INVESTIGATION OF EFFECTS OF GROUND WATER WITHDRAWALS FROM THE PAMET AND CHEQUESSET AQUIFERS, CAPE COD NATIONAL SEASHORE

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NPS/NRWRD/NRTR-93/14

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ABSTRACT

Ground water is pumped from the Pamet aquifer on the outer part of Cape Cod to supply Provincetown, Massachusetts with potable water. Ground water withdrawals exceeds 300 million gallons per year (gpy). Peak demand in the summer tourist season is about 1.45 million gallons per day (gpd). Ground water withdrawals cause the water table to be lowered, resulting in decreased freshwater discharge from the aquifer to wetlands and riparian areas. Ecosystems in these natural discharge areas are dependent on freshwater discharge from the aquifer to maintain water levels, hydroperiods, salinity, balances, and normal soil/sediment chemistry (pH, saturation, redox). The volume of freshwater discharging along ocean shores is trivial in comparison with the seawater into which it mixes. Therefore, reductions in this discharge are unlikely to affect ecological processes along high energy ocean shorelines.

Computer simulations of ground water flow were conducted to evaluate the relative impact of various ground water withdrawal scenarios. Locations and rates of withdrawals were varied to evaluate the effects of both existing wellfields and potential new sites. In general, wellfields located closer to the ground water discharge areas near wetlands and riparian areas will have a greater effect on freshwater discharge from the aquifers. Computer simulations predict that about half the water withdrawn at the Knowles Crossing wellfield will come from a reduction of freshwater discharging from the aquifer to the Salt Meadow and Pilgrim Lake. Ground water withdrawals from the wells at the North Truro Air Base and South Hollow wellfield will have the least effect on freshwater discharge to wetlands and riparian areas at the southern and northern boundaries of the Pamet aquifer.

A comprehensive ground water management and development plan is needed to provide guidance to towns regarding the limits of potential ground water supplies in the area. The plan should include identification of ecosystem features and areas that are dependent on maintaining freshwater aquifer discharge; and it should provide an estimate of the level of ground water development that can be allowed while still maintaining the natural hydrology, nutrient availability, and salinity balance in wetland discharge areas.

INTRODUCTION

The town of Provincetown obtains part of its municipal water supply from wells located on the North Truro Air Base (Figure 1). The Air Base is being decommissioned and the land will be transferred to the jurisdiction of Cape Cod National Seashore (CACO). Provincetown would like to continue using these wells to meet peak demand in the summer tourist season. The National Park Service (NPS) is concerned about potential effects of ground water withdrawals, particularly with respect to diminution of ground water discharge to wetland and riparian ecosystems. Wetlands on CACO lands may be threatened by encroachment of upland plant species if water table elevations are reduced during the growing season and nutrient availability and salinity balances are changed.

Provincetown obtains its entire water supply from wells located in the town of Truro and completed in the Pamet aquifer (Figure 2). The aquifer is bounded on the east and west by the Atlantic Ocean. The northern boundary is Pilgrim Lake and Salt Meadow. The southern boundary is the Pamet River. Provincetown has several wellfields in this aquifer and may want to construct additional wells in the future. The existing wellfields are being pumped at near capacity during the peak demand summer months. Provincetown has used the wells at the North Truro Air Base as a supplemental supply during the summer months since 1978. Withdrawals from the wells at the North Truro Air Base average about 300,000 gpd from June through October.

Precipitation is the only source of recharge to the aquifer. Natural discharge occurs at the margins of the aquifer; either to the ocean or to the wetland and riparian areas of the Pamet River or Pilgrim Lake, and Salt Meadow along the southern and northern boundaries. A major NPS concern is that reduced aquifer discharge could result in lower freshwater wetland water levels. Lower water levels can affect plant communities and succession by associated changes in nutrient availability.

Freshwater discharge to wetlands along the northern and southern boundaries of the Pamet aquifer will be affected most by withdrawals near these aquifer limits. Withdrawals from wells near the middle of the aquifer (such as at the Air Base) will have the least effect on discharge to the wetland areas. Therefore, shifting withdrawals from the Knowles Crossing Wellfield to the North Truro Air Base will lessen the existing impact on wetland areas. At current levels of demand, this would involve withdrawing water from the wells at the Air Base at an average annual rate of 200,000 gpd. Larger withdrawals, possibly in the range of 300,000-500,000 gpd can probably be sustained from the two wells at the Air Base. Additional field investigations are needed to establish the safe yield of these wells. Reduction or elimination of withdrawals from the Knowles Crossing wellfield will help to reduce impacts in the Salt Meadow and Pilgrim Lake areas.

The ground water of Cape Cod directly supports the majority of the Cape's inland water resources and influences estuarine ecosystems by discharge of freshwater from the aquifers to maintain the balance between saltwater and freshwater. Since ground water is the sole source of drinking water on the outer Cape, residential population growth and tourism have resulted in a related increase in the withdrawal of ground water. Ground water withdrawals change the local water balance and the rate and pattern of ground water flow, which can result in impacts to ground water dependent ecosystems. Effects from ground water withdrawals depend on the location of the wells, local hydrogeologic conditions, the amount and rate of withdrawals, and whether the water is returned to the same aquifer after use. Artificial ground water recharge may lessen the effect of withdrawals, but may affect the quality of ground water (Mitchell and Soukup 1981).

This report is the result of an investigation undertaken to evaluate the effect of ground water withdrawals from the Pamet aquifer for municipal supplies in Provincetown. A computer model of the ground water flow system was prepared. Simulations were made for several ground water withdrawal scenarios. Both withdrawal rates and locations of withdrawals were evaluated with respect to the effect on water table elevation and freshwater discharge from the aquifer to river drainages and wetland areas.

It must be emphasized that this computer model is only the first step toward analyzing the potential effect of ground water withdrawals. Model predictions regarding the quantity of water discharged from the aquifer to wetlands and rivers have not been verified or calibrated against field measurements. The utility of this model is to allow comparison of the magnitude of effects that can be expected from different ground water withdrawal scenarios. For example, one scenario may be expected to reduce freshwater discharge by twice the amount of another scenario. Although a simplified analysis of this type could have been made in a qualitative manner, a computer model was prepared to enhance the analyses by depicting the areal extent of drawdown from pumping different combinations of wells at different rates, thus allowing identification of potential interference problems between wells. It is anticipated that this computer model will be refined and updated as our understanding of the aquifer system increases and more field data becomes available. Recommendations for field measurements and data collection to meet these objectives are included later in the report.

HYDROGEOLOGY

Aquifers on Cape Cod are naturally separated from one another by streams and glacial outwash valleys where the water table drops nearly to sea level. While the aquifers are physically in contact with one another, they are hydrologically separate. Ground water elevations, movement, and water quality in one aquifer does not affect neighboring aquifers. Freshwater from the aquifers flows radially from recharge areas in the middle of the aquifer toward discharge areas in the surrounding ocean and intertidal estuaries. Figure 2 shows the areal extent and relative locations of aquifers in the outer Cape area.

The outermost part of Cape Cod (Provincetown area), north and west of Pilgrim Lake and Salt Meadow (Figure 1), is underlain by the Pilgrim aquifer (Figure 3). The area south and east of Pilgrim Lake and Salt Meadow and north of the Pamet River (North Truro area) is underlain by the Pamet aquifer (Figure 4). The area south of the Pamet River and north of Blackfish Creek is underlain by the Chequesset aquifer (Figure 5). The areal extent of these aquifers is approximated by the 4 or 5 foot (ft) water table elevation contour line. Only the northernmost part of the Chequesset aquifer is included in this investigation and report. These aquifers have been called by various names in other reports. The nomenclature used above, and throughout this report, is consistent with that used by the Cape Cod Commission and its predecessor, the Cape Cod Planning and Economic Development Commission.

Generally, the direction of ground water flow in aquifers on the outer Cape is from the central area of the aquifer, where the water table is highest, toward the nearest discharge area; either the ocean, wetlands, or rivers. Ground water flow paths, direction, and rate of flow are influenced by local hydrogeologic conditions. Ground water withdrawals from large-capacity municipal supply wells create cones of depression in the natural water table and may result in changing either or both the direction and quantity of ground water flowing toward wetlands and rivers. Wells located near wetlands or rivers will have a greater effect on reducing freshwater discharge from the aquifer to the wetlands and rivers than will wells located farther away.

The hydrogeology of the Pamet aquifer has been studied by several previous investigators. Previous reports include a hydrologic atlas (LeBlanc, et al. 1986), reports on evaluations of site investigations at proposed wellfields (Delaney and Cotton 1972, and Guswa and Londquist 1976), a report on computer flow models for the entire Cape Cod peninsula (Guswa and LeBlanc 1985), additional computer model simulations for the Pamet aquifer (LeBlanc 1982), an evaluation of the entire Provincetown water supply system (Camp, Dresser, & McKee [CDM] 1985), and an aquifer assessment and ground water protection plan (Cambareri, et al. 1989). Only a brief description of the hydrogeology is presented in this report. Readers wanting more detail should consult the reports listed above.

The Pamet aquifer is a Pleistocene glacial outwash deposit composed of unconsolidated sand and gravel with some silt and clay. Fresh ground water is contained in the unconsolidated sediments under unconfined (water table) conditions. The sediments are generally very permeable and readily yield water to wells.

Important features of the hydrologic cycle for outer Cape Cod are shown schematically in Figure 6. Schematic diagrams of the saltwater-freshwater interrelationships are shown in Figure 7.

The fresh ground water flow system in the Pamet aquifer is bounded laterally by surface-water bodies, the ocean or rivers. Vertical boundaries are the water table and the interface (transition zone) between fresh and saline ground water. The lateral boundaries are the ocean to the east and west, and wetlands, streams, or ponds at or near sea level to the north (Pilgrim Lake and Salt Meadow) and south (Pamet River). These boundaries separate the ground water flow system in the Pamet aquifer from adjacent flow systems in the Pilgrim aquifer (north of Salt Meadow), or the Chequesset aquifer (south of the Pamet River). Under present hydrologic conditions, ground water does not flow between these nearly independent aquifers.

The top boundary of the ground water flow system is the water table. The average maximum altitude of the water table in the Pamet aquifer is about 6 ft above sea level. At most locations in Truro, the water table is more than 5 ft below land surface. However, some kettle holes intersect the water table and contain ponds or wetlands that are expressions of the water table. The Route 6 wetland, 1,500 ft north of CACO Test Site 4 includes 12 acres and is probably an expression of the water table.

The lower boundary of the freshwater flow system is the boundary between fresh and saline ground water. The interface between freshwater and saltwater in the aquifer is not a sharp boundary, but rather is a zone of mixing called the transition zone. Freshwater discharges from the aquifers to the ocean in a narrow band near the shore.

The Pamet aquifer is recharged by infiltration of precipitation. Although the recharge rate has not been measured directly, an average recharge rate of 18 inches per year was estimated (by previous investigators) by an empirical technique that relates recharge to climatological data (Guswa and LeBlanc 1981) and has been generally accepted as the average annual recharge rate for other investigations conducted in this area.

Water discharges to streams, wetlands, and the ocean at the lateral boundaries of the aquifer. Some of this discharge occurs as springs where land surface intersects the water table. Springs are common where headlands drop steeply to the edge of coastal wetlands. Pilgrim Spring, an historic spring in the CACO, is a well-known example. Ground water is withdrawn from the Pamet aquifer by pumping from water supply wells. Most of the water withdrawn by low-yield private wells for domestic use in Truro is returned to the aquifer by seepage from onsite wastewater disposal systems. Average ground water withdrawal (1987-91) for export to Provincetown has been 800,000 gpd or about 300 million gpy.

The rate of recharge from precipitation fluctuates seasonally and annually and causes water levels in the aquifers to fluctuate. The elevation of the freshwater-saltwater interface responds much more slowly than the water table to fluctuations in recharge. Movement of the interface in response to recharge variations has not been observed in the Pamet aquifer or elsewhere on Cape Cod (LeBlanc 1982).

Although recharge and discharge vary seasonally and over longer periods, the flow system in the Pamet aquifer is in a state of dynamic equilibrium. Average recharge by precipitation is in balance with discharge to the ocean, streams, ponds, wetlands, and wells, and no long-term trend of rising or declining water levels has been observed. A sustained change in the average rate of recharge by precipitation or in the rate of withdrawal from wells can alter this dynamic balance. As a result, the positions of the water table and the freshwater-saltwater interface, and the rate of discharge to the lateral boundaries of the aquifer also will change. Wetland and pond water levels and the discharge rates of springs will be affected by the water table fluctuations. However, ponds and wetlands that are perched above the main ground water body will not be directly affected by fluctuations of the water table.

Data from CACO Test Site 4 during the period from 1979-83 (Frimpter 1984) show the effect of overpumping (exceeding the safe yield) in this type of hydrogeologic setting. This well was pumped on a seasonal basis to meet higher demand during May through November of those years. Withdrawal rates in July, August, and September were about 650,000 gpd. Chloride concentrations and electrical conductivity measured in a monitoring well 250 ft from the pumped well varied seasonally in direct response to the amount of water withdrawn. During periods when the well was pumped, the saltwater interface was drawn upward and chloride concentrations and conductivity increased. During periods when the well was not pumped, the saltwater interface receded and chloride concentrations and conductivity decreased, but did not return to the original levels. A gradual upward trend of minimum chloride levels was observed, indicating that the saltwater-freshwater interface was moving toward a new equilibrium and possibly threatening the continued use of Test Well 4 as a water supply. Data indicated that a sustained withdrawal rate of 300,000 gpd could be achieved without inducing saltwater upconing into the well.

LeBlanc (1982) investigated potential hydrologic effects for several ground water withdrawal scenarios in this area by use of a computer flow model. Saltwater upconing and freshwater discharge at the margins of the aquifer were both evaluated. Freshwater discharge to the ocean and wetlands in the Salt Meadow area in northeastern Truro were predicted to decrease as much as 50 percent in some cases. The model grid for his work had a very coarse (.25 mile [mi]) grid spacing. One of the purposes for creating a new computer model for the current investigation was to use a smaller grid spacing to allow more detailed resolution of potential effects.

GROUND WATER WITHDRAWALS

Records of ground water withdrawals from each of the existing wellfields for the past 5 years (1987-91) were obtained from the Provincetown Water Department and are summarized in Table 1. Values in this table are computed from annual water use records (i.e., amount of water withdrawn in a year divided by 365 days per year yields average daily withdrawal rate). The average daily withdrawal rate for the last 5 years was used as an estimate of current withdrawal rates for Simulation 2. Locations of existing and potential wellfields are shown on Figure 8.

Ground water withdrawals for each wellfield are summarized in the following paragraphs. Information regarding safe yield of the wells or wellfields was obtained from reports by CDM (1985) and Cambareri, et al. (1989). Safe yield is defined as the maximum amount of water that can be withdrawn on a continuing basis from a single gravel packed well without causing upconing of saltwater into the well. Safe yield, as used in this context, is in no way related to, and does not include consideration of any other effects, such as:
lowering the water table; dewatering wetlands; disruption of local ground water flow patterns; or decreasing freshwater discharge to wetlands and riparian areas.

Knowles Crossing Wellfield

The Knowles Crossing wellfield is less than a mile south of the Salt Meadow and Pilgrim Lake wetland areas. The long-term safe yield for this wellfield has been estimated at 0.2 million gallons per day (mgd) (200,000 gpd). Ground water withdrawals from this wellfield have averaged about 0.085 mgd for the 5-year period (1987-91). During the peak summer demand season (July and August) withdrawals from this wellfield have averaged 0.25 mgd.

Cape Cod National Seashore Test Site 4 (NPS)

The well at CACO Test Site 4 was constructed in 1978 as a temporary, emergency supply when the South Hollow wellfield was shutdown due to a gasoline spill in the area. The well is located at the bottom of a kettle on CACO land east of Route 6 and about halfway between the South Hollow and Knowles Crossing wellfields. The long-term safe yield of the well is about 0.3 mgd. The well was used from 1978 through 1985 when the South Hollow wellfield was returned to service. NPS policy has not allowed use of this well since that time because water is available from other sources. Withdrawals from this well were not investigated in this investigation because the proximity of the South Hollow and Knowles Crossing wellfields would result in mutual interference if wells from all 3 locations were pumped. The location of CACO Test Site 4 is such that withdrawals from this site would have effects very similar to the Knowles Crossing wellfield.

South Hollow Wellfield

The South Hollow wellfield is near the center of the Pamet aquifer, approximately 1.5 mi from discharge areas at Salt Meadow and the Little Pamet River. The long-term safe yield for this wellfield has been estimated at 0.8 mgd (800,000 gpd). Ground water withdrawals from this wellfield have averaged about 0.6 mgd for the 5-year period (1987-91). During the peak summer demand season (July and August) withdrawals from this wellfield have averaged 0.9 mgd.

North Truro Air Base Wells

There are 2 wells at the North Truro Air Base that have been used to supplement municipal water supplies for Provincetown during the summer months since 1978. The long-term safe yield for the two wells has been estimated at 0.57 mgd (570,000 gpd). Ground water withdrawals from this wellfield have averaged about 0.12 mgd for the 5-year period (1987-91). During the peak summer demand season (July and August) withdrawals from this wellfield have averaged 0.3 mgd.

Long Nook Road (potential site)

A wellfield has been proposed for the Long Nook Road area within the CACO boundary. The site was investigated by Guswa and Londquist (1976). Because of the potential for interference with wells at the North Truro Air Base, long-term safe yields at this site is 0.67 mgd, considerably less than the estimate of 1.0 mgd if no other wells were operating in the area.

Mitre Site (potential site)

The Mitre Site is the name given to the site of an old radar station in South Truro. The area was identified as a potential wellfield by CDM (1985). The site is within CACO boundaries. Several environmentally sensitive areas are nearby, including Featherbed Swamp, Great Pond, Round Pond, and other ponds. Although the hydrogeology of this area has not been investigated, the assumption is made that conditions are similar to those found in the Pamet aquifer in North Truro. Long-term safe yield of this site was estimated by CDM to be about 0.8 mgd.

Other Sites

Cambareri, et al. (1989) identified potential well sites using a site screening procedure that included consideration of the 1989 water table map, potential contamination source map, the composite assessor's map and data base file. A complete description of the screening criteria and discussion of the merits of the 5 identified sites are included in the report (Cambareri, et al. 1989). Only sites 4 and 5 (Figure 8) met all of the screening criteria. Hydrogeologic conditions and well yields at the sites are probably very similar to other existing and potential wellfields in the Pamet aquifer. These sites were not included in the computer simulations in this investigation because potential yields and effects are probably similar to those of the Long Nook Road site or the North Truro Air Base wells.

DESCRIPTION OF THE COMPUTER MODEL

The computer modeling done for this investigation indicates the probable effects of ground water withdrawals on freshwater discharge from the aquifers. It is not meant to be a comprehensive study of all possible effects. A detailed site investigation should be conducted at any potential new wellfield prior to site development to determine aquifer yield and potential effects of the site.

The computer model used in this investigation is MODFLOW, the U.S. Geological Survey (USGS) modular, three-dimensional, finite-difference ground water flow model. The model does not simulate the interface between freshwater and saltwater, but that was not the purpose of this assessment. Previous work by other investigators was used to identify the maximum safe yield of wells in the Pamet aquifer. This report focuses on variations of freshwater discharge to zones of interest at the perimeter of the aquifer, and the amount of water table drawdown to be expected from varying rates and locations of ground water withdrawals. It is assumed that the simulated rates of withdrawals are within the limits, determined by other investigators, to prevent saltwater upconing into the production wells.

A very dense grid network was prepared for this model to allow a better description of discharge zones and the extent of predicted drawdown. Previous work by LeBlanc used a grid spacing of .25 mi. This model uses a grid spacing of 416 ft in both the x and y directions. (The grid spacing is 0.2 inches [in] overlaid on a 1:25,000 base map.) The model extends beyond the Salt Meadow and Pilgrim Lake area at the north end. The southern boundary of the modeled area extends approximately to the Herring River-Gull Pond area. The southern boundary was extended to this point to allow assessment of a potential wellfield at the "Mitre Site", south of the Pamet River. The model grid contains 115 rows and 55 columns and is oriented approximately northwest-southeast (NW-SE). The model grid is shown in Figure 9.

Constant head cells, having head set equal to 0.0 ft, were used to represent the boundary of the aquifer and the ocean. Variable head cells were used to represent the interior part of the aquifer where the elevation of the water table was allowed to vary. Rivers and wetland cells were represented as constant head areas within the aquifer model, having the head set equal to 1.0 ft. Discharge of freshwater from the aquifer to the ocean, rivers, and wetland cells was computed as a function of the difference between the head in the adjacent aquifer cell and the specified constant head at the ocean, river, or wetland.

The computer model used in this investigation contains only one layer. The simulated bottom of the aquifer is 80 ft below sea level. This corresponds approximately to the 3 upper layers of the computer model as defined by Guswa and LeBlanc (1985) and LeBlanc (1982). Multiple layers were used in those models to allow simulation and evaluation of saltwater upconing and thus allow assessment of safe yield of the aquifer.

An average annual recharge rate of 18 inches/year (in/yr) was used in this investigation. This is the generally accepted rate in this area and was used in previous investigations on the outer Cape.

A single value of hydraulic conductivity was used for all areas of the aquifer in this model. Previous investigations have varied hydraulic conductivity spatially, but the amount of detailed hydrogeologic data available for the present investigation precluded varying hydraulic conductivity. Predicted results may not be as accurate on a site-specific basis, but the general model results should not be affected appreciably. Hydraulic conductivity values determined from previous investigations in this area are summarized by CDM (1985, Table A-1, Appendix A, p. 9). The weighted geometric mean of hydraulic conductivity at 6 sites ranges from 137 to 191 ft/day. In this model, the hydraulic conductivity was set equal to 125 ft/day at all nodes in the model. Hydraulic conductivity for the computer flow model is lower than that reported for tests at individual wells due to the effects of treating the aquifer as a single layer, having uniform hydrologic properties through the entire thickness.

During model calibration, the recharge rate was kept constant at 18 in/yr and hydraulic conductivity was varied. Larger values of hydraulic conductivity allow water to move more easily through the aquifer resulting in a lower water table. Smaller values of hydraulic conductivity restrict water moving from recharge to discharge areas and cause a higher water table.

Calibration of this model was done by adjusting the hydraulic conductivity until the simulated water table was a close match to the measured water table. Water table contours for steady-state conditions with no ground water withdrawals (Simulation 0) approximate maps of similar conditions as shown by LeBlanc (1982). Qualitative verification of the model was made by comparing water table contours from Simulation 2 (average water use rates for 1987-91) with a water table map for January, 1989 (Cambareri, et al. 1989).

Ground water discharge areas in the model grid were flagged to identify areas of interest for determination of freshwater discharge from the aquifer. These areas include: the Atlantic Ocean; Salt Meadow and Pilgrim Lake; Little Pamet River; Pamet River; Bound Brook; and Herring River (Figure 9). Freshwater discharge from the aquifer to each of these areas was computed for each simulation to allow comparison of the effects of various ground water withdrawal scenarios.

SIMULATED GROUND WATER WITHDRAWALS

Ground water withdrawal scenarios that were simulated in this investigation are summarized in this section. The basic strategy was to first make simulations with no withdrawals (pre-development conditions) to provide a basis for comparison with other simulations. Additional simulations were made with current withdrawal rates and larger withdrawal rates from existing wellfields, shifting withdrawal among existing wellfields, and additional withdrawal from new wellfields.

All of the simulations were for steady-state conditions (i.e., constant withdrawal rates and infinite time). Seasonal variation of withdrawals were not simulated. But in order to provide that level of detail, much more data on seasonal variation of model parameters (recharge, evapotranspiration, water table fluctuation, etc.) and other factors such as pumping and recharge from private wells and septic systems, would be needed. The results presented in this report are based on average annual conditions and do not take into account short-term seasonal fluctuations. Short-term increases of ground water withdrawals (i.e., peak summer demand) can cause an upconing of the saltwater-freshwater interface. However, the large volume of water in storage in the aquifer provides some "buffering" capacity to movement of the interface. Increased ground water withdrawal in the summer will result in lowering the water table and may result in less freshwater being discharged to wetland areas during critical periods of the growing season.

Ground water withdrawal rates for each of the simulations are presented in Table 2. Withdrawal rates simulated with the computer model were kept at, or below, the safe yield as determined by other investigators.

Simulation 0 is for steady-state conditions with no wells present. This simulation was made to provide an estimate of the initial (pre-development) water table elevations and freshwater discharge rates to the ocean and various wetland/river areas of interest. Simulated water table contours are shown in Figure 10.

Maps of predicted drawdown for each of the simulations described in this report are shown in Figures 11 through 18. Drawdown is the difference between the pre-development water table elevations (Simulation 0, Figure 10) and the water table elevations computed for each simulation.

Simulation 1 is representative of ground water withdrawal rates presently occurring during the peak of the summer season, July and August. In this simulation, these higher rates are maintained throughout the year rather than only during the summer. This simulation represents the maximum amount of water that could be withdrawn on an average annual basis from the existing wellfields. In order to actually achieve these rates, withdrawal rates would be greater in the summer and less in the winter, but these would be the average ground water withdrawal rates on an annual basis.

Simulation 2 represents current average annual withdrawals from the existing wellfields. Withdrawal rates for this simulation are based on data from Provincetown's annual water use reports.

Simulation 3 shifts some of the withdrawals from the Knowles Crossing wellfield to the North Truro Air Base wells. This simulation assumes that the North Truro Air Base wells would be operated on a year-round basis and the Knowles Crossing wellfield would only be operated as a supplemental supply in the summer. In this and all subsequent simulations, both the North Truro Air Base and South Hollow wellfields are operated at approximately their maximum safe yield rates (0.6 and 0.3 mgd, respectively) to prevent saltwater upconing.

Simulation 4 eliminates pumping from the Knowles Crossing wellfield to show the effect of eliminating withdrawals near the Salt Meadow area. Withdrawals occur at only the South Hollow wellfield and the North Truro Air Base.

In simulations 5 through 8, withdrawal rates for the Knowles Crossing, South Hollow and North Truro Air Base wellfields are maintained at the same rates as in Simulation 3. Total ground water withdrawals from these 3 existing wellfields for these simulations have an average annual withdrawal rate of 1.0 mgd. Simulations 5 through 8 were made to show the effect of new wellfields at the Long Nook Road and Mitre sites.

Simulation 5 assumes withdrawals from a wellfield along Long Nook Road at a rate of 0.25 mgd. Simulation 6 assumes that withdrawals from the wellfield are increased to 0.5 mgd. There is significant well interference (overlap of drawdown) between this wellfield and the North Truro Air Base wells at the higher (0.5 mgd) rate. Therefore, Simulations 7 and 8 use a withdrawal rate of 0.25 mgd for the Long Nook Road wellfield.

Simulations 7 and 8 shows the effect of withdrawals from the Mitre site of 0.25 and 0.5 mgd respectively. These simulations were made to assess the effect of ground water withdrawals in this area on aquifer discharge to the Pamet River, Bound Brook, and Herring River systems and to show the extent of the predicted drawdown relative to ponds south of the site.

EFFECTS OF GROUND WATER WITHDRAWALS ON AQUIFER DISCHARGE

Freshwater discharge from the aquifer is reduced by 2 mechanisms: physical interception of the water by withdrawals from wells; and decreasing ground water flow by lowering the water table elevation (i.e., reducing the driving force [head] which moves water toward discharge areas). Table 3 summarizes the results of the ground water modeling with respect to the amount of water flowing from the aquifer to various discharge zones.

Table 4 shows the change of aquifer discharge from pre-development conditions (no wells) for each of the scenarios of ground water withdrawals previously described. The basis of these calculations is comparison with simulated aquifer discharge for pre-development conditions (Simulation 0). Simulated changes in aquifer discharge have not been verified by field measurements. Caution should be used when interpreting the absolute value of the numbers presented in Table 4. If a particular simulation predicts that discharge from the aquifer will decrease by 20,000 gpd, the actual number may be more or less than that. The utility of the ground water flow model is to allow comparison of the predicted effects that various distributions of withdrawal will have on aquifer discharge.

Aquifer discharge to Salt Meadow is most affected by withdrawals from the Knowles Crossing wellfield. At a withdrawal rate of 0.25 mgd, almost half the water withdrawn from the well is predicted to come from a reduction of aquifer discharge to the Salt Meadow area. With no withdrawals from the Knowles Crossing wellfield, aquifer discharge to Salt Meadow is still predicted to be about 0.03 mgd less than for pre-development conditions. This decrease is due to lowering the water table elevation within the area of drawdown created by withdrawals from the South Hollow and North Truro Air Base wells. Simulations using a withdrawal rate of 0.1 mgd for the Knowles Crossing wellfield (which is less than the present average withdrawal rate of 0.25 mgd) predict a reduction in aquifer discharge of about 0.03 mgd, or about 30 percent of the water withdrawn from the wellfield.

Aquifer discharge to the Little Pamet River is affected most by withdrawals from the South Hollow, North Truro Air Base, and Long Nook Road wellfields. Simulation 1 with maximum withdrawals (1.2 mgd, total) from the North Truro Air Base and South Hollow wellfields predicts almost as much reduction in aquifer discharge (0.09 mgd) as does withdrawing nearly the same amount of water (Simulation 5, 1.25 mgd total) but spread out to include withdrawals from the Long Nook Road site (0.11 mgd reduction in aquifer discharge). In both of these scenarios, aquifer discharge is reduced by about 10 percent of the withdrawal rate from the wells. Simulations 3 and 4 which use present average withdrawal rates from the South Hollow and North Truro Air Base well fields but do not include the Long Nook Road wellfield predict a reduction of aquifer discharge of about 0.07 mgd, or about 7 percent of the ground water withdrawals from the South Hollow and North Truro Air Base wells.

Aquifer discharge to the Pamet River is mainly affected by withdrawals from the potential wellfields at Long Nook Road or the Mitre site. Simulations 1 through 4, with no withdrawals from the Long Nook Road or Mitre sites, predict a reduction of aquifer discharge of 0.01 to 0.02 mgd. These numbers are below the level of confidence for the accuracy of the model. When withdrawals from the Long Nook Road and Mitre sites are included in the simulations, aquifer discharge is predicted to decrease by about an additional 0.04 to 0.11 mgd, or about 15 percent of the amount withdrawn from the Long Nook Road and Mitre sites.

Aquifer discharge to Bound Brook and the Herring River is affected only when water is withdrawn from a wellfield at the Mitre site, south of the Pamet River. Aquifer discharge is predicted to decrease by about 30 percent of the ground water withdrawal rate.

Another method of analyzing the effects of ground water withdrawals on aquifer discharge is to calculate the change of aquifer discharge as a percentage of discharge under pre-development conditions. Reducing aquifer discharge by 0.1 mgd is a 10 percent reduction for a discharge area that would normally receive 1 mgd (e.g., Little Pamet), but only a 3 percent reduction for a discharge area that would normally receive 3 mgd (e.g., Pamet River). The predicted reduction of aquifer discharge for each simulation, expressed as a percentage of "base flow" is presented in Table 5. The effects of each wellfield or site on freshwater discharge are discussed in the following section.

ASSESSMENT OF EXISTING/POTENTIAL WELLFIELDS

Knowles Crossing Wellfield

The Knowles Crossing Wellfield is less than a mile south of the Salt Meadow and Pilgrim Lake wetland areas and less than one-half mile northwest from a wetland adjacent to Route 6. Withdrawals from this wellfield lower the water table in the area, resulting in reduced freshwater discharge to the Salt Meadow wetlands. Computer model simulations predict a reduction of freshwater discharge from the aquifer of 30,000 gpd when this wellfield is pumped at a rate of 100,000 gpd. Drawdown from the Knowles Crossing wellfield probably also affects ground water flow paths in the vicinity of the Route 6 wetlands. The naturally low water table elevation in this area limits the amount of water that can be withdrawn before encountering saltwater upconing problems. Shifting withdrawals from this wellfield to the wells at the North Truro Air Base results in increased freshwater discharge from the aquifer to the Salt Meadow wetlands.

Cape Cod National Seashore Test Site 4 (NPS)

This well is located on CACO property between the Knowles Crossing and South Hollow wellfields. The well was used as a supplemental supply during the period that the South Hollow wellfield was closed due to a gasoline spill in the area. Safe yield of the well at CACO Test Site 4 is estimated to be 0.3 mgd. This well was not included in computer simulations in this investigation because: 1) the yield is not significantly greater than from the Knowles Crossing wellfield, 2) proximity to the Knowles Crossing and South Hollow wellfields would result in interference between CACO Test Site 4 and those wellfields, resulting in no substantial net increase in aquifer yield, 3) the site is a relatively undeveloped area of the National Seashore and therefore there is reluctance to allow continued access to the site for maintenance activities, and 4) proximity to the Route 6 wetlands and Salt Meadow makes it likely that withdrawals from this site would have substantial effects on freshwater discharge from the aquifer to the wetland areas.

South Hollow Wellfield

The South Hollow wellfield is located about halfway between the Salt Meadow and Little Pamet drainages (aquifer discharge areas). Most of the water intercepted by this wellfield would otherwise discharge to the ocean. The wellfield is being operated near its safe yield. Further expansion in this area is not feasible because additional wells would have mutual interference with the existing wellfield and no additional supply would be realized. Computer simulations predict that withdrawals from this wellfield will have a slight effect on discharge to the Salt Meadow and Little Pamet wetlands.

North Truro Air Base Wells

Withdrawals from wells at the North Truro Air Base probably have the least effect on freshwater discharge from the aquifer to Salt Meadow, and the Little Pamet or Pamet River drainages. Simulated withdrawals from wells at the Air Base were increased almost threefold (0.12 to 0.3 mgd) from Simulation 2 to Simulation 3, but freshwater discharge to wetlands and rivers decreased only slightly (about 1 percent). The proximity of the ocean and South Hollow wellfield limit the quantity of water that can be withdrawn from wells at the North Truro Air Base before encountering problems with saltwater upconing. Within the entire Pamet aquifer, withdrawals from this site will have the least effect on freshwater discharge from the aquifer to wetlands and riparian areas at the northern and southern boundaries of the aquifer.

Long Nook Road (potential site)

Withdrawals from a potential wellfield on Long Nook Road were simulated at rates of 0.25 and 0.5 mgd. At a withdrawal rate of 0.5 mgd, substantial interference is predicted between this wellfield and the wells at the North Truro Air Base. CDM (1985) estimated that safe yield from the Long Nook Road site would be 0.67 mgd if the wells at the North Truro Air Base were not being used. The safe yield for wells at North Truro Air Base was estimated at 0.57 mgd if there are no withdrawals from the Long Nook Road site. Because of the proximity of the two sites, there would be much mutual interference if wellfields at both sites were operating. The combined yield of the North Truro Air Base and Long Nook Road sites is about 0.84 mgd (CDM, 1985), much less than the sum of their individual yields (over 1.2 mgd) and not a great deal more than either of the sites could supply alone. Freshwater discharge from the aquifer to the Little Pamet and Pamet River drainages decreases substantially (5 to 9 percent) when withdrawals are simulated from the Long Nook wellfield.

Mitre Site (potential site)

Ground water withdrawals from a potential wellfield at the Mitre Site were simulated at rates of 0.25 and 0.5 mgd. At the lower withdrawal rate, 0.25 mgd, there is no measurable effect on aquifer discharge to the Pamet River drainage. Discharge to the Bound Brook and Herring River drainages is predicted to decrease by one-third the amount of water withdrawn by the wellfield. Simulated water table drawdown in the vicinity of the wellfield extends to the Featherbed Swamp area and may affect ground water flow paths in the vicinity of ponds to the south of the site. At the higher withdrawal rate, 0.5 mgd, aquifer discharge to the Bound Brook and Herring River drainages decreases by about one-third the amount withdrawn from the wellfield. Simulated water table drawdown at this withdrawal rate will substantially affect ground water flow patterns in the vicinity of the Featherbed Swamp and the ponds.

Other sites

In October, 1989, the Cape Cod Planning and Economic Development Commission published a report titled, *Truro/Provincetown Aquifer Assessment and Ground water Protection Plan* (Cambareri, et al. 1989). In that report several alternative wellfield sites in North Truro were identified. None of these sites were included in the computer model for this investigation. Conversations with Jim Cook from the Provincetown Water Department indicated that private/commercial development at the sites identified in that report has made those sites less desirable for development as wellfields.

One site that remains as a possible wellfield is Site 4, in the area of Great Hollow, between the NPS boundary and Route 6, approximately .75 mi south of the South Hollow wellfield. Drawdowns from a wellfield in this area would probably overlap with drawdown from the South Hollow and North Truro Air Base wells, creating mutual interference among the 3 wellfields and leading to decreased aquifer yields. Effects on freshwater discharge from the aquifer due to withdrawals from Site 4 would probably be similar to those predicted for the potential wellfield at Long Nook Road.

Site 5 is approximately 2,100 feet south of the Long Nook Road site and is located adjacent to CACO land, east of Highway 6 and south of Higgins Hollow. It is about 9,000 feet south of existing wellfields and would tap an unexploited portion of the Pamet aquifer, while being far enough from existing sites to minimize the potential for interference. But because the site is south of the Long Nook Road site, it is closer to the Pamet River. Ground water withdrawals at Site 5 will have a greater effect on freshwater discharges from the aquifer to the Pamet River than will withdrawals from the Long Nook Road site.

The alternative sites identified by Cambareri, et al. (1989) were not included in the computer simulations of ground water flow for the following reasons: 1) site specific hydrogeologic information is not available for these areas; 2) the probable effects of ground water withdrawals at these sites can be inferred from predicted effects for other nearby sites; 3) Site 4 would interfere with ground water availability from the North Truro Air Base and South Hollow wellfields; and 4) Site 5 is outside the area designated as a source area for Provincetown water development.

The purpose of this report is not to evaluate every possible site for ground water development. A comprehensive ground water development plan is needed for the outer Cape. Such a plan should include consideration of the overall level of development for the area, which will in part determine the need for development of additional ground water supplies.

DISCUSSION

Although the determination of ecological effects from decreasing freshwater aquifer discharge is beyond the scope of this investigation, it is suspected that the relationship will not be simplistic. That is, a 10 percent decrease in freshwater discharge will probably not cause a 10 percent decrease in wetland area. Potential effects will need to be evaluated on a site-specific basis and will depend on physical parameters of the habitat and biological factors of species utilizing that habitat.

Reductions in aquifer discharges to wetlands and riparian areas along river drainages are associated with various ground water withdrawal scenarios. Lowered water tables and the associated reductions of freshwater discharge to wetlands and riparian areas may result in the modification of streamflow volumes, increases in estuarine salinity, and alterations of nutrient input to wetlands. These effects are generally described in a report by Jason M. Cortell and Associates (1983, pp. 8-20 and 8-21) as:

> "Within estuarine systems, fresh water inputs by rivers are critical in determining the physical, chemical, and biological character of the estuary. ...the distribution of any material dissolved or suspended in estuarine waters is determined by the circulation of fresh and salt water. Of particular significance is the potential effect of fresh water river inflow on salinity distributions and the maintenance or enhancement of nutrient concentrations requisite to estuarine productivity....Given these potential fresh water inflow-related influences, it is likely that reductions in aquifer discharges and hence, river inputs to estuaries like the Lower Pamet River, would result in alterations of nutrient balances and salinity gradients."

> "...wetland nutrient concentrations may also be affected by reduced aquifer discharges...groundwater provides over 20 times the amount of nitrogen than rain and that nitrogen derived from ground water is important to the nitrogen economy of a salt marsh...it is anticipated that wetlands throughout the Truro sub-basin will be subject to decreases in nutrient availability as a result of groundwater withdrawal."

"Reductions of discharge to Salt Meadow may also serve to lower existing water table elevations, reduce stream flow, and decrease availability of nutrients. Although groundwater withdrawal may be limited to the summer months, and long-term steady state drawdowns may be minimal, short-term drawdown during the growing season, particularly in conjunction with naturally occurring water table fluctuations in water table elevations, will likely result in more favorable conditions for the establishment and growth of plant species typical of upland communities."

Ground water withdrawals from any area on the outer Cape will likely result in changes to the natural environment. Withdrawals from certain areas will result in greater effects. However, interpreting specific ecological effects of the simulated drawdowns is beyond the scope of this investigation. Ecological features that can not tolerate significant changes to the natural hydrology should be identified and measures taken to insure the integrity of those features. In this investigation, it was assumed that reducing freshwater discharge to the ocean is not a significant environmental effect because of the mixing that occurs as soon as the freshwater enters the ocean. Freshwater discharge to wetlands, marshes, and rivers is an important environmental consideration because of its importance in providing nutrients and maintaining freshwater-saltwater balances as described above.

Ground water in the aquifers of the outer Cape flows from recharge areas, generally the midline of land masses, toward discharge areas at the margins: the ocean, rivers, and wetland areas. A qualitative judgment of the potential for a well or wellfield to affect freshwater discharge from the Pamet or Chequesset aquifers can be made by observing the location of the well(s) with respect to discharge areas. Wells located nearer surface water drainages will reduce freshwater discharge to those areas by a combination of intercepting ground water and lowering the water table elevation which reduces the driving mechanism to move ground water toward discharge areas.

Ground water withdrawals from the Pamet aquifer to supply Provincetown with potable water are presently approaching 1.5 mgd in July and August. The existing wellfields at Knowles Crossing, South Hollow and the North Truro Air Base are able to meet these demands. However, there is no backup supply in the event that one of these wellfields is shut down for any reason, and there is no allowance for future increases in demand either by Provincetown or other communities on the outer Cape.

New wellfields could be constructed at the Long Nook Road and Great Hollow sites. These wellfields would probably produce about 0.25 mgd each on an intermittent basis but would cause some reduction of freshwater discharge from the aquifers to the river drainages and wetlands. Withdrawals from these sites should not be used to allow increase in the base demand for water by Provincetown. Rather, these new sites should be developed to spread the withdrawals over a larger area, thereby lessening the local effect of large volume ground water withdrawals from any single wellfield. Additional sites would also provide some level of insurance against the possibility of losing one of the existing wellfields as a source.

The effect of additional ground water withdrawals in this area will depend greatly on the location of new wellfields and withdrawal rates at both existing and new wellfields. Effects for each proposal will need to be addressed on an individual basis. There are no wellfield locations, either existing or new sites, that will not cause an effect on the water resources and dependent ecosystems of the area.

Water conservation, possibly including treatment and reuse or artificial recharge beds to return the water to the Pamet aquifer may become necessary in the future. Returning treated water to the original source aquifer may be one way to counteract the environmental effects of the present system of exporting water from the Pamet aquifer for use in Provincetown.

FUTURE INVESTIGATIONS

Additional investigations are needed to fully understand the effects of ground water development on the outer Cape. These investigations are not solely the responsibility of the CACO as the scope and results are of concern to everyone living in the area. The NPS has a mandate to "preserve and protect" and thus may have a different interpretation of what constitutes a significant environmental effect than other entities. Some of the needed investigations are listed below. This list is not meant to be comprehensive as other persons may have different interests and concepts about the important features needing study. This listing should only be used as a starting point in discussions with interested parties to develop a comprehensive ground water management plan for the outer Cape.

1. Monitor water table elevations to determine the amount and extent of drawdown from existing wellfields and the seasonal variation or fluctuation of the water table.

2. Monitor ground water quality to identify potential problems (e.g., saltwater upconing at large yield wells or nutrient loading from septic field leachate).

3. Investigate the hydrologic interrelationships of ground water and surface water at areas of concern such as the Pilgrim Lake and Salt Meadow area bounding the Pamet aquifer on the north and the Pamet and Little Pamet River drainages bounding the aquifer on the south. Use this

information to make better estimates of the quantity of freshwater discharging from the aquifer in these areas.

4. Identify ecosystem features and areas that are dependent on maintaining freshwater aquifer discharge. Estimate the level of ground water development that can be allowed while still maintaining the natural ecology of sensitive areas.

5. Investigate the potential savings that may result from a water conservation program. Water reuse and treatment followed by returning water to the Pamet aquifer (artificial recharge) may be a method for lessening the effect of ground water withdrawals. Decreasing demand and/or reducing the net export of water from the Pamet aquifer should become a long-term goal to benefit everyone in the area.

6. Develop a comprehensive ground water management and development plan for the outer Cape. Limits to the potential supply of potable water and sewage disposal are critical components of such a plan from a hydrological perspective and will be important in determining the level of development that can occur.

7. Conduct scientific studies to determine what possible off-shore ecological systems are dependent on freshwater discharging from the aquifer to the nearshore ocean environment. In this investigation, it was assumed that reductions of freshwater discharge in these areas was not a significant effect due to the almost immediate mixing of the freshwater with seawater.

CONCLUSIONS AND RECOMMENDATIONS

1. The outer Cape contains a limited, finite amount of fresh ground water. Development of ground water for potable water supplies affects the natural ecological systems by reducing freshwater discharge from the aquifer(s) to wetland and riverine areas. Natural salinity and nutrient balances are affected by this change in the hydrologic balance.

2. Ground water withdrawal from the Knowles Crossing wellfield is probably the most environmentally damaging of any of the existing sites. Decreasing ground water withdrawals from the Knowles Crossing wellfield will result in greater volumes of freshwater discharge from the aquifer to the wetlands in Salt Meadow. Consideration should be given to reducing or eliminating withdrawals at this site and replacing it with water from the South Hollow or North Truro Air Base wellfields.

3. Withdrawals from CACO Test Site 4 (NPS) will not substantially increase yields from the aquifer and would reduce freshwater discharge from the aquifer to the wetlands in Salt Meadow. Future use of this site is not recommended.

4. Withdrawals from the South Hollow wellfield and North Truro Air Base wells have the least effect on freshwater discharge from the Pamet aquifer to wetlands and river drainages bounding the aquifer on the southern and northern boundaries.

5. Wellfields located closer than a mile from the Salt Meadow, Little Pamet, or Pamet drainages have a substantial effect on freshwater discharge from the Pamet aquifer to those drainages. Approximately 20 percent of water withdrawn from the wells in these areas would be obtained from decreased aquifer discharge to the wetlands or rivers.

6. Wellfields located more than a mile from river drainages mainly affect the discharge of freshwater from the aquifer to the ocean.

7. A wellfield located at the Mitre site will change ground water flow paths and alter the natural hydrologic conditions in the vicinity of the Featherbed Swamp wetland and great ponds near this site (Great Pond, Snow Pond, Round Pond, Slough Pond, etc). Locating this wellfield further north (but still south of the Pamet River) would cause much greater effects on freshwater discharge from the Chequesset aquifer to the Pamet River drainage. This does not appear to be a benign location for a wellfield. Further consideration of this site is not recommended.

8. Governmental entities on the outer Cape need to work together to develop a comprehensive ground water management and development plan. There is a finite amount of ground water that can be removed from aquifers in the area before serious environmental effects are manifested. In addition to the well-documented concerns regarding water use and growth in Provincetown, consideration must also be made for future growth in Truro, both for the cumulative effect of private wells and septic systems and community supply wells. Wellfleet may also want to develop community wellfields in this area at some time in the future. A regional ground water development plan should address the sequence of development, average annual withdrawals for each site, and contingency plans for emergencies.

9. Permits for ground water withdrawals and future wellfield construction should be tied to a requirement for review of the present water table monitoring program to determine its adequacy for assessing effects of the

present (and proposed) wellfields on aquifer discharge to river drainages and wetland areas. Additional monitoring wells, as needed, should be installed as part of any wellfield construction plan. Mitigation plans are needed to minimize the environmental effects of ground water with drawals.

10. Additional data and field measurements are needed for verification of future computer models of ground water flow and to allow early detection of potential problems. Monitoring needs include: streamflow gaging; regular monitoring of water table elevations (winter and summer); additional monitor wells near discharge areas; and verification of areas of influence (drawdown) for each wellfield.

11. Consideration should be given to development of several smaller yield wellfields rather than looking for sites capable of producing a million gallons per day. Large yield wellfields are accompanied by large effects. Investigation should be made to determine the probable effects of withdrawing smaller volumes of water from several locations to achieve the same net yield as from a single well or wellfield.

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TABLE 1. Summary of average daily ground water withdrawals from existing wellfields in North Truro for the period 1987-91.
All values are in gallons per day.

	Knowles Crossing	South Hollow	North Truro Air Base	Daily Average
1987	83,382	595,130	182,924	861,436
1988	61,888	583,220	108,978	754,086
1989	100,794	553,540	106,770	761,104
1990	83,658	569,115	108,375	761,148
1991	94,260	679,100	84,000	857,360
Average	84,800	596,021	118,209	799,027

Table 2. Ground water withdrawal rates for computer simulations of groundwater flow. All values are in millions of gallons per day (mgd).

	SIMULATION NUMBER								
	0	1	2	3	4	5	6	7	8
KCWF	0	0.25	0.08	0.1	0	0.1	0.1	0.1	0.1
SHWF	0	0.9	0.6	0.6	0.6	0.6	0.6	0.6	0.6
NTAB	0	0.3	0.12	0.3	0.3	0.3	0.3	0.3	0.3
LNWF	0	0	0	0	0	0.25	0.5	0.25	0.25
MITRE	0	0	0	0	0	0	0	0.25	0.5
TOTAL	0	1.45	0.8	1.0	0.9	1.25	1.5	1.5	1.75

KCWF = Knowles Crossing Wellfield
SHWF = South Hollow Wellfield
NTAB = North Truro Air Base Wells
LNWF = Long Nook Road Wellfield (proposed)
MITRE = Mitre site Wellfield (proposed)

Summary of ground water withdrawals for computer simulations

	MGD	SIMULATED GROUND WATER WITHDRAWALS
Simulation 0	0.0	None
Simulation 1	1.45	Maximum safe yield from existing wellfields (Current peak withdrawals, July & August average)
Simulation 2	0.8	Average annual withdrawals from existing wellfields
Simulation 3	1.0	Increase pumping at NTAB
Simulation 4	0.9	Eliminate withdrawals from Knowles Crossing wellfield
Simulation 5	1.25	Simulation 3 plus 0.25 mgd at LNWF
Simulation 6	1.50	Simulation 3 plus 0.5 mgd at LNWF
Simulation 7	1.50	Simulation 5 plus 0.25 mgd at MITRE
Simulation 8	1.75	Simulation 5 plus 0.5 mgd at MITRE

Table 3. Simulated freshwater aquifer discharge. All values are in millions of gallons per day.									
	SIMULATION NUMBER								
	0	1	2	3	4	5	6	7	8
Wells	0	1.45	0.80	1.00	0.90	1.25	1.50	1.50	1.75
Ocean	9.20	8.00	8.54	8.36	8.44	8.20	8.03	8.06	7.93
Salt Meadow	0.74	0.63	0.69	0.68	0.71	0.68	0.68	0.68	0.68
Little Pamet	1.02	0.93	0.96	0.95	0.95	0.91	0.88	0.91	0.91
Pamet River	3.08	3.06	3.07	3.06	3.06	3.02	2.98	2.98	2.95
Bound Brook	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.21	1.20
Herring River	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.17	2.10

In all cases, the total discharge is 17.5 million gallons per day.

Summary of ground water withdrawals for computer simulations

	MGD	SIMULATED GROUND WATER WITHDRAWALS
Simulation 0	0.0	None
Simulation 1	1.45	Maximum safe yield from existing wellfields (Current peak withdrawals, July & August average)
Simulation 2	0.8	Average annual withdrawals from existing wellfields
Simulation 3	1.0	Increase pumping at NTAB
Simulation 4	0.9	Eliminate withdrawals from Knowles Crossing wellfield
Simulation 5	1.25	Simulation 3 plus 0.25 mgd at LNWF
Simulation 6	1.50	Simulation 3 plus 0.5 mgd at LNWF
Simulation 7	1.50	Simulation 5 plus 0.25 mgd at MITRE
Simulation 8	1.75	Simulation 5 plus 0.5 mgd at MITRE

Table 4. Reduction of freshwater aquifer discharge due to ground water withdrawals. All values are in millions of gallons per day.

	SIMULATION NUMBER							
	1	2	3	4	5	6	7	8
Ocean	1.20	0.66	0.84	0.76	1.00	1.17	1.14	1.27
Salt Meadow	0.11	0.05	0.06	0.03	0.06	0.06	0.06	0.06
Little Pamet	0.09	0.06	0.07	0.07	0.11	0.14	0.11	0.11
Pamet River	0.02	0.01	0.02	0.02	0.06	0.10	0.10	0.13
Bound Brook	0	0	0	0	0	0	0.01	0.02
Herring River	0	0	0	0	0	0	0.07	0.14

Summary of ground water withdrawals for computer simulations

	MGD	SIMULATED GROUND WATER WITHDRAWALS
Simulation 0	0.0	None
Simulation 1	1.45	Maximum safe yield from existing wellfields (Current peak withdrawals, July & August average)
Simulation 2	0.8	Average annual withdrawals from existing wellfields
Simulation 3	1.0	Increase pumping at NTAB
Simulation 4	0.9	Eliminate withdrawals from Knowles Crossing wellfield
Simulation 5	1.25	Simulation 3 plus 0.25 mgd at LNWF
Simulation 6	1.50	Simulation 3 plus 0.5 mgd at LNWF
Simulation 7	1.50	Simulation 5 plus 0.25 mgd at MITRE
Simulation 8	1.75	Simulation 5 plus 0.5 mgd at MITRE

Table 5.	Reduction of freshwater aquifer discharge due to ground water withdrawals expressed as a percentage of discharge that would be expected if no withdrawals were occurring.							
	SIMULATION NUMBER							
	1	2	3	4	5	6	7	8
Ocean	11	7	9	8	11	13	12	14
Salt Meadow	15	7	8	4	8	8	8	8
Little Pamet	9	6	7	7	11	14	11	11
Pamet River	1	<1	1	1	2	3	3	4
Bound Brook	0	0	0	0	0	0	1	2
Herring River	0	0	0	0	0	0	3	6

Summary of ground water withdrawals for computer simulations

	MGD	SIMULATED GROUND WATER WITHDRAWALS
Simulation 0	0.0	None
Simulation 1	1.45	Maximum safe yield from existing wellfields (Current peak withdrawals, July & August average)
Simulation 2	0.8	Average annual withdrawals from existing wellfields
Simulation 3	1.0	Increase pumping at NTAB
Simulation 4	0.9	Eliminate withdrawals from Knowles Crossing wellfield
Simulation 5	1.25	Simulation 3 plus 0.25 mgd at LNWF
Simulation 6	1.50	Simulation 3 plus 0.5 mgd at LNWF
Simulation 7	1.50	Simulation 5 plus 0.25 mgd at MITRE
Simulation 8	1.75	Simulation 5 plus 0.5 mgd at MITRE

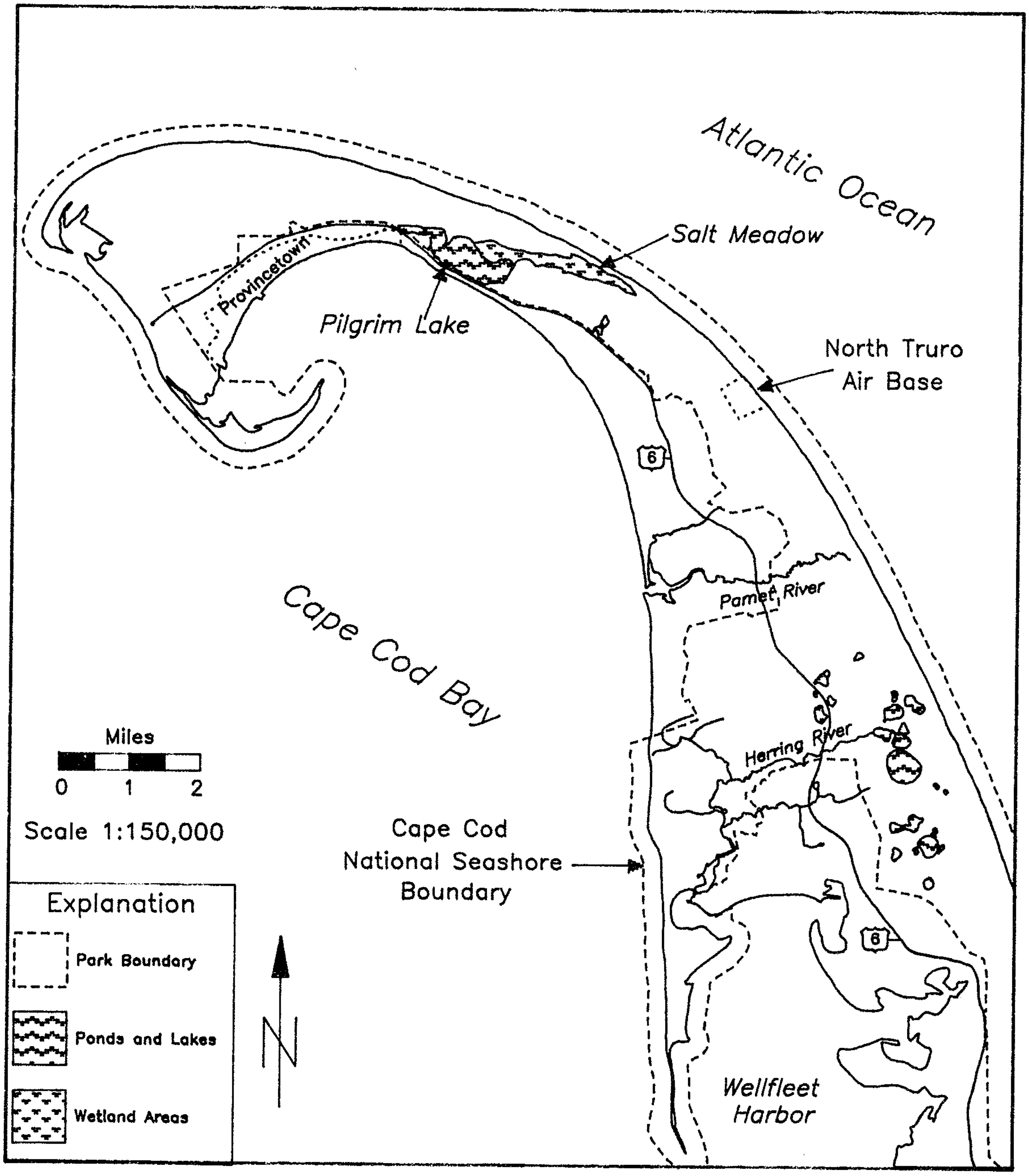
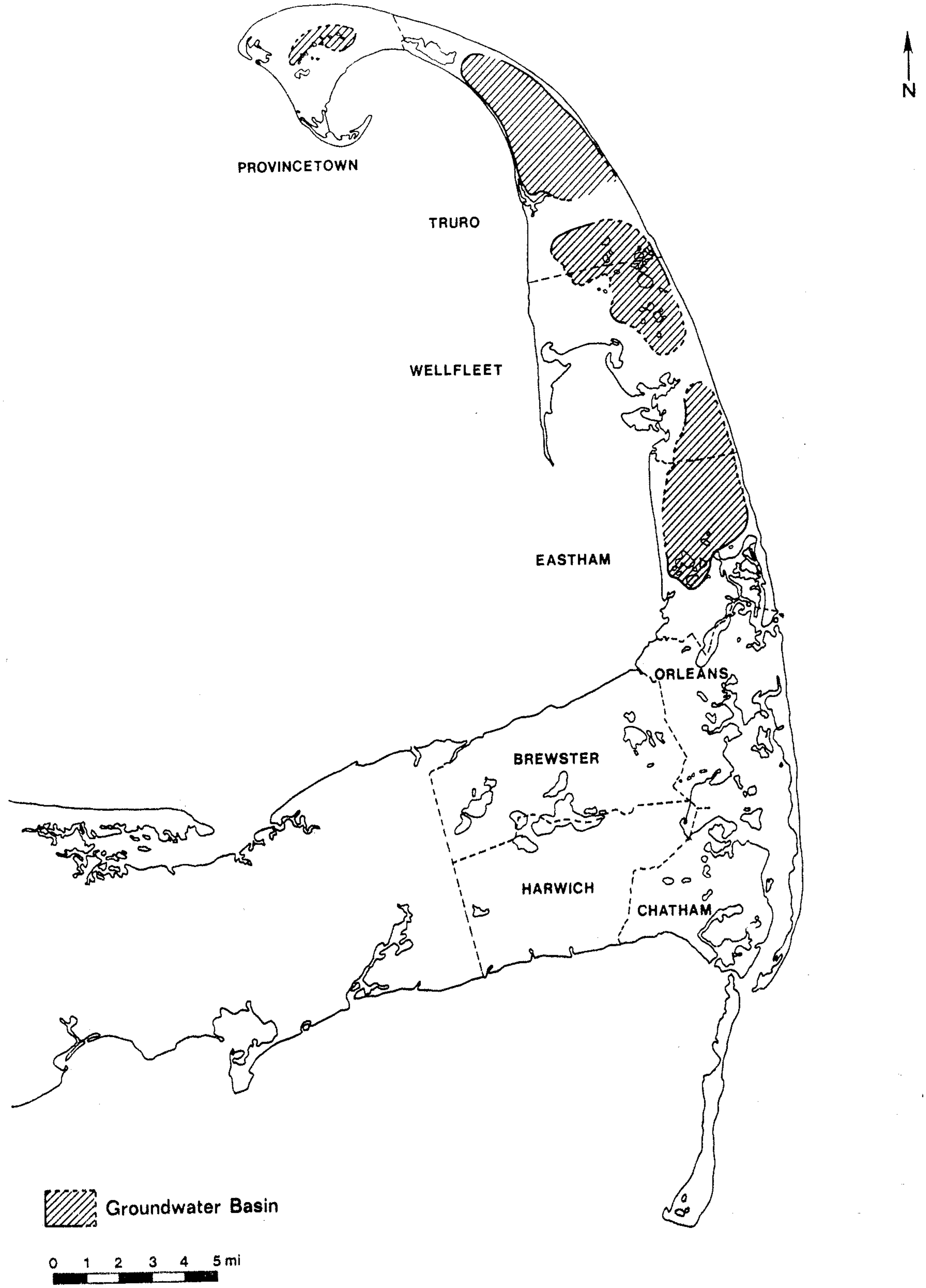
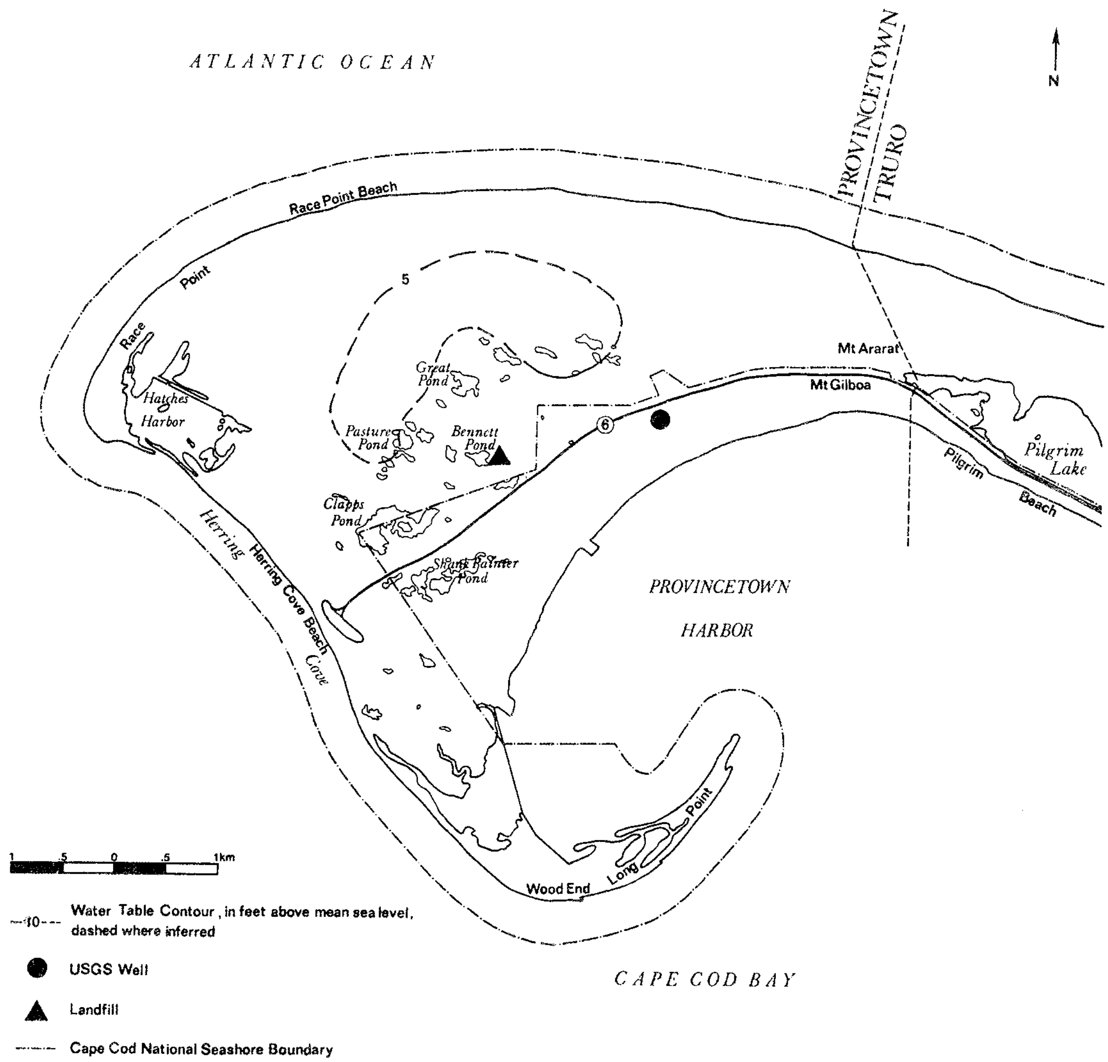


Figure 1. General area map of outer Cape Cod.



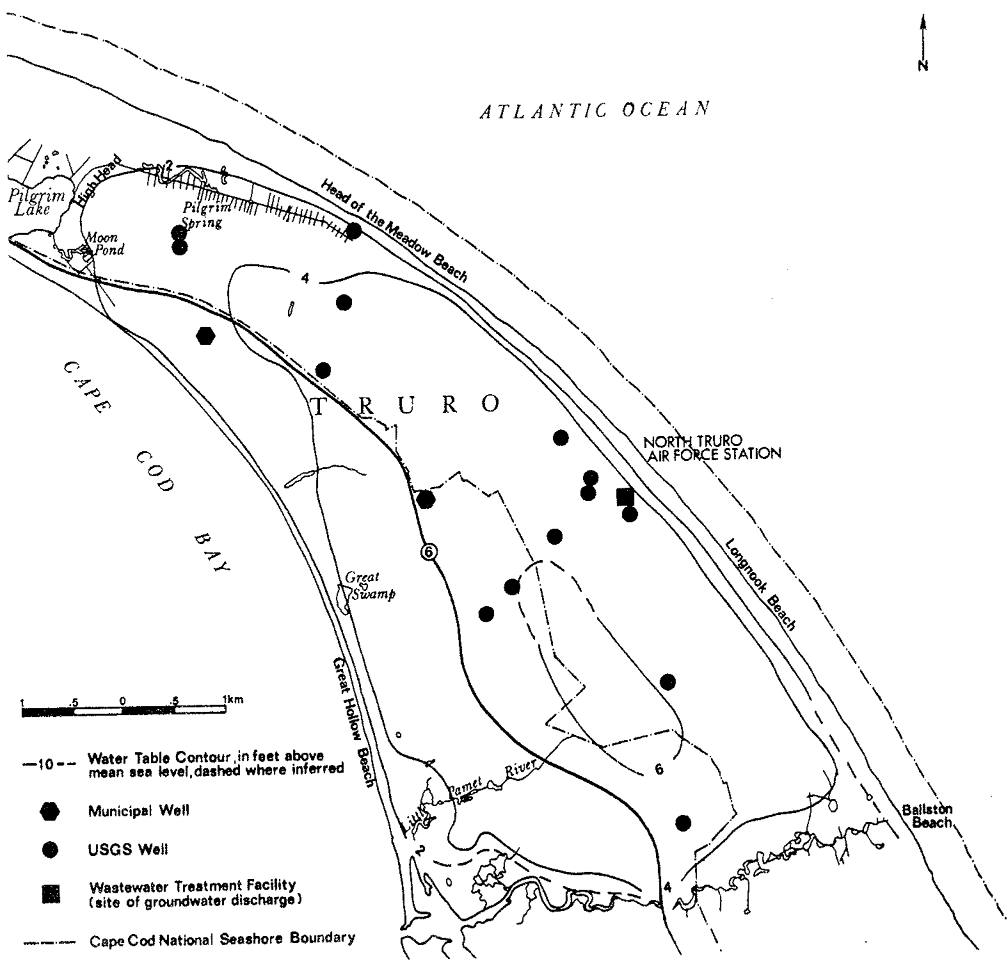
(Source: Mitchell and Soukup 1981. Figure 6.)

FIGURE 2. Location of aquifers on outer Cape Cod.



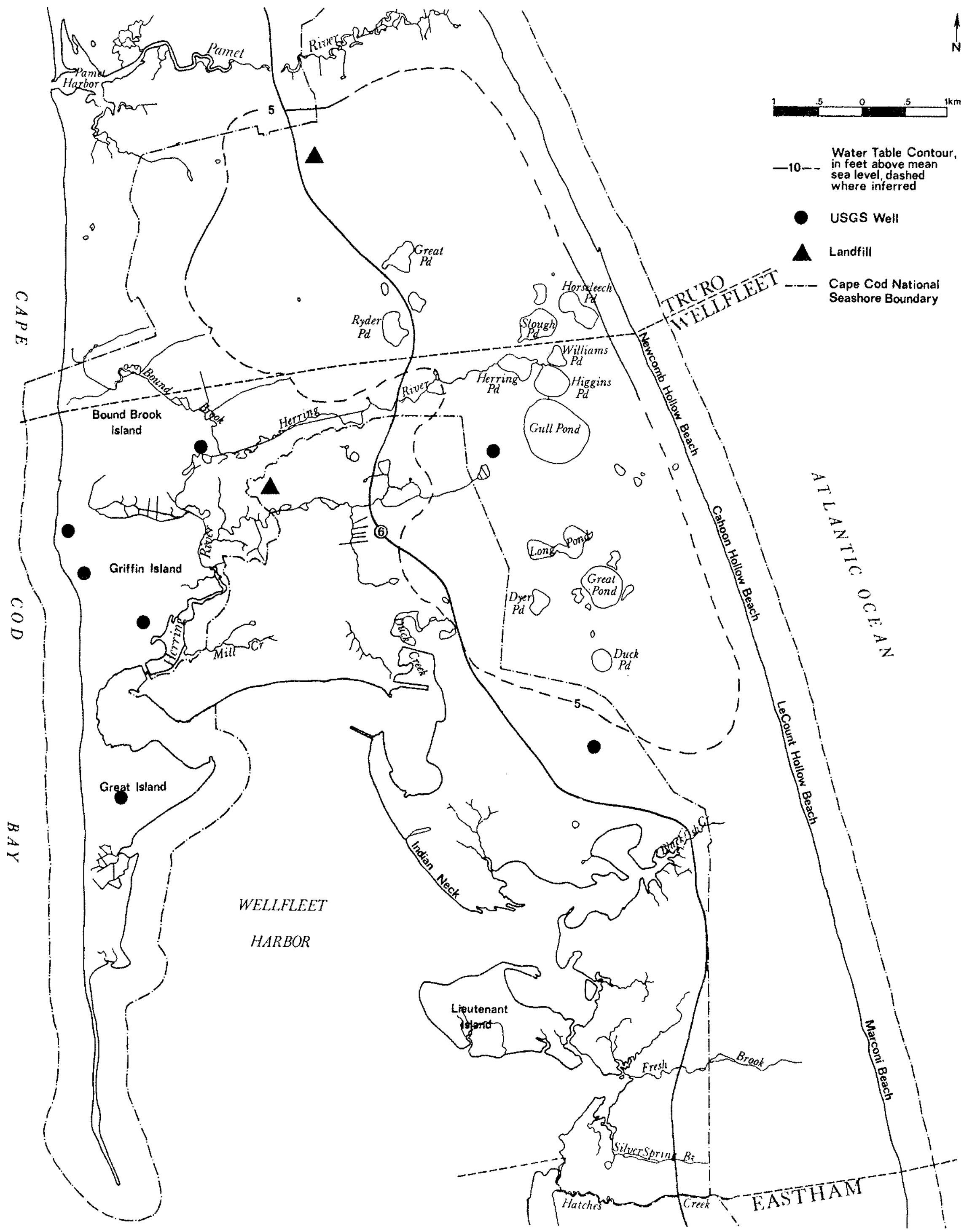
(Source: Mitchell and Soukup 1981. Figure 7.)

FIGURE 3. Pilgrim aquifer.



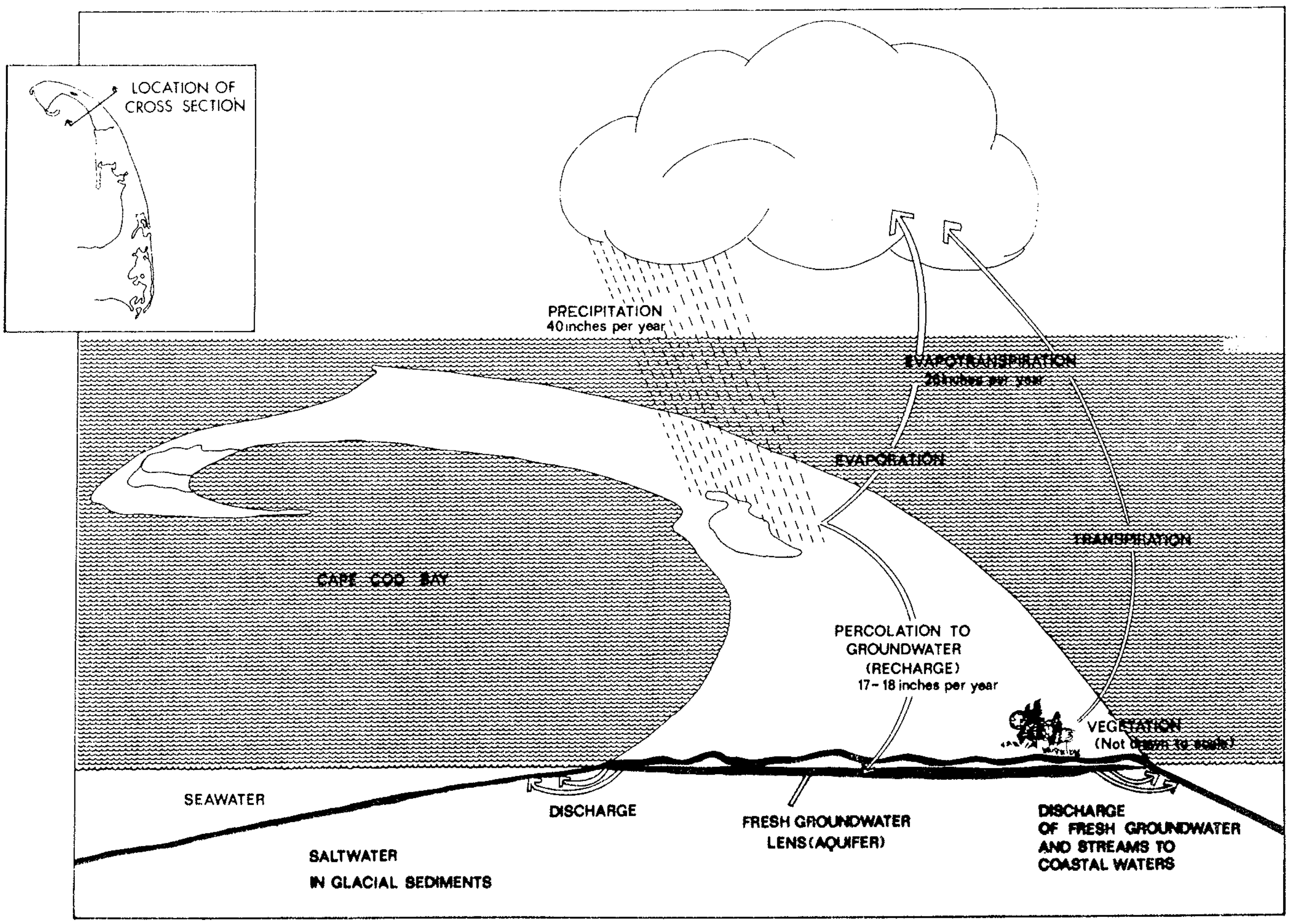
(Source: Mitchell and Soukup 1981. Figure 8.)

FIGURE 4. Pamet aquifer.



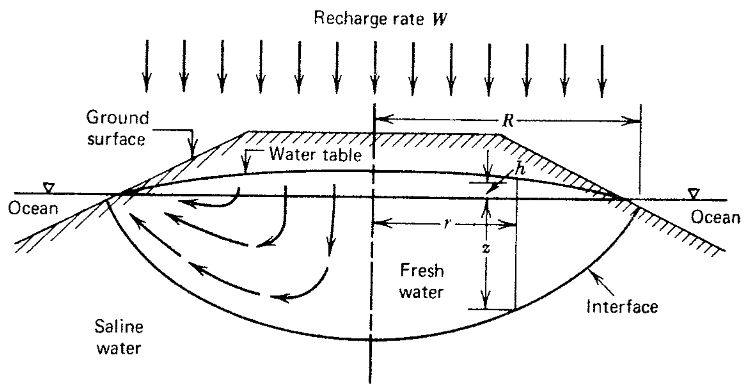
(Source: Mitchell and Soukup 1981. Figure 9.)

FIGURE 5. Chequesset aquifer.

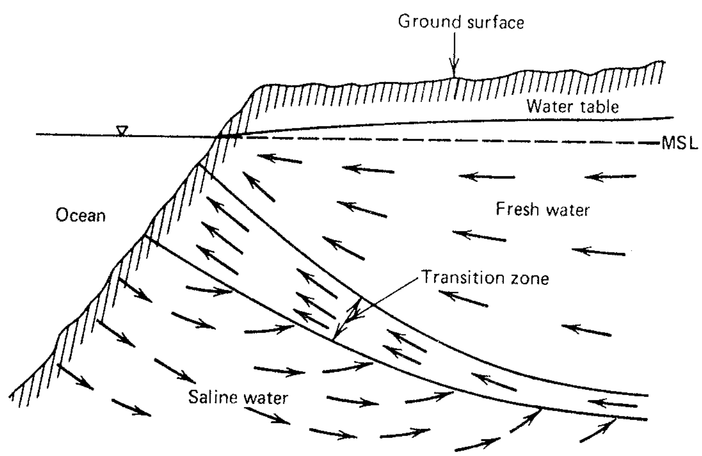


(Source: Mitchell and Soukup 1981. Figure 4.)

FIGURE 6. Hydrologic cycle on outer Cape Cod.



A freshwater lens forms a "bubble" overlying the saltwater. Recharge occurs over the entire area by infiltration of precipitation. Discharge occurs by ground water outflow in the nearshore area. (Source: Todd 1980. Figure 14.11).



Vertical cross section showing the flow patterns of fresh- and saltwater in an unconfined coastal aquifer. (Source: Todd 1980. Figure 14.6).

FIGURE 7. Schematic diagram of freshwater-saltwater interrelationships on outer Cape Cod.

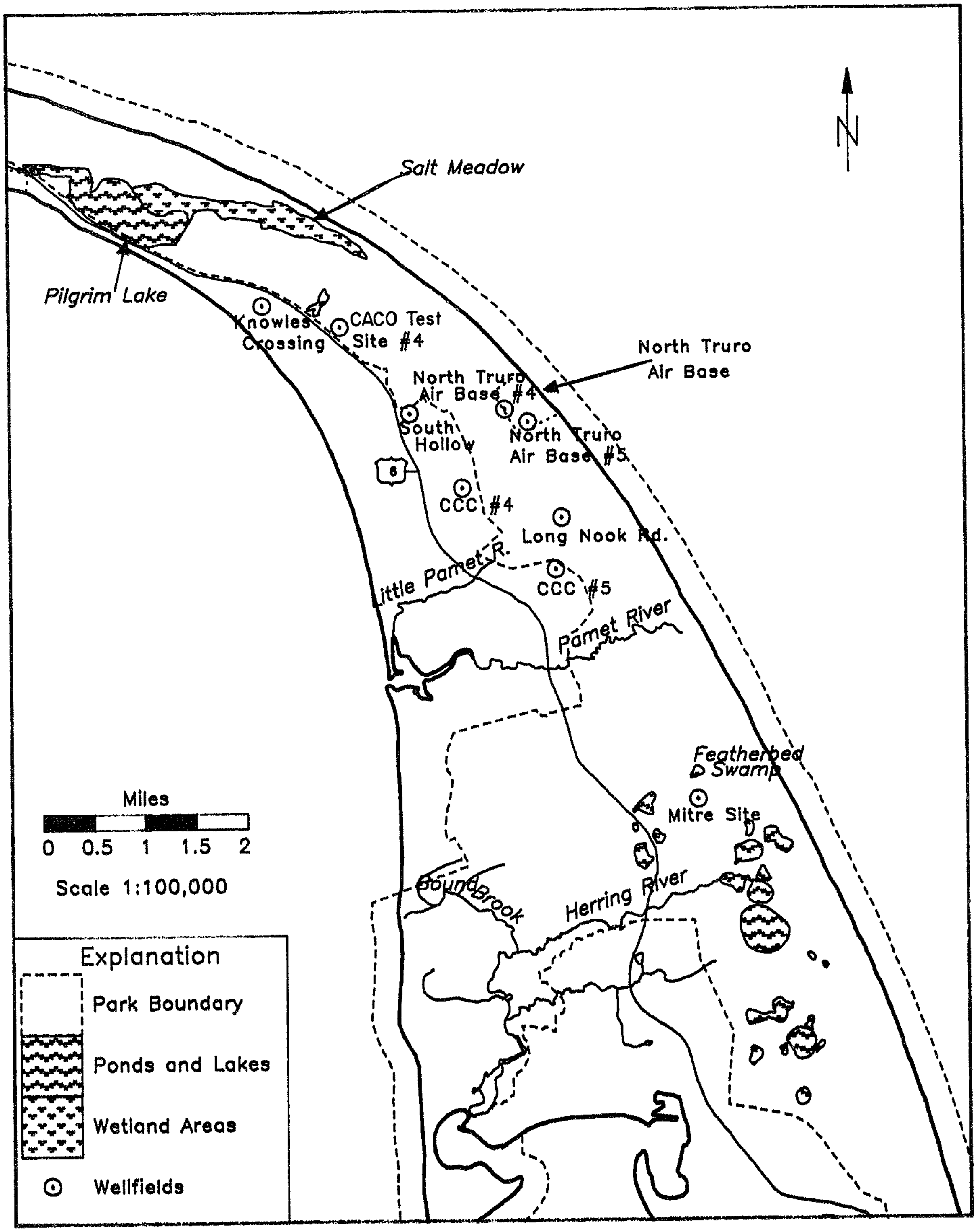


Figure 8. Location of existing and potential wellfields.

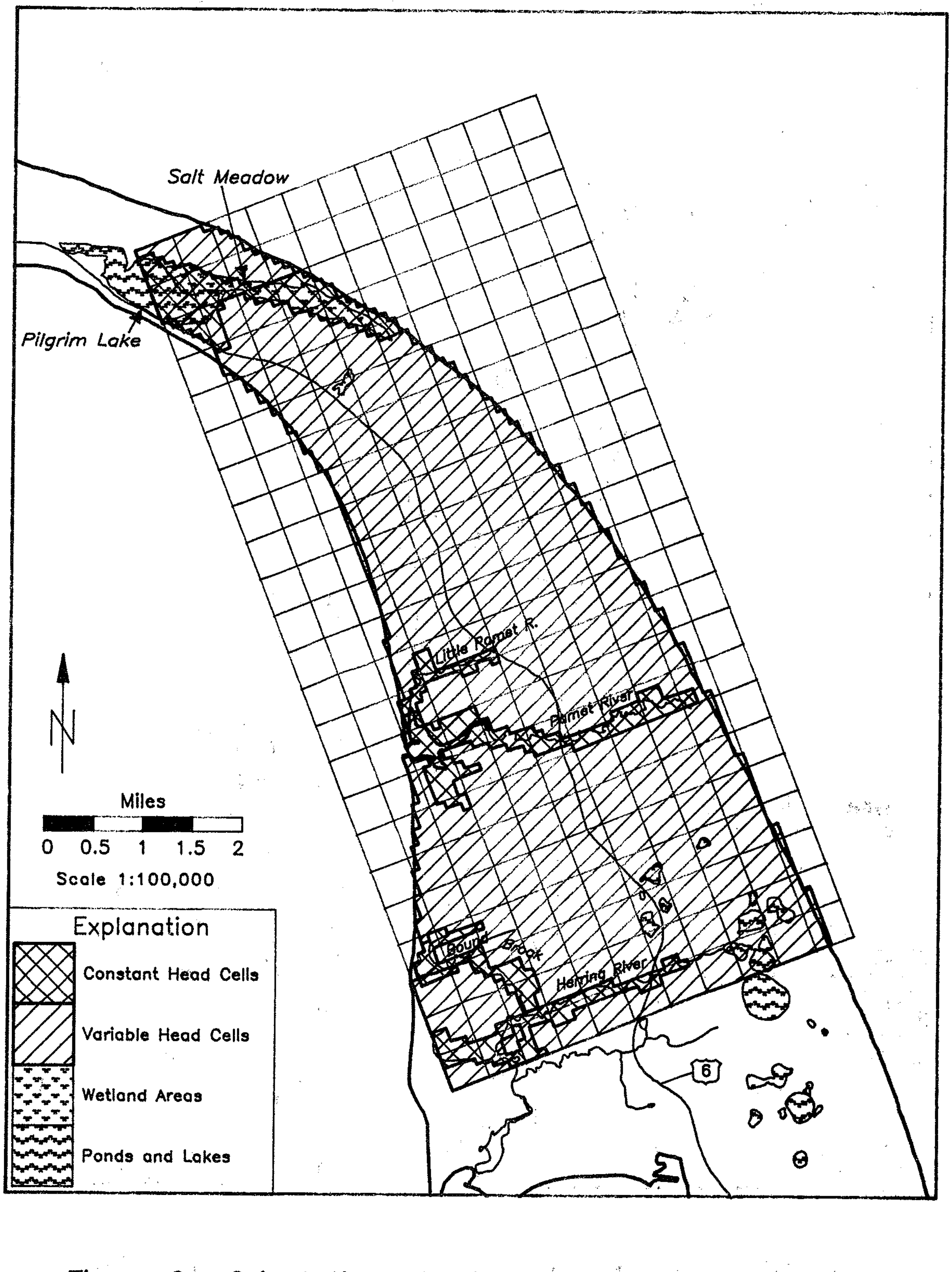


Figure 9. Orientation of grid for the computer model.

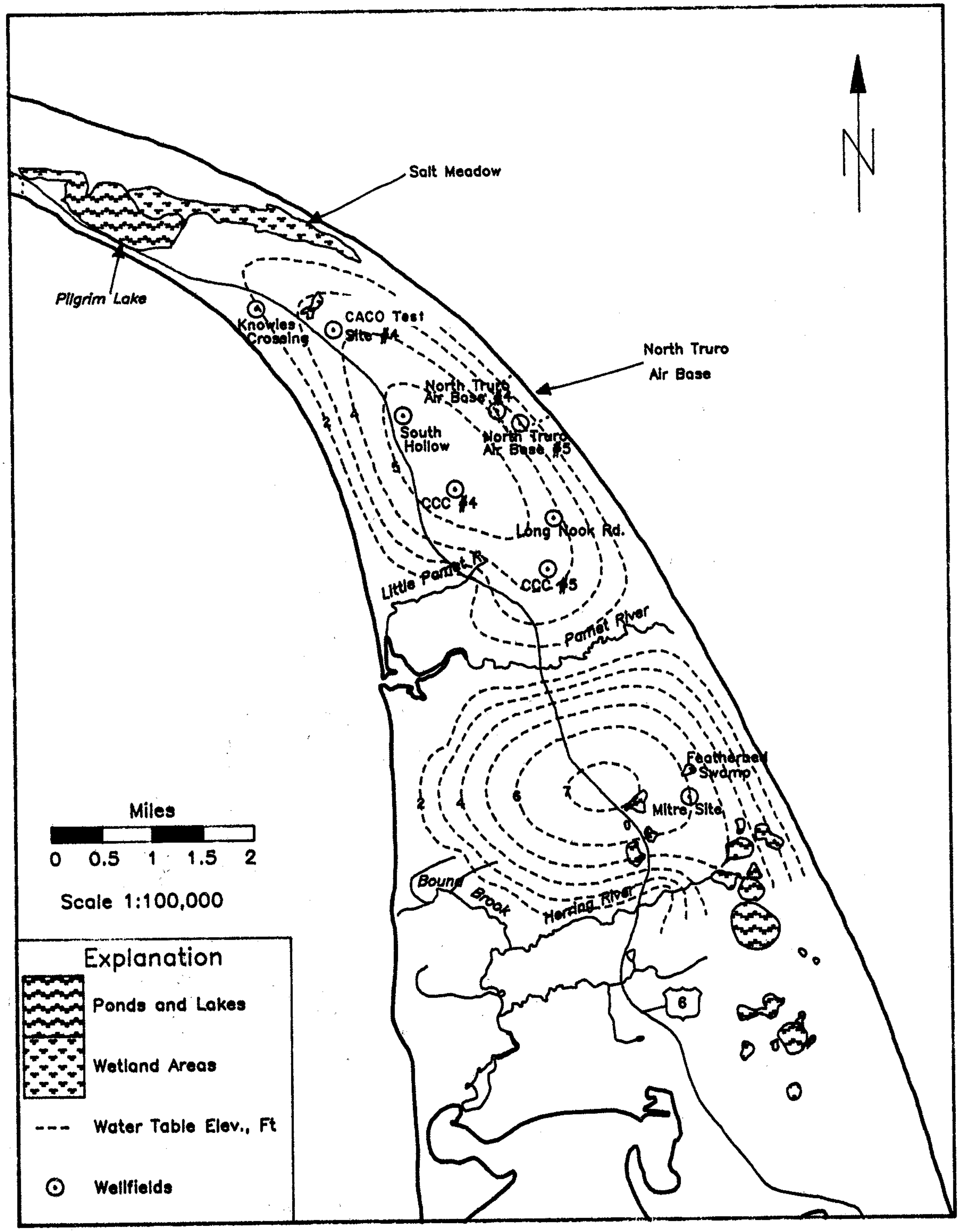


Figure 10. Simulated water table elevation, Simulation 0.

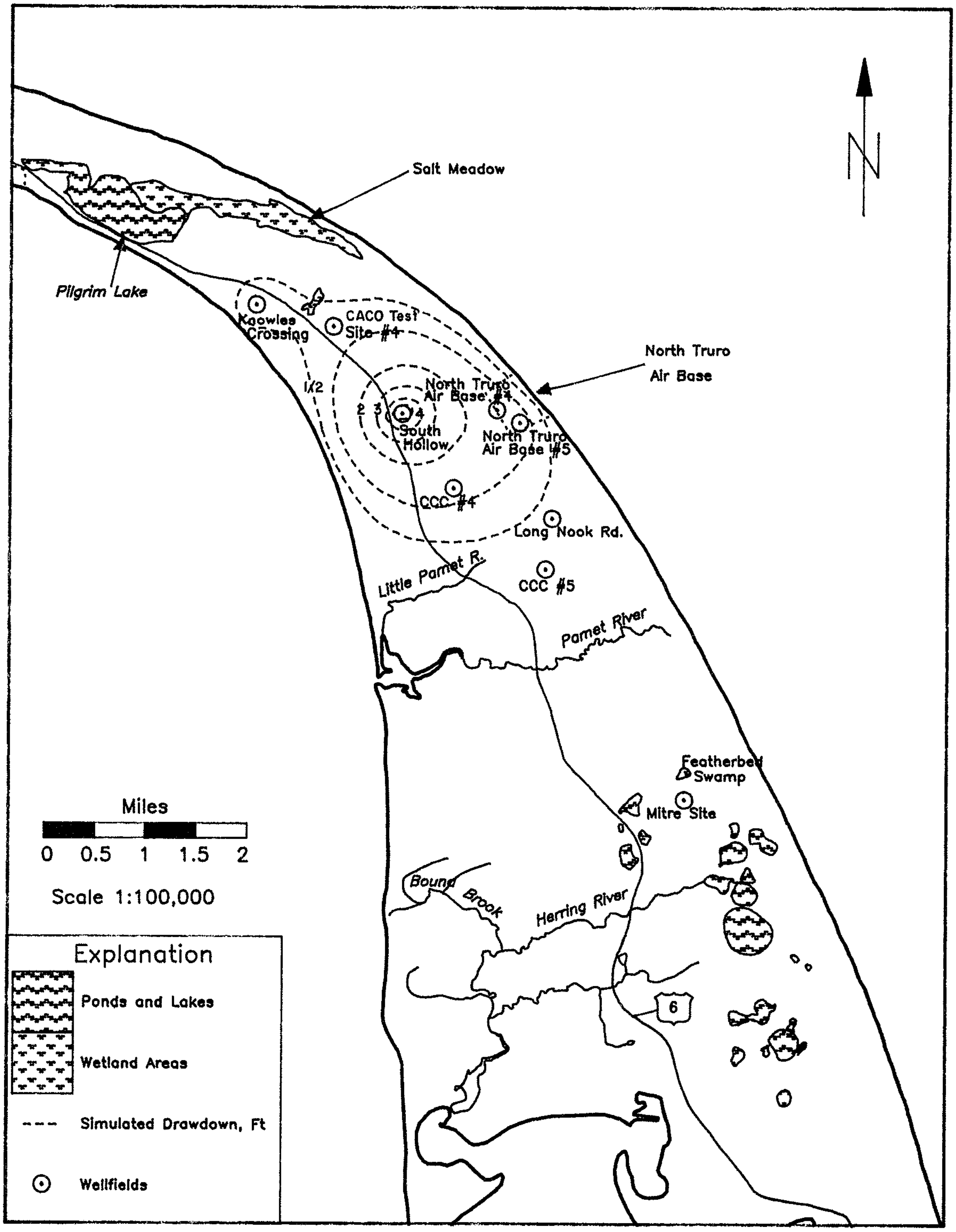


Figure 11. Simulated steady—state drawdown, Simulation 1.

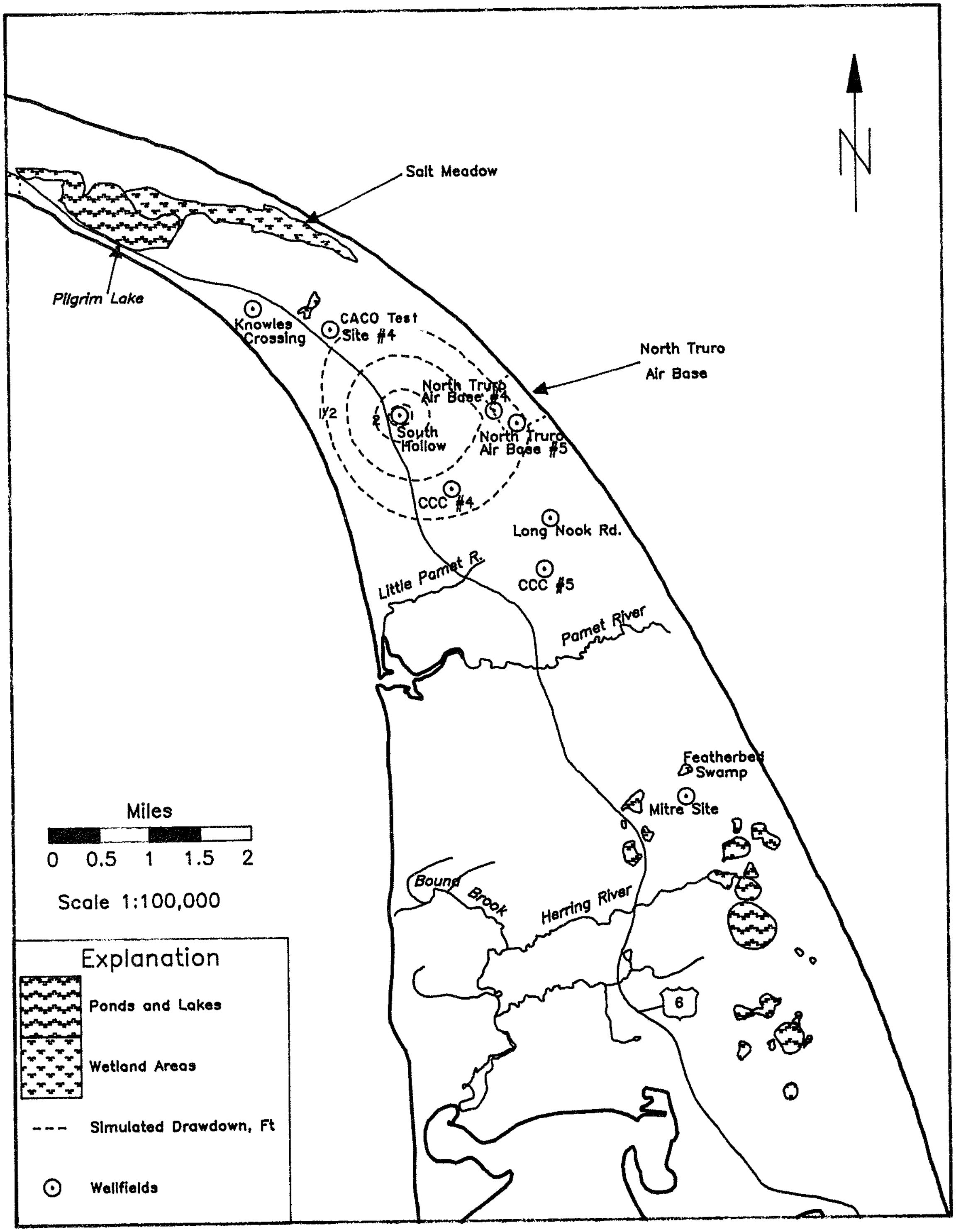


Figure 12. Simulated steady–state drawdown, Simulation 2.

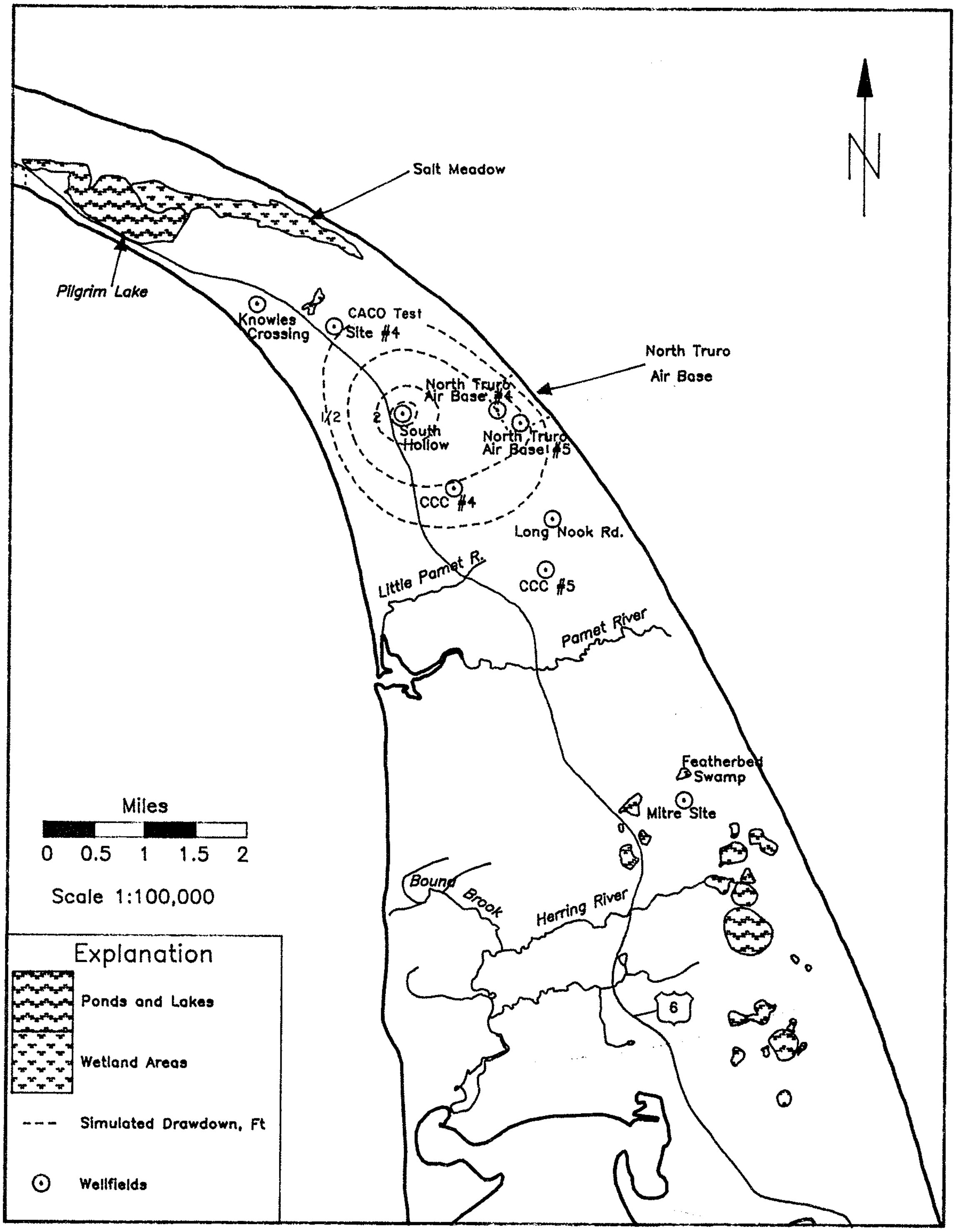


Figure 13. Simulated steady–state drawdown, Simulation 3.

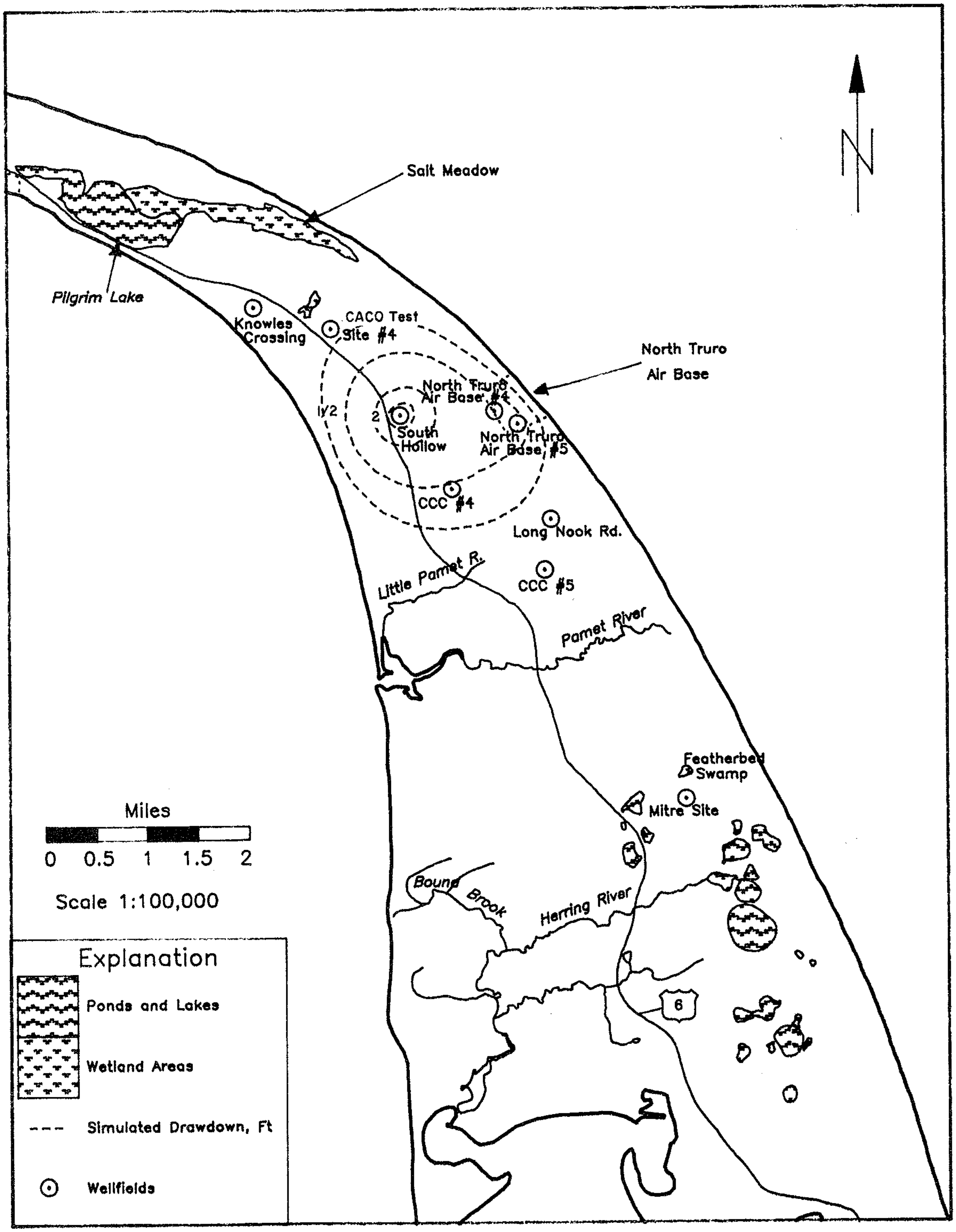


Figure 14. Simulated steady-state drawdown, Simulation 4.

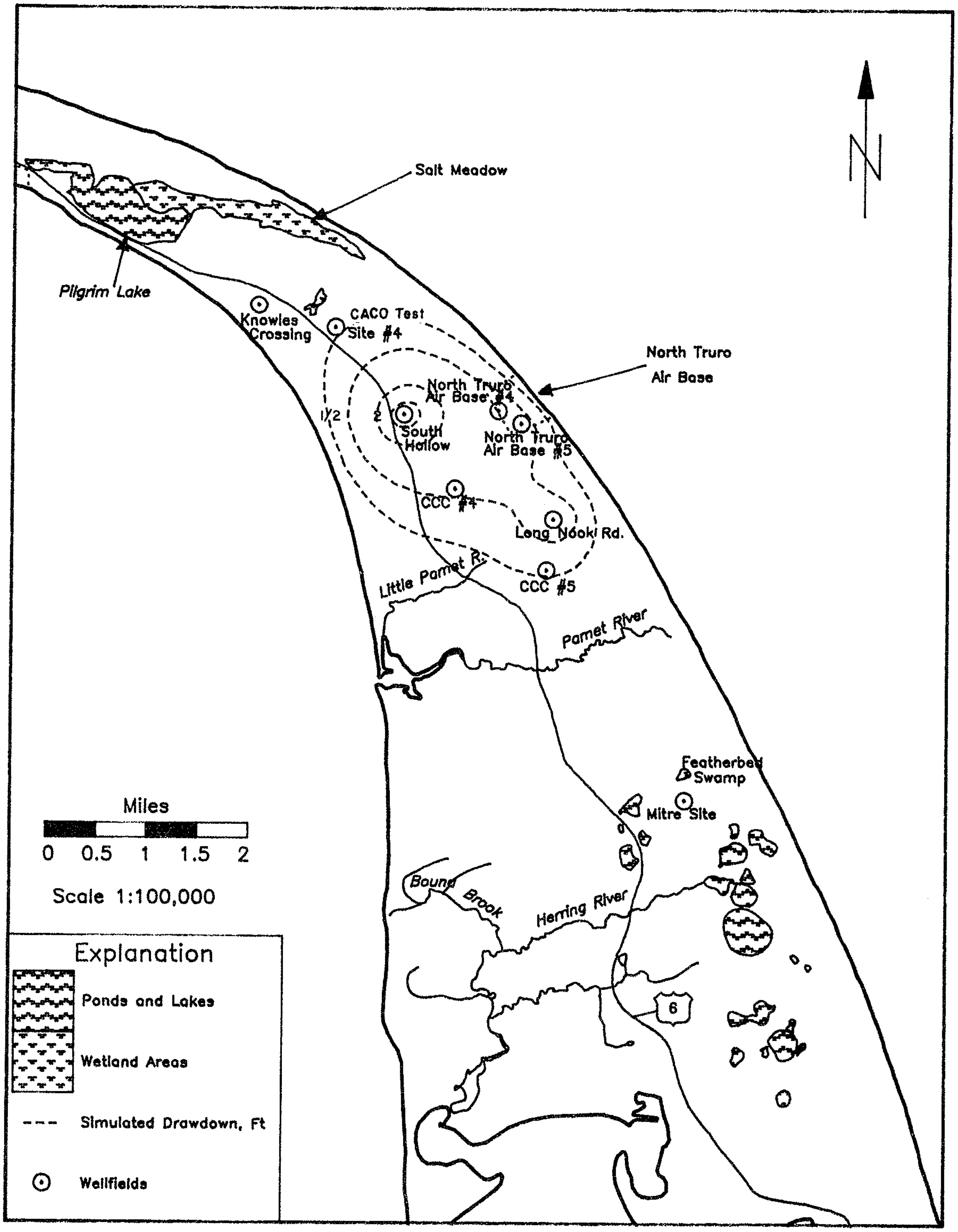


Figure 15. Simulated steady–state drawdown, Simulation 5.

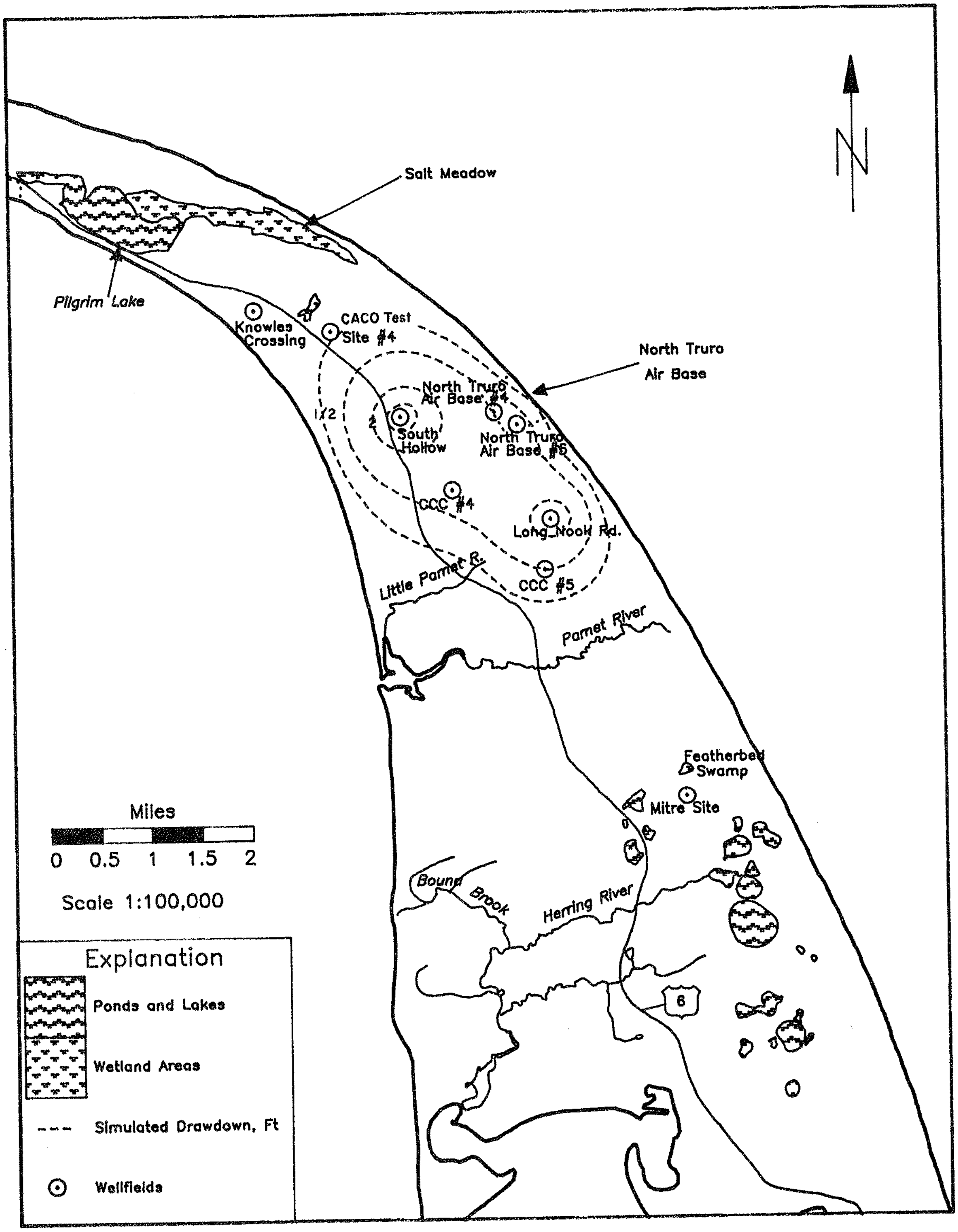


Figure 16. Simulated steady–state drawdown, Simulation 6.

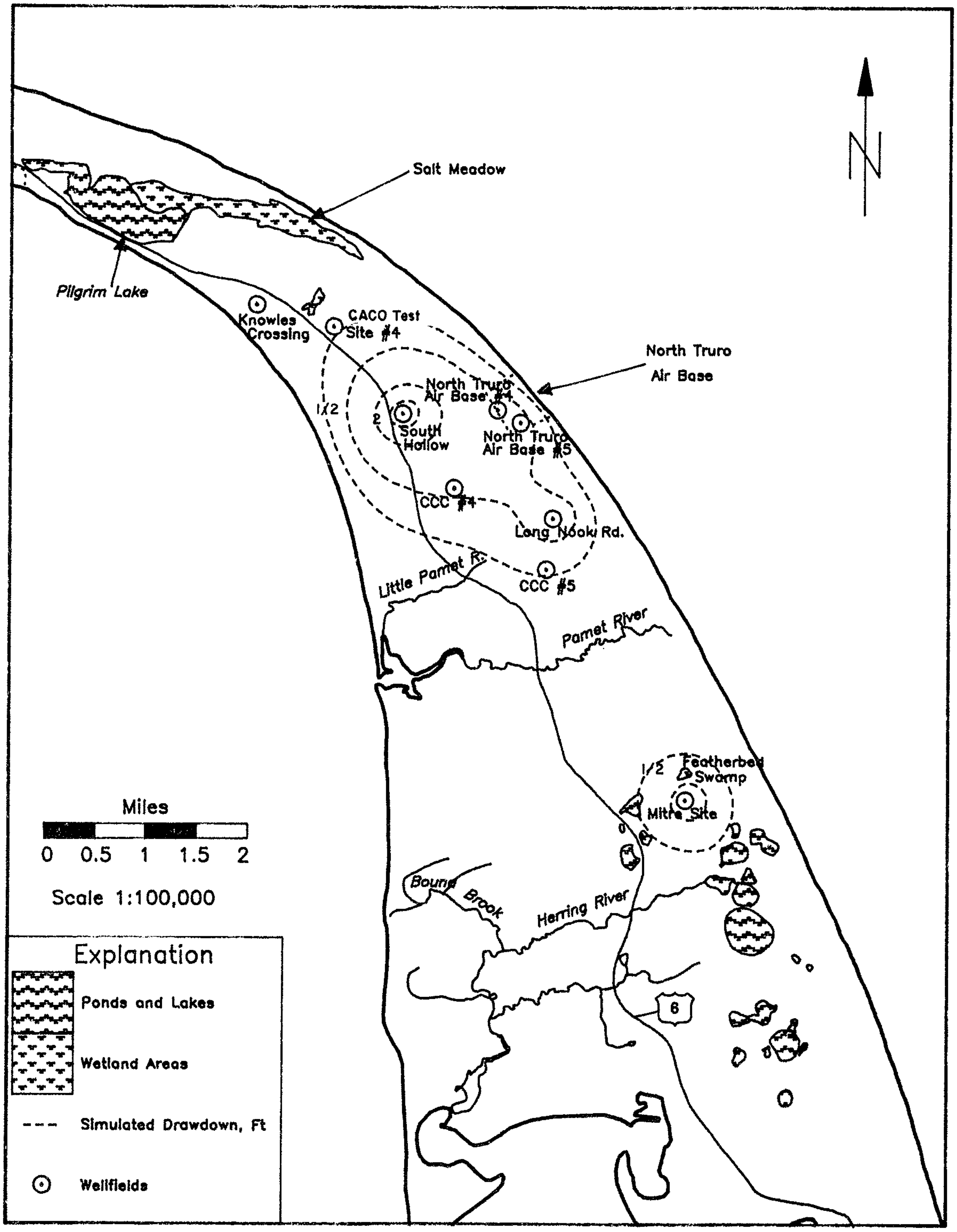


Figure 17. Simulated steady–state drawdown, Simulation 7.

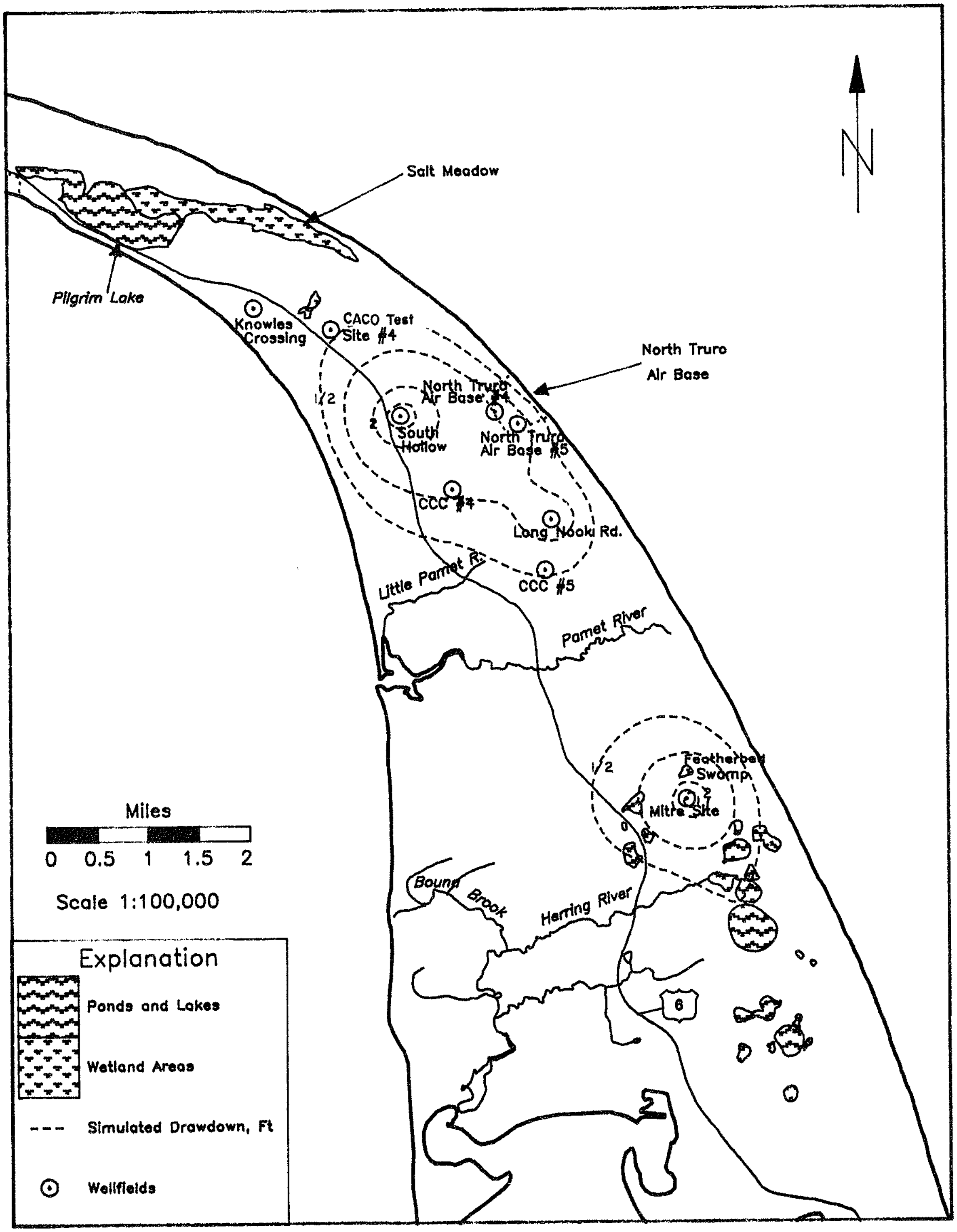


Figure 18. Simulated steady-state drawdown, Simulation 8.

As the nation's principal conservation agency, the Department of the Interior has the responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental an cultural values of our national parks and historical places, and providing for 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. The department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting 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.

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