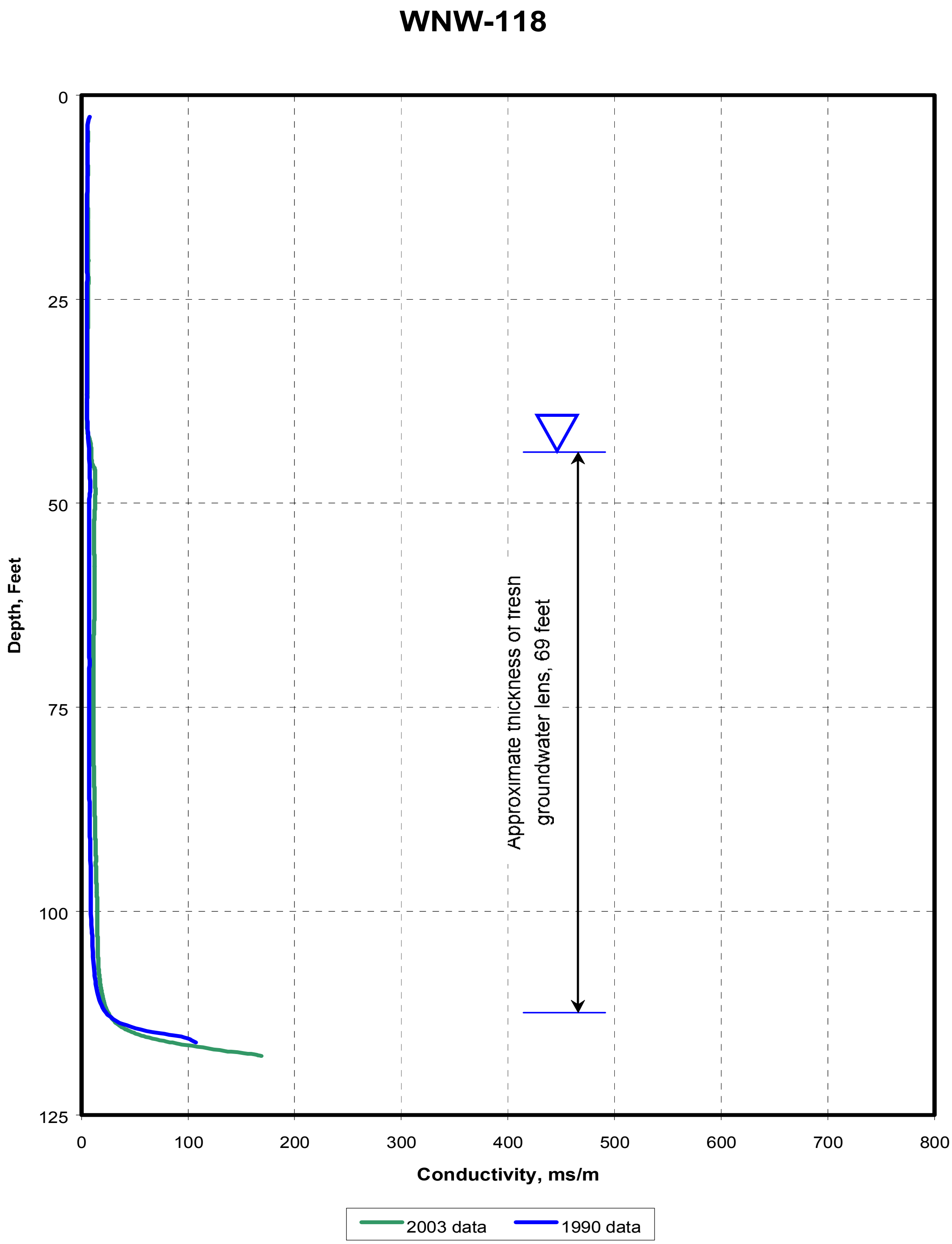


Figure 16. Electromagnetic Induction Logs for Well WNW-118

WNW-133

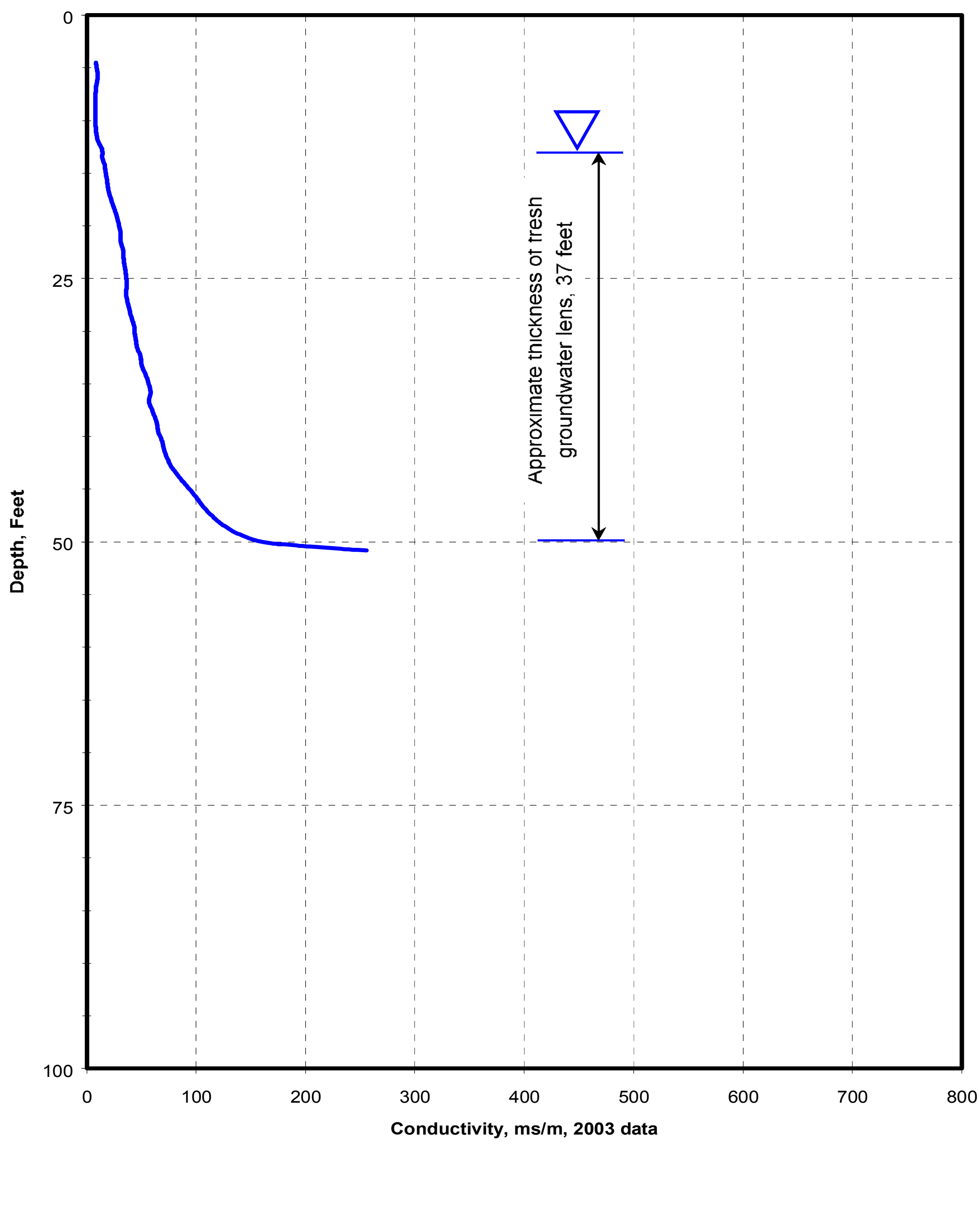


Figure 17. Electromagnetic Induction Log for Well WNW-133

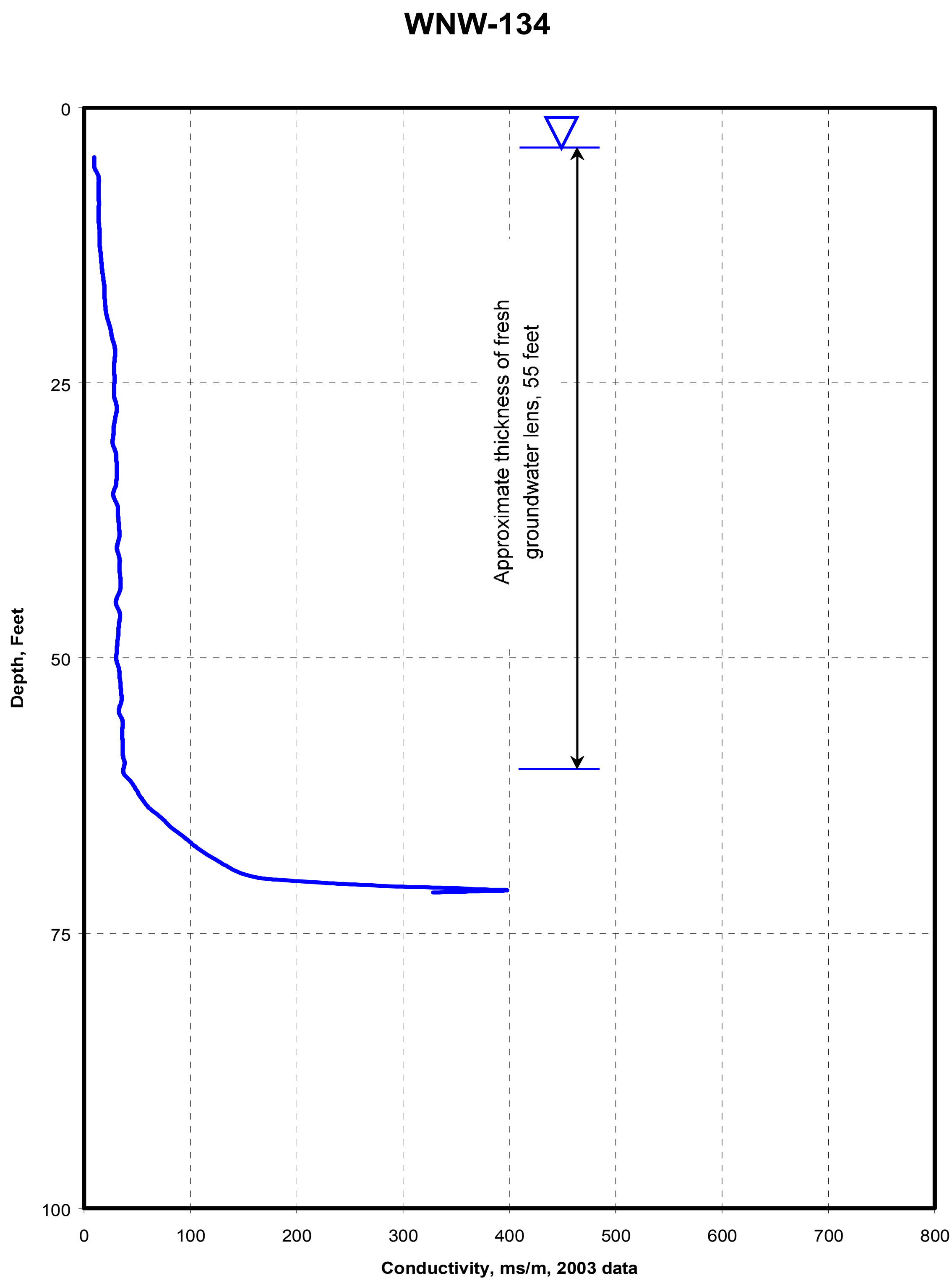


Figure 18. Electromagnetic Induction Log for Well WNW-134

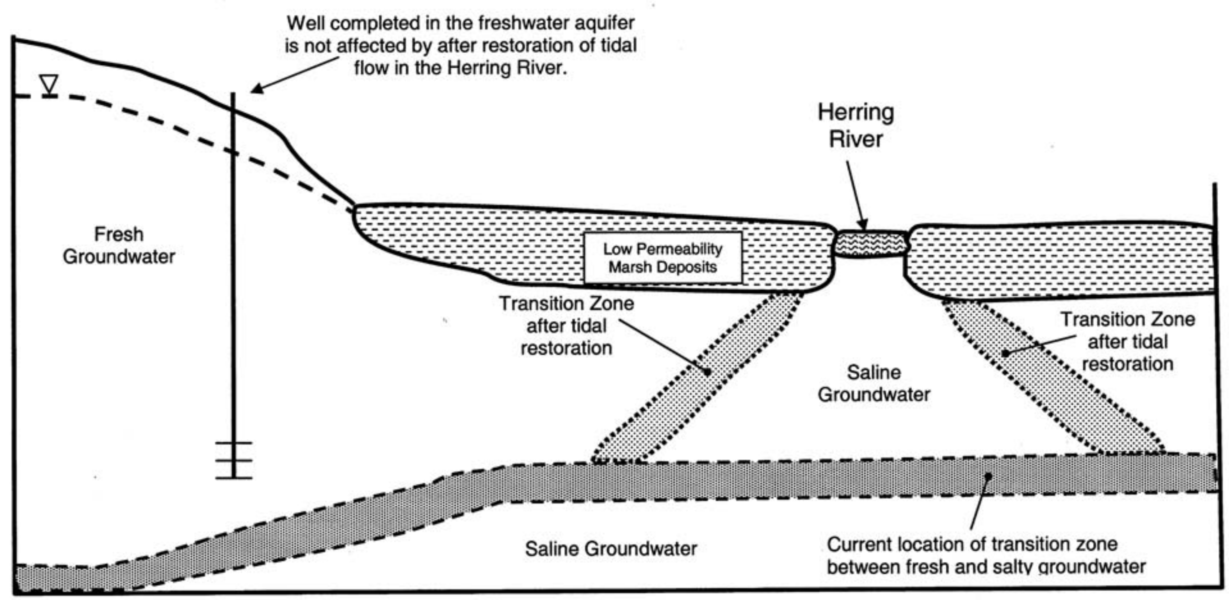


Figure 19. Cross section sketch showing the probable change in the location of the fresh/salt groundwater interface after restoration of tidal flow in the Herring River.

As the nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

NPS D-346, March 2004