Pamet River Investigation
Groundwater Assessment Study
Truro, Massachusetts

Groundwater Impacts Associated with the
Removal of the Tide Gate and Dike Structures

FINAL REPORT
May, 1997

prepared by

Cape Cod Commission
Water Resources Office

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prepared by

Eduard M. Eichner, Water Resources Scientist
Thomas C. Cambareri, Water Resources Program Manager
Kenneth Livingston, Project Assistant
Bob Sobczak, Project Hydrologist
Ben Smith, GIS Analyst

WATER RESOURCES OFFICE

Cape Cod Commission
Armando Carbonell, Executive Director

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Executive Summary

The Pamet River, which is located within the Town of Truro, MA and the Cape Cod National Seashore, is divided into an estuarine and freshwater river system by a clapper valve that prevents Cape Cod Bay salt watertides from reaching upper portions of the river. During significant Atlantic Ocean storms in 1978, 1991, and 1992, Ballston Beach, which is located at the eastern end of the Upper Pamet River system, was overwashed. The 1992 storm resulted in the Upper Pamet River valley being flooded with four feet of saltwater. Discussions among town, county, state, and federal officials in the aftermath of the 1992 storm resulted in a significant number of questions to address regarding the future management of the Pamet River and the increasingly frequent breaches of Ballston Beach. A study of groundwater and tidal actions was proposed to address some of these questions and was funded by the Town of Truro, the Cape Cod Commission, the National Park Service, and the Army Corps of Engineers.

This report details the hydrogeologic investigation of the Pamet River in Truro, MA conducted by the Cape Cod Commission Water Resources Office under contract to the Army Corps of Engineers. This investigation focussed on an evaluation of the groundwater impacts associated with the removal of the clapper valve at Wilder Dike. The investigation included the installation and surveying of 24 monitoring wells and 2 stream gauges; measurement of stream flows, groundwater levels, surface water levels, and tidal fluctuations; identification of private wells; and analysis of potential impacts using numerical and analytical groundwater models.

The Pamet River is at the margin of two groundwater lenses, the Pamet lens to the north, and Chequesset lens to the south. Water level measurements in the Pamet River valley indicate upward gradients toward the river, confirming that the Pamet River is a discharge area for these lenses. A calibrated groundwater model developed for this study and based on the collected hydrogeologic information suggests that the marsh surrounding the Pamet River serves to isolate the river from all but limited direct contact with the aquifer underlying the marsh. Modeling results indicate that 85% of the river discharge comes from surface water drains (*i.e.*, mosquito ditches) from the surrounding aquifer that flow across the top of the marsh and discharge into the river. Field observations combined with modeling results suggest that the remaining 15% of the river flow comes from direct groundwater discharge through highly conductive portions of the river bottom.

One of the primary concerns about removal of the clapper valve is the potential impact on private wells and septic systems in the Upper Pamet River valley. Commission staff used an analytical model to assess the effect of removing the tidal gate on groundwater fluctuations in the river valley. This evaluation of potential groundwater fluctuations used maximum tidal ranges predicted by the removal of constrictions near Wilder Dike and Route 6: 0.9 ft at Ballston Beach and 2.4 ft at

Route 6. The resulting analyses suggests only minimal increases (< 0.01 ft) in the range of groundwater fluctuations 500 ft from the river (the distance to the closest house) and virtually unmeasurable changes in water levels near septic systems and wells greater than 500 ft from the river. The low permeability characteristics of the marsh peat serve to dampen tidal impacts on groundwater levels.

The field data collected and modeling results indicate that the limited flow characteristics of the peat in the marsh system surrounding the Upper Pamet River would cause tidal ranges within the river to have minimal effect on groundwater levels in the Upper Pamet River valley. In addition, the significant thickness of the aquifer system (greater than 150 ft in the middle portion of the Upper Pamet River valley) and upward groundwater gradients suggest that saltwater flow from the river into the surrounding groundwater lenses will be prevented.

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I. INTRODUCTION

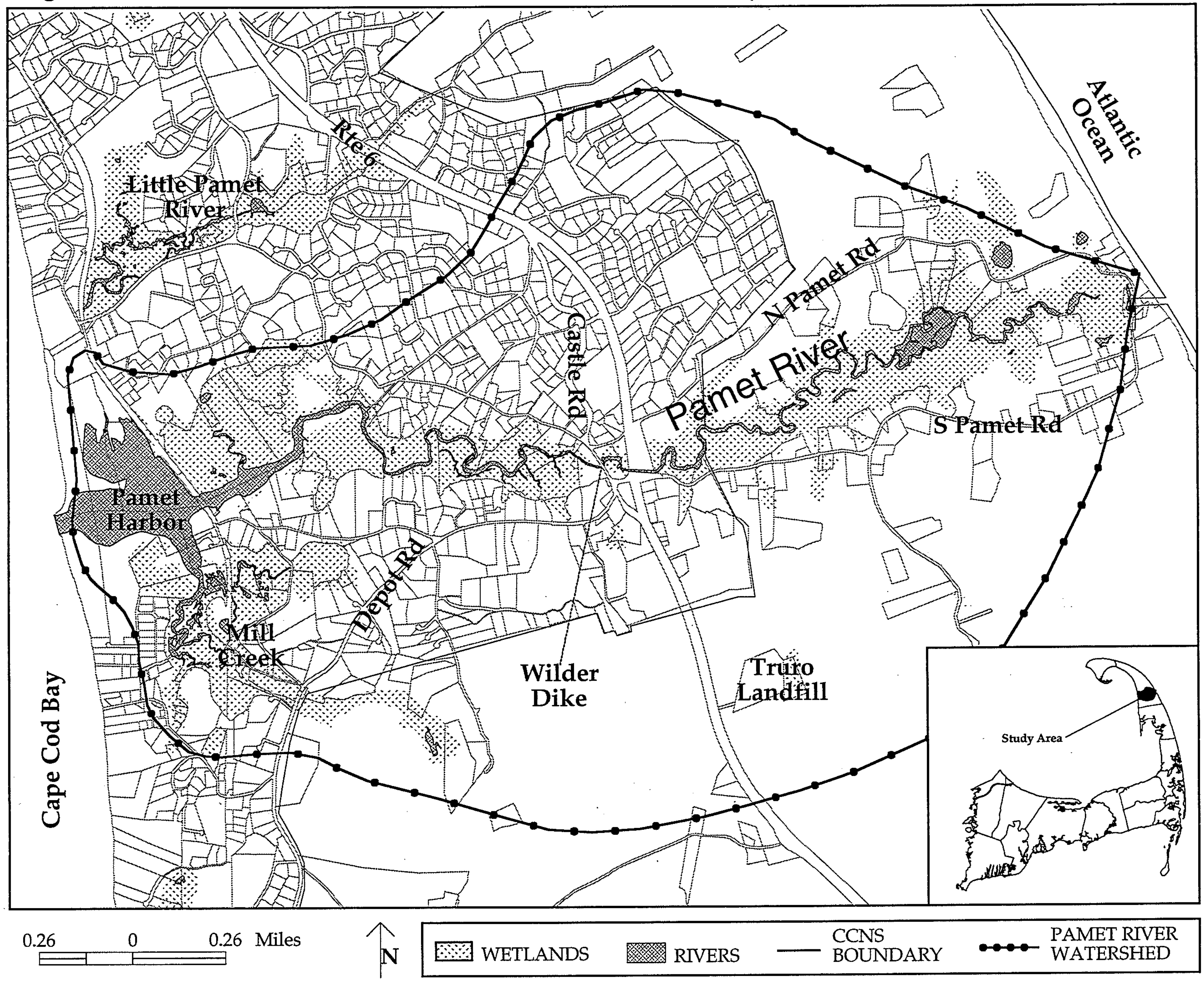
The Pamet River is an estuarine and freshwater river system located within the Town of Truro, MA and Cape Cod National Seashore (Figure 1). The Pamet River is divided into two hydrologically different sections by Wilder Dike and a tidal gate near Route 6. The tidal gate prevents the saltwater tides from reaching the upper Pamet River system. As a result of the tidal gate, the upper portion of the River has become a freshwater dominated ecosystem, while the lower portion is influenced by tides from Cape Cod Bay.

During significant storms in 1978, 1991, and 1992, Ballston Beach, which is located at the eastern edge or Atlantic Ocean side, of the Pamet River system was breached and overwashed. The storm in December 1992 resulted in the Upper Pamet River valley being flooded with four feet of saltwater from the Atlantic Ocean. The large inflow of saltwater was able to only slowly drain into the lower Pamet River because the tidal gate was closed during the hours around high tide. In addition, the size of the Route 6 culvert did not allow a significant volume of water to leave the upper system during low tide.

Discussions among town, county, state, and federal officials in the aftermath of the 1992 storm resulted in a significant number of questions regarding the future management of the Pamet River and how natural processes, such as the increasingly frequent overtopping of Ballston Beach, might impact management plans (Pamet River Workshop, March, 1993). As a result of these discussions, a consensus was achieved to assess the potential impacts of removing the tidal gate and allowing tidal actions within the upper Pamet River. Previous investigations of the potential restoration of tidal flows in other areas of the Lower Cape had suggested an aquifer thickness of 43 to 95 ft would prevent impacts on private wells (Fitterman and Dennehy, 1992) and impacts would be limited to changes in the plant community within the affected marsh (Roman, 1987; Roman, *et al.*, 1995). Concerns that have been raised about the removal of the Pamet River tidal gate have included degradation in drinking water quality in wells adjacent to or located in the Pamet River floodplain and flooding of existing septic systems due to an expected rise in groundwater levels throughout the Upper Pamet River valley.

In order to assess some of these questions, the Town of Truro and the National Park Service (NPS) requested the Army Corps of Engineers (ACOE) to conduct an investigation of the impact of removing the tide gate and dike structure located at Route 6 on the Pamet River. One portion of the study was designed to investigate the potential groundwater impacts. The following groundwater study was completed for $25,000, $6,000 of which was supplied by a grant to the Town from Cape Cod Commission Water Resource Office contract funds with the remaining balance supplied by the Town of Truro, the NPS, and the ACOE. The entire Pamet River Investigation study is being conducted by the ACOE under the Planning Assistance to States (PAS) Program. This report details the groundwater

Figure 1. Pamet River Watershed, Truro, MA.



study conducted by the Cape Cod Commission (CCC) under contract to the ACOE to assess the potential impacts of removing the tide gate on drinking water and groundwater levels in the upland area of the Upper Pamet River.

History and Current Conditions in the Pamet River

Glacial melting during the retreat of the last Pleistocene ice advance approximately 12,000 years ago formed the Pamet River valley (Koteff, *et al.*, 1967; Oldale, 1968). The word "pamet" is recognized by geologists as a channel in glacial deposits eroded by glacial meltwater (Strahler, 1966). The main channel of the Pamet River extends east from Cape Cod Bay across Truro and terminates approximately 150 feet west of Ballston Beach, which is on the Atlantic Ocean.

The river has been artificially separated into two sections, the Lower Pamet, an intertidal estuary, and the Upper Pamet, a freshwater river. The Lower Pamet marsh area, including the river, covers approximately 229 acres and the Upper Pamet marsh approximately 159 acres (Cape Cod Commission - GIS Dept.). Three side arms, the Little Pamet to the north, and Mill Creek and Bang's Creek to the south, flow into the Lower Pamet system.

The two sections were created by the installation of Wilder Dike and the tidal gate. Wilder Dike, which is located at Castle Road in Truro, was constructed in 1869 to replace a rotting railroad bridge across the mid-section of the Pamet River. The tidal gate at Wilder Dike and dike structures related to Route 6 were constructed in 1950s (Giese, *et. al.*, 1990).

The tidal gate utilizes a clapper valve to prevent saltwater and tidal influences from moving east of Castle Road. The clapper valve pivots based on fluctuations in freshwater and saltwater elevations (Figure 2). As currently configured, the clapper valve is forced closed by tidal saltwater approximately two (2) hours before high tide. The valve remains closed for four to six (4-6) hours. While the valve is closed, fresh surface water from the Upper Pamet fills the area to the east of the clapper valve, rising to ~ 0.75 ft above saltwater levels on the western side. Approximately three hours after high tide, the clapper valve gradually opens and freshwater drains from the Upper Pamet.

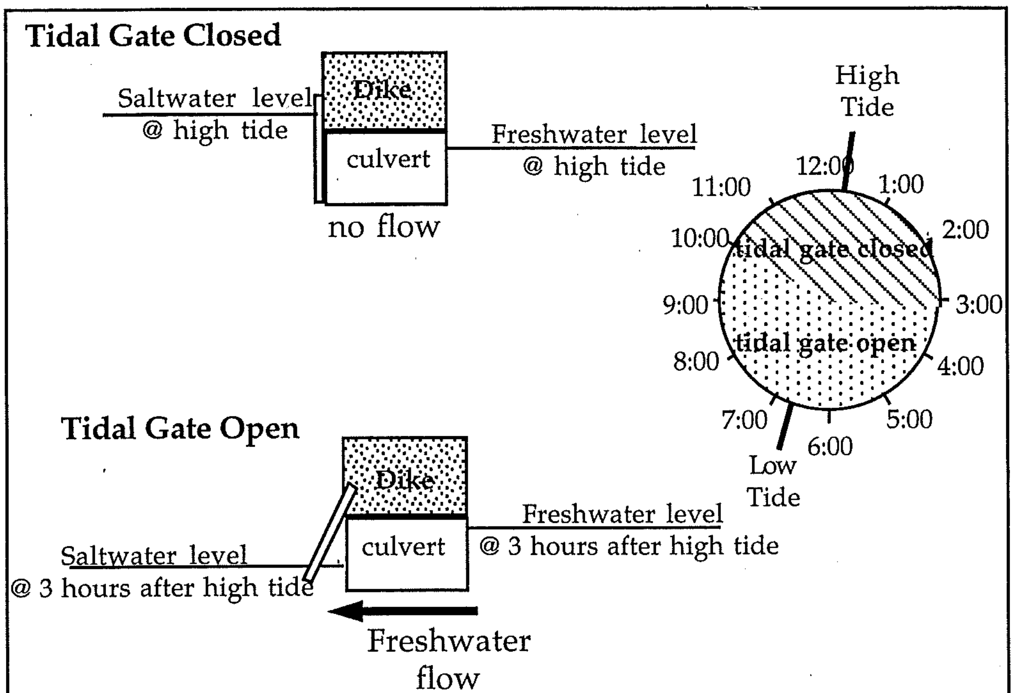


Figure 2. Operation of Pamet River clapper valve.

Water quality near the tidal gate is determined by the stage of the tide. With the tidal gate closed, the water just west of Castle Road is brackish (17 - 20 parts per thousand (ppt)) (Lewis, 1989). With the opening of the tidal gate, salinity concentrations decrease to near 1 ppt as freshwater flows through the tidal gate.

Since the mid-1970s various reports have evaluated the tidal conditions within the river and discussed the restoration of tidal flow to the entire Pamet River (see Appendix I (Annotated Bibliography) for a review of pertinent studies). Initial research by Giese and Westcott (1980) predicted the Pamet River estuary's size may be 16% less than pre-dike conditions. Subsequent development of a one-dimensional model by Giese and coworkers (1990) suggested that the removal of the clapper valve would result in minimal changes to the volume affected by the tides (*i.e.*, the tidal prism). This model averaged the velocity and tidal flow across the tidal channel and relied on assumptions about the tidal channel length (2.4 miles), width (15 ft), and depth (3 ft). The model predicted the current volume of the tidal prism (6.3×10^5 m^3 (mean tide)) would not be significantly altered if tidal influences are allowed east of Wilder Dike. The model predicts that tidal influence would extend across Route 6, but the current mean high tide at Castle Road would be lowered.

The re-introduction of tidal flow has been suggested as a means to increase the Pamet's tidal prism and reduce the rate of sand and mud buildup in the vicinity of

Pamet Harbor (Giese and Westcott, 1980; Horsley and Witten, Inc., 1994; Robinson, 1985b). It has also been suggested that the return of tidal flow throughout the Pamet River system may improve the water quality and shellfishing and finfishing opportunities within the river (Horsley and Witten, Inc., 1994). These benefits have been countered by concerns about the potential adverse effects on private wells, septic systems, and the freshwater biota in and around the Upper Pamet River.

Study focus

The Cape Cod Commission was selected by the Army Corps of Engineers (ACOE) to assess the potential groundwater impacts in the Upper Pamet River area that would be caused by the removal of the tide gate and dike structures on the Pamet River. The scope of services approved by the ACOE included: 1) review of existing hydrogeologic studies, 2) location of existing drinking water wells, 3) installation of shallow and deep groundwater wells, 4) collection of water levels and flow information, 5) development of groundwater model for the Upper Pamet, and 6) preparation and presentation of a final report. This report details each of these steps.

II. CONCEPTUAL HYDROGEOLOGY OF THE UPPER PAMET RIVER

The Pamet River is at the margin of two groundwater lenses, the Pamet lens to the north, and Chequesset lens to the south (Guswa and LeBlanc, 1981). Previous water table maps of the area (Cambareri, *et al.*, 1989a and 1989b; Cape Cod Commission, Wellfleet Harbor Mini-Bay Project) indicate that the Pamet River is a discharge area for both lenses. Based on these water tables, the watershed to the river is 2,694 acres, with 1,314 acres to the east of Route 6 (see Figure 1). Based on the Commission's Geographic Information System (GIS) information, the surface of the Upper Pamet River is 14.21 acres and the surrounding marsh is approximately 159 acres.

Initial hypotheses about the hydrogeology in the area have suggested that the surrounding groundwater lenses discharge through the sandy bottom of the Pamet River. Observations of the marsh ecosystem have indicated that freshwater vegetation overlay freshwater marsh peat, which in turn overlays approximately 3 ft of salt-marsh peat (John Portnoy, National Park Service, personal communication). In certain sections, the peat extends to a depth of 15 feet below the land surface. The salt-marsh peat is thought to be the result of more than 1,000 years of salt-marsh growth prior to the construction of the dike and tidal gate structures.

Peat layers conduct little groundwater movement through them, as compared to sand and gravel sediments (Freeze and Cherry, 1979). The thick deposits of marsh peat in the Upper Pamet River area, if continuous, would tend to isolate the river from the underlying aquifer (Figure 3).

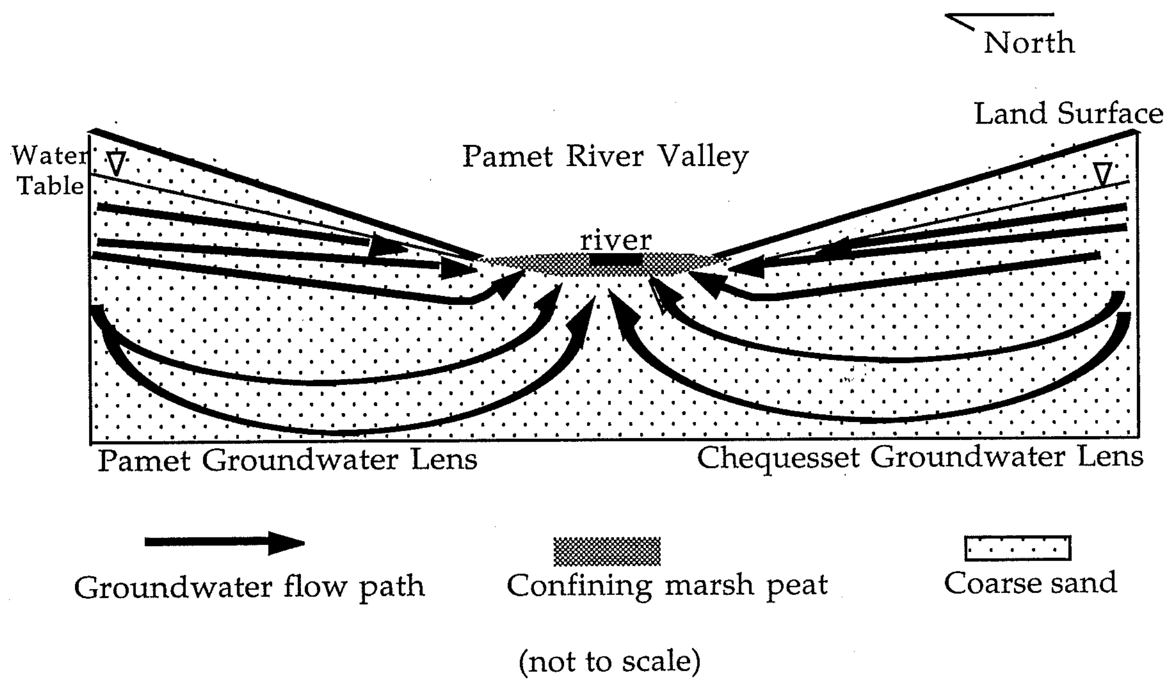


Figure 3. Conceptual Groundwater Flow within the Pamet River Valley.

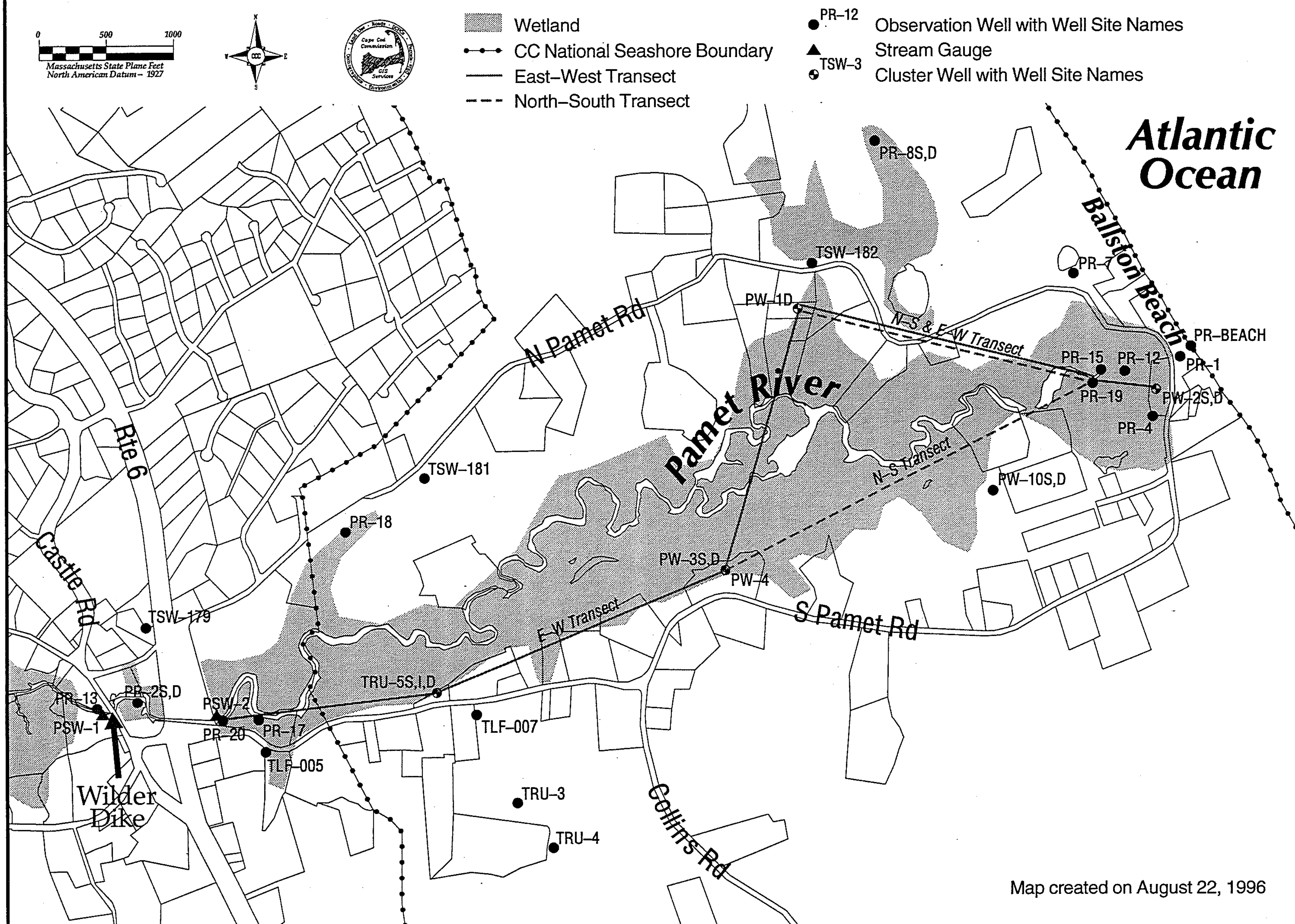
III. HYDROGEOLOGIC ASSESSMENT AND DATA ACQUISITION METHODS
Commission staff reviewed existing studies of the Upper Pamet River area to identify previously installed monitoring wells (Cambareri, *et al.*, 1989a and 1989b; LeBlanc, *et al.*, 1986; Marc Adams, National Park Service, personal communication) and to identify potential locations for additional wells. Eleven pre-existing wells were identified for inclusion in the monitoring network for this study.

Twenty-four additional monitoring wells and 2 stream gauges were installed for this investigation (Figure 4). The wells installed are: fourteen (14) hand augered one-inch PVC wells at depths between 7 ft and 12 ft below land surface; six (6) three-quarter inch steel drive point wells at depths between 15 ft to 25 ft below land surface; three (3) drilled wells at a depth of 50 ft, and one (1) drilled well at a depth of 150 ft below land surface. Elevations of all wells were determined relative to the National Geodectic Vertical Datum (NGVD), which is likely within 0.5 ft of mean sea level in this location. See Table 1 for characteristics of monitoring wells and stream gauges.

The drilled wells (PW-1, PW-2d, and PW-3d) were installed using a lead screened auger by Desmond Well Drilling, Inc. on May 20 and 21, 1996 (see Appendix II for well logs). Water samples were taken approximately every 5 ft as the auger was advanced. Salinity (%), specific conductivity (µmhos/cm), and temperature (°C) measurements were collected at each sampling point after three well volumes had been pumped from the well.

Study Area and Data Point Map–Upper Pamet River

Figure 4



Map created on August 22, 1996

Table 1. Physical characteristics of monitoring wells.

Site Name	Depth (ft)	Well Type	Elevation of Well (ft)	Approximate elevation of top of screen (ft)	Approximate elevation of bottom of screen (ft)
PR-1	20	3/4" DP	10.325	-7.675	-9.675
PR-2d	25	3/4" DP	4.545	-18.455	-20.455
PR-2s	7	1" PVC	4.625	-0.375	-2.375
PR-4	7	1" PVC	7.555	2.555	0.555
PR-7	7	1" PVC	7.560	2.560	0.560
PR-8d	25	1" PVC	7.785	-15.215	-17.215
PR-8s	7	1" PVC	7.100	2.100	0.100
PR-10d	20	3/4" DP	10.320	-7.680	-9.680
PR-10s	7	1" PVC	9.120	4.120	2.120
PR-12	7	1" PVC	5.570	0.570	-1.430
PR-13	12	1" PVC	8.620	-1.380	-3.380
PR-15	7	1" PVC	3.780	-1.220	-3.220
PR-17	7	1" PVC	3.895	-1.105	-3.105
PR-18	12	1" PVC	8.860	-1.140	-3.140
PR-19	30	3/4" DP	3.450	-24.550	-26.550
PR-20	20	3/4" DP	6.060	-11.940	-13.940
PR-Beach	12	1" PVC	10.495	0.495	-1.505
PW-1	50	2" PVC	6.900	-38.100	-43.100
PW-2d	50	2" PVC	5.810	-39.190	-44.190
PW-2s	7	1" PVC	5.275	0.275	-1.725
PW-3s	7	1" PVC	6.130	1.130	-0.870
PW-3d	150	2" PVC	7.265	-137.735	-142.735
PW-4	50	2" PVC	6.945	-38.055	-43.055
TLF-005	N/A	2" PVC	N/A	N/A	N/A
TRU-3	65	2" PVC	7	-48	-58
TRU-4	85	2" PVC	15	-60	-70
TRU-5s	20	2" PVC	7.03	-7.97	-12.97
TRU-5i	47	2" PVC	7.03	-34.97	-39.97
TRU-5d	60	2" PVC	6.95	-48.05	-53.05
TSW-179	N/A	microwell	9.97	N/A	N/A
TSW-181	N/A	microwell	9.02	N/A	N/A
TSW-182	N/A	microwell	7.02	N/A	N/A
TSW-184	N/A	microwell	19.83	N/A	N/A
TSW-185	N/A	microwell	15.71	N/A	N/A
PSW-1	stream gauge		-1		
PSW-2	stream gauge		0		

Drive point wells were installed using a 60 pound slide hammer with 5 ft sections of steel pipe. Holes of 3/64 inch diameter were drilled in the bottom 1 to 2 ft of the first pipe section to serve as an effective well screen. The wells were developed by slug tests to ensure hydraulic connection to the underlying aquifer. Drive point well locations PR-19 and PR-20 are of particular note because these wells were driven through the bottom of the river. Water level measurements were taken after the installation of every 5 ft section of pipe at these two wells sites.

Water table measurements were taken from measuring points on July 15, July 25, August 2, and August 6. Water levels were obtained in the wells using a Slope Indicator electric tape (Model# 51453). Water levels at the two stream gauges (PSW-1 and PSW-2) were read from previously installed gauges. On July 15, water level measurements were collected from 5 locations near Route 6 and Wilder Gate and at 4 locations near Ballston Beach over a 12 hour tidal cycle in half-hour increments. These readings were taken during a new moon tide, which had a high tide elevation of 9.4 ft NGVD at the Cape Cod Bay side of the Pamet River (personal communication, Pamet Harbor Yacht Club).

Stream flow measurements were taken August 1 and 6 using a Rickly Hydrological Co. pygmy meter. Flow measurements were taken at two locations: 1) the culvert opening just east of Route 6 and 2) a transect just west of Route 6, perpendicular to wells PR-2s and 2d. Flow measurements were taken at the first site in 1 ft increments across the front of the culvert opening. A cross-sectional area of the culvert was calculated to assess the volume of freshwater leaving the Upper Pamet during the low tide period when the clapper valve is open. At the second location flow measurements were taken in 2 ft increments across the river.

Parcel information and building locations were used to assess the location of private wells. Parcel information is based on Town of Truro 1993 assessor's information, which was previously digitized by the Cape Cod Commission GIS Dept. Building locations within parcels are based on US Geological Survey topographic maps and a review of 1993 aerial photographs of the area. The parcel and building location information was combined through the use of the CCC GIS.

IV. ASSESSMENT FINDINGS AND DISCUSSION

Identification of Existing Residential Homes and Private Wells

There are approximately thirty (30) residential homes bordering the Upper Pamet River. The majority (26) of these private homes are located above the 10 ft elevation contour. The minimum distance between residential homes and the river channel is approximately 500 ft.

A survey of private well water quality for the Lower Cape was completed previously by the Lower Cape Water Management Task Force (LCWMTF) (Sobczak and

Cambareri, 1995). The LCWMTF database includes nitrate, sodium, specific conductance, and iron levels for private wells. Between 1987 and 1994, approximately 783 private wells were sampled within the Town of Truro. Seventy-seven private wells are identified as being located within the Pamet River watershed. The wells have been classified based on location within one of the four geographic quadrants within the Pamet River watershed, with Route 6 and the river serving as dividing lines. Table 2 presents the statistical averages of four geographic quadrants of the Pamet River watershed.

Table 2. Average Drinking Water Quality in Private Wells in the Pamet River Watershed.

LOCATION	NUMBER OF SAMPLES	NITRATE LEVEL (ppm)	SPECIFIC CONDUCTANCE (µmhos/cm)	SODIUM (ppm)	IRON (ppm)
North Lower Pamet River Quadrant	24	1.34	187	26	0.47
South Lower Pamet River Quadrant	21	1.64	168	20	0.31
North Upper Pamet River Quadrant	12	0.65	137	16	0.54
South Upper Pamet River Quadrant	20	0.66	143	19	0.40
Truro (Whole Town)	783	1.10	146	19.86	0.41
Drinking Water Standards		10*		20**	0.3***

*MA Drinking Water Standard (*i.e.*, maximum contaminant limit)

** MA Drinking Water Guideline (*i.e.*, standard promulgated by USEPA but not yet effective)

*** MA Secondary Maximum Contaminant Level (*i.e.*, aesthetic standards, not health based)

Within the Lower Pamet quadrants, where tidal influences currently occur, sodium and specific conductance levels within private wells are higher than in the Upper Pamet quadrants (see Table 2). Existing sodium and specific conductance characteristics of the Upper Pamet quadrant wells are somewhat lower than Truro as a whole. Nitrate-nitrogen concentrations in the Lower Pamet quadrants are more than double those in the Upper Pamet quadrants, but this would be expected due to the relative lack of development in the surrounding National Seashore in the Upper Pamet watershed. There also appears to be a difference between the water quality at the margin of the two different lenses; iron concentrations are higher in the northern quadrants (the Pamet Lens) than in the southern quadrants (the Chequesset Lens).

Screened Auger Groundwater Quality
Figure 5 presents the specific conductance readings recorded at PW-1, PW-2, and PW-3 as the screened auger was advanced. Specific conductance is a measure of the concentration of dissolved substances, or ions, in a sample of groundwater. Higher concentrations in freshwater are usually indicative of contamination. Frimpter and Gay (1979) found a median specific conductance of 123 µmhos/cm in 202 samples throughout Cape Cod. The highest concentration found in Truro landfill monitoring has been 2,150 µmhos/cm (Cambareri, *et al.*, 1989a). Saltwater from the Atlantic Ocean would have a concentration of approximately 50,000 µmhos/cm.

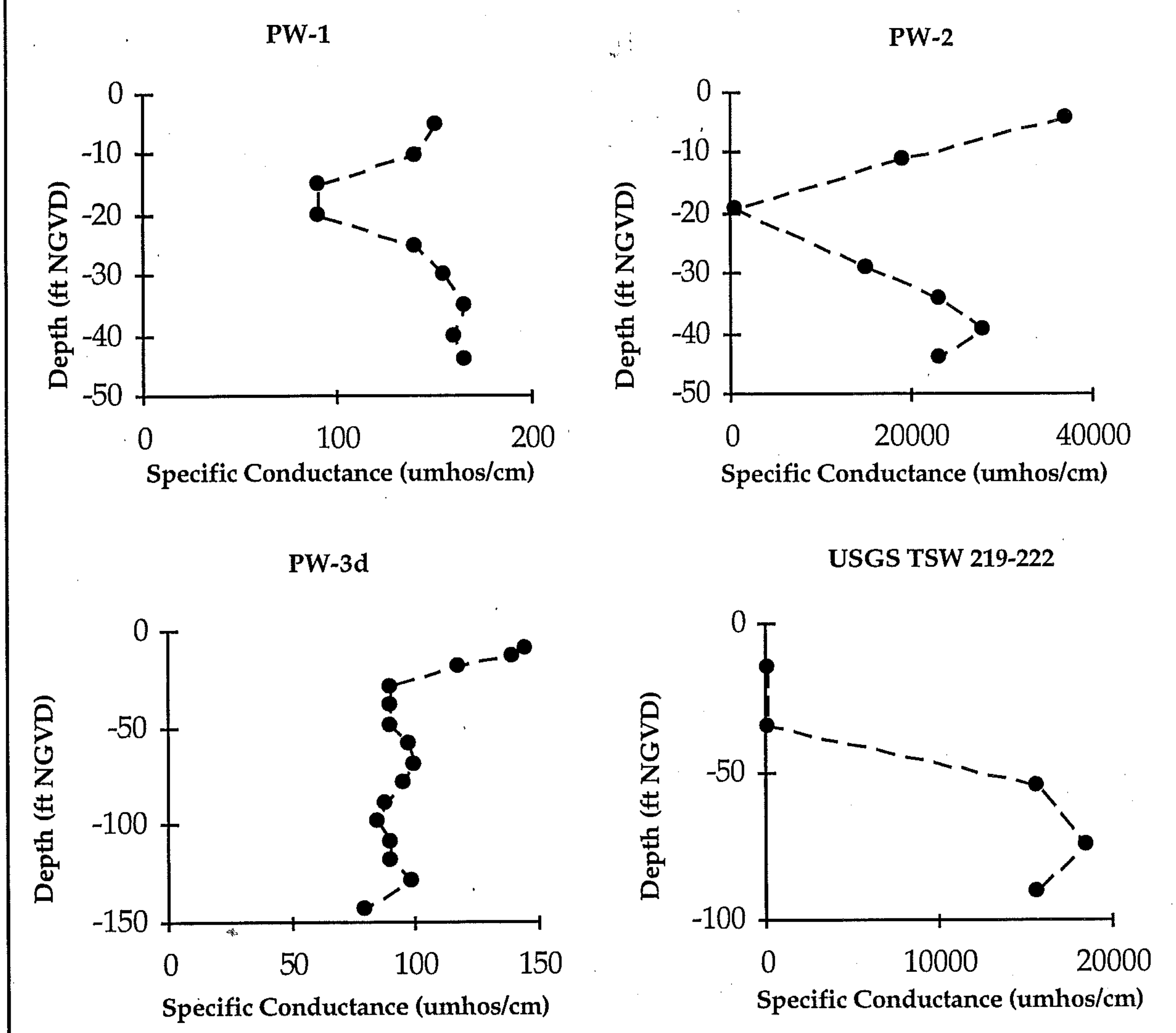


Figure 5. Specific Conductance Readings for Drilled Wells.

At PW-2 (Ballston Beach parking lot), no freshwater was encountered. Groundwater encountered throughout the 50 ft depth of the well was generally between 13.5 and 23.5% salinity, with specific conductance readings of between 600 and 37,000 µmhos/cm. A U.S. Geological Survey zone of transition well (TSW 219-222) that was installed near this location in 1975 found a chloride concentration of approximately 100 ppm at - 10 ft NGVD and nearly 12,000 ppm at - 60, - 75, and - 90 ft NGVD. The higher specific conductance in PW-2 compared to the earlier USGS well seems to indicate an increase in salt groundwater at the eastern end of the Pamet. This increase may be the result of the Atlantic Ocean overwash events. Lewis (1989) had previously documented that surface water salinity concentrations in the first 100 feet of the Pamet River were 20 ppt, but this level quickly decreases to 0 ppt 100 feet from the head of the river.

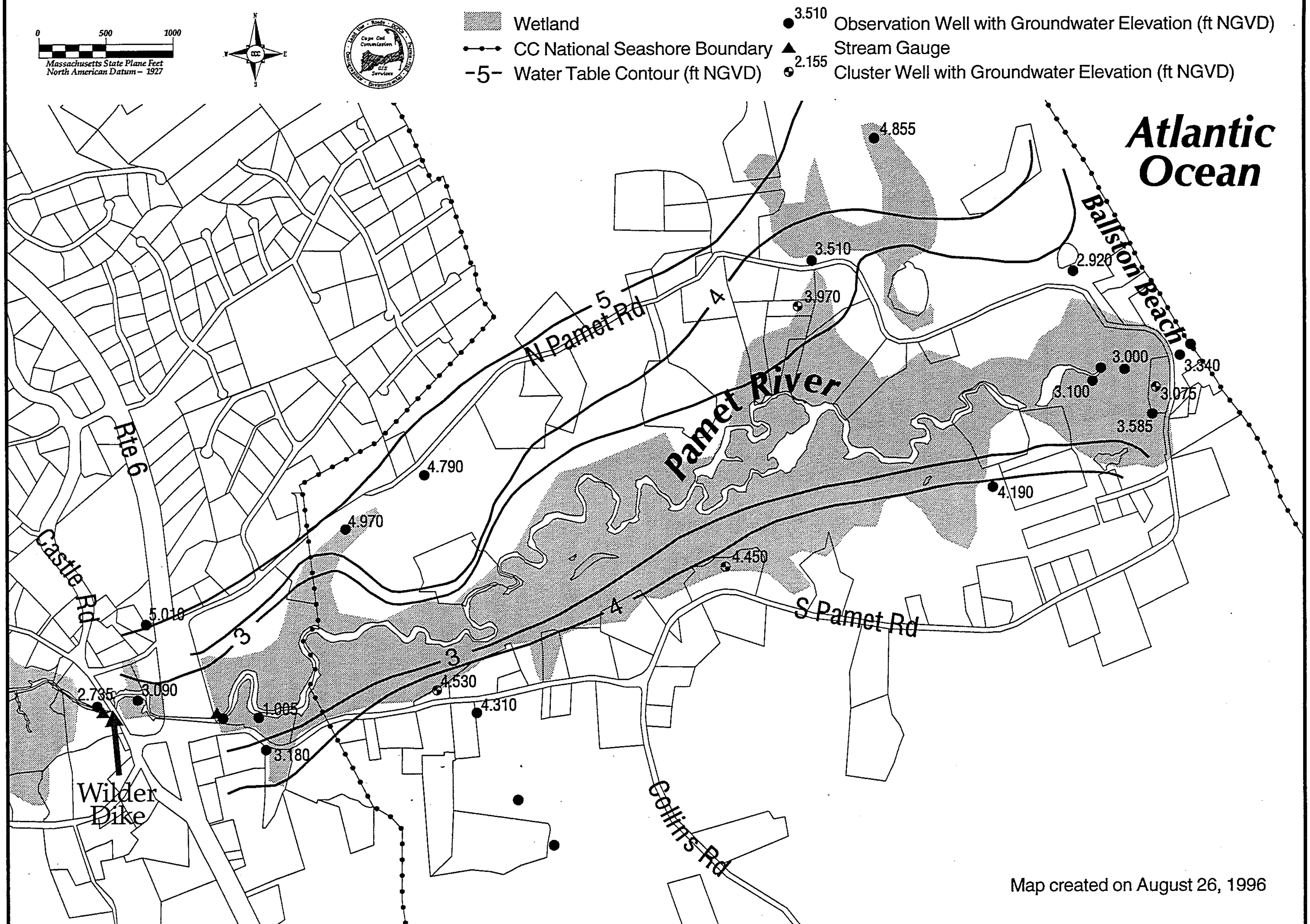
In contrast, saltwater was not encountered at PW-3 and specific conductivity readings suggest good quality water. PW-3 was drilled to 150 ft and water table elevation at this site is between 3 and 5 ft NGVD. Based on the Ghyben-Herzberg approximation (Freeze and Cherry, 1979), the saltwater interface should be located between 120 and 200 ft below the water table. Water pumped from the bottom of the borehole had no salinity and low specific conductivity (80 µmhos/cm). Thus, the saltwater interface is deeper than 150 ft at this location. The significant thickness of the groundwater lens in this area suggests that typical private wells, which penetrate 20 to 30 ft into the aquifer, are well separated from the saltwater interface.

Regional Water Levels

Groundwater levels collected from the top of the Pamet and Chequesset aquifers (*i.e.* the water table) generally show a decrease in elevation as one moves from either the north or south toward the Pamet River (Figure 6). These decreases in elevation indicate that groundwater in the northern and southern portions of the study area is flowing toward the Pamet River. Comparison of water levels collected during this study with historical water levels at TSW-179 indicate August 1996 water levels were slightly above average. The water level at TSW-179 has averaged 4.48 ft NGVD with a range of between 5.46 and 3.6 ft NGVD based on 12 years of monthly measurements (Figure 7). The July 1996 water level in this well was 4.84 NGVD.

Water Table Contours Map–Upper Pamet River

Figure 6



Map created on August 26, 1996

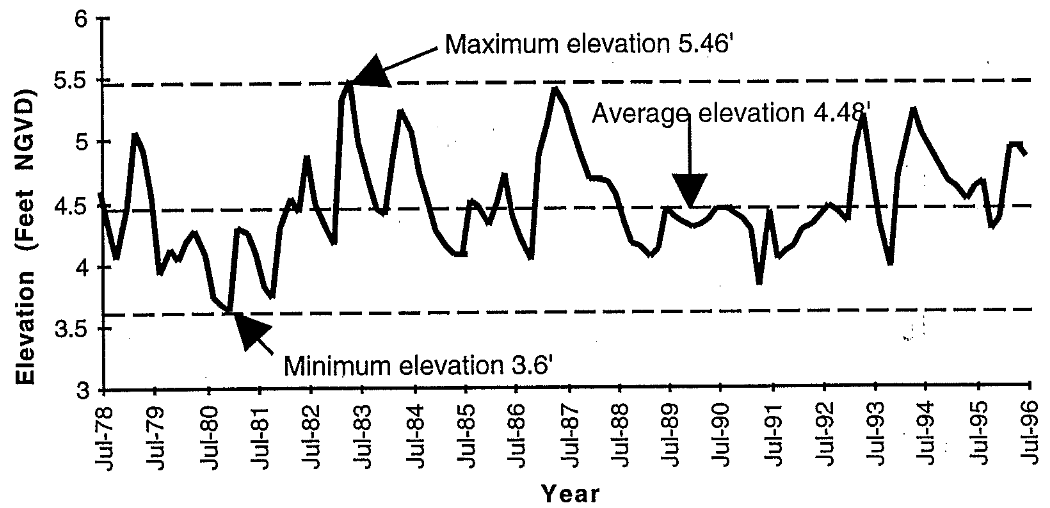


Figure 7. Hydrograph for USGS Monitoring Well TSW-179.

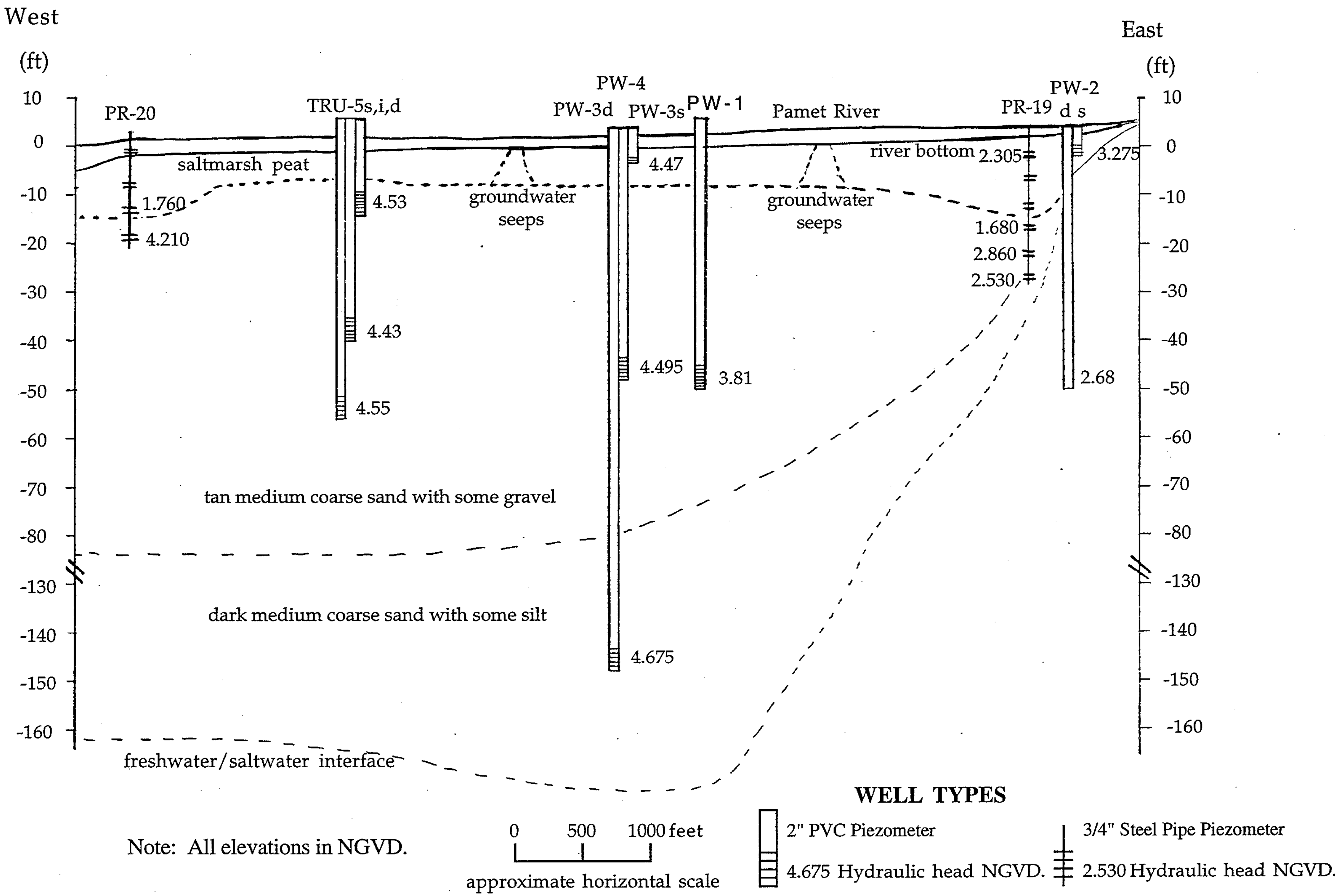
Vertical Groundwater Gradients

Water levels in wells below the water table can indicate the direction of flow at depth. Water levels along a longitudinal cross-section (Figure 8) and perpendicular cross-section (Figure 9) indicate regional horizontal and local vertical flow toward the Pamet River.

In Figure 9, the well cluster at PW-3, which is located approximately 500 feet from the river, indicates lower groundwater elevations closer to the surface than at depth. These levels indicate that there is a upward component of groundwater flow toward the river. A similar pattern was observed at PR-19, near the culvert to Route 6.

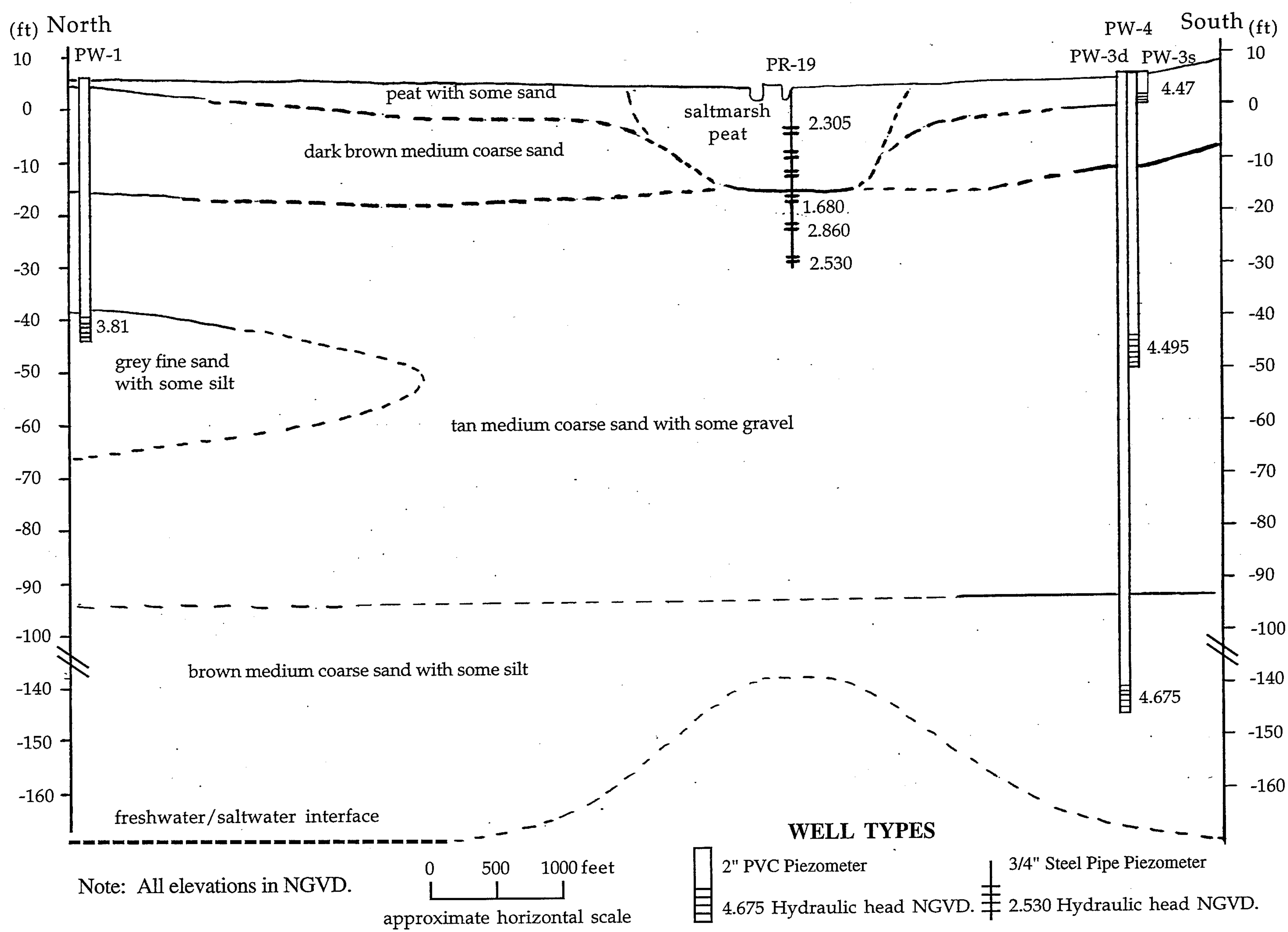
A layer of peat was encountered at the locations of wells driven through the river bottom (PR-19 and PR-20). The presence of peat was determined by the relative ease of driving the wells. The peat extends approximately 18 feet below the land surface at the Ballston Beach location (PR-19) and approximately 16 feet below the land surface at Route 6 (PR-20). These thicker layers of peat may be indicative of a thicker layer throughout the river bottom. Hydraulic heads directly below the peat are above the land surface (*i.e.*, artesian flow conditions) in both PR-19 (Table 3) and PR-20 (Table 4). The artesian conditions indicate that the peat layer acts as a confining layer, which restricts groundwater flow into the river. During the installation of PW-3, a fibrous peat and clay layer was also encountered approximately 1 ft below the land surface and it is approximately 3 ft thick. Hand augered wells installed in close vicinity to the riverbed also encountered a clay/peat layer at a depth of 1 ft below land surface. The existence of a relatively thick layer of peat (3 to 5 ft) was also

Figure 8. East-West Transverse Cross-Section of the Upper Pamet River, Truro, MA.



Note: All elevations in NGVD.

Figure 9. North/South Transverse Cross-Section of the Upper Pamet River, Truro, MA.



established at numerous sites surrounding the river when a 4 ft steel probe could be easily and completely inserted.

Table 3. Water Levels at PR-19 (1,000 ft west of Ballston Beach) (8/7/96).

Well Length (ft)	Elevation (ft)	Elevation of Bottom Of Well (ft)	Depth to Water (ft)	Water Elevation in well (ft)
Surface water	--	--	--	2.5
5	2.855	-2.145	0.55	2.305
10	2.610	-7.39	5.67	-3.060*
15	2.740	-12.26	9.57	-0.830*
20	2.780	-17.22	1.10	1.680
26.5	4.420	-22.08	1.56	2.860
30	3.450	-26.55	0.92	2.530

All Elevations relative to NGVD
* Water level in peat; did not allow to equilibrate.

Table 4. Water Levels at PR-20 (Route 6 culvert) (8/7/96).

Well Length (ft)	Elevation (ft)	Elevation of Bottom of Well (ft)	Depth to Water (ft)	Water elevation in Well (ft)
Surface water	--	--	--	1.75
5	3.250	-1.75	1.49	1.760
10	1.910	-8.09	4.85	-2.940*
15	1.780	-13.22	9.36	-7.580*
24	6.060	-17.94	1.85	4.210

All Elevations relative to NGVD
* Water level in peat; did not allow to equilibrate.

Stream Flow Measurements

During this study, stream flow measurements were taken August 2 at the culvert opening east of Route 6 (PSW-2) and August 6 in the river adjacent to PR-2s and 2d. Preliminary stream flow measurements on August 2 were taken at two times: 1) approximately two hours before the clapper valve closed and 2) approximately five minutes before the clapper valve closed. Stream flows at PSW-2 were calculated to be 9.63 and 6.39 cubic feet per second (cfs), respectively (Table 5). The readings on August 2 may have been confounded by 1.25 inches of rain in the study area during the prior two days (Jenny Woods, National Park Service, personal communication).

Table 5. Stream Flow Measurements.

Location	Date	Time	Total Flow (cfs)
At Route 6 culvert (PSW-2)	8/2/96*	9:00	9.63
	"	9:10	9.40
	"	9:20	8.99
	"	11:03	6.39
Near PR-2	8/6/96#	9:50	10.87
	"	9:55	10.49
	"	10:30	9.46
	"	11:00	8.36
	"	11:30	7.66
	"	12:00	5.89
	"	12:30	5.65

* High tide at 2:19 p.m. # High tide at 5:57 p.m.

On August 6, stream flow readings were taken over a 2.5 hour period after the clapper valve opened. These readings were taken to establish base flow within the river. Base flow is the sustained rate of groundwater discharge in a stream after the accounting of transient precipitation events, stream bank storage, and tidal effects. The August 6 readings show a gradual decline in stream flow from 10.87 cfs to 5.65 cfs (see Table 5). Since surface water elevations and the stream flow during the period of the last two reading showed little change, the 5.65 cfs reading at 12:30 p.m. can be considered to be baseflow discharge (Figure 10).

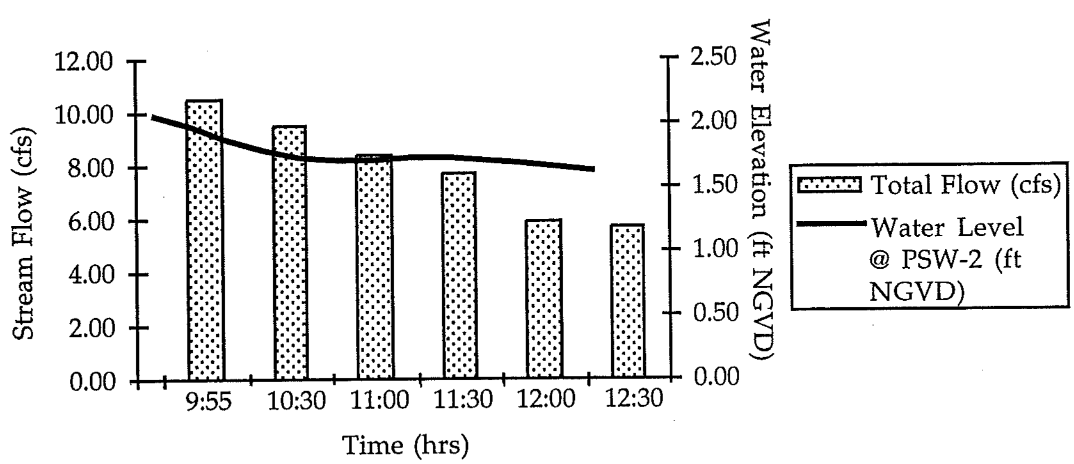


Figure 10. Stream Flow and Surface Water Levels at Route 6 Culvert.

The baseflow measurement in the Pamet River system will always be a direct reflection of the elevation of the water table in the study area. August 1996 base flow measurement is higher than most of the readings collected by Lewis (1989) at the Route 6 culvert (3.6 to 5.2 cfs using dye and 6.5 cfs using a meter). Lewis' readings were collected in the summer of 1988 when water levels in the study area were approximately a foot below the August 1996 levels (see Figure 7). These lower water levels would tend to decrease the discharge into the river from the surrounding lenses leading to a lower base flow.

A previous assessment of streamflow in the Waquoit Bay watershed (Cambareri, *et al.*, 1993) found that annual average recharge within a river watershed agrees with measured water flow within the river. If the average Cape Cod annual recharge rate (18 in/yr) is applied across the previously delineated 1,469 acre watershed of the Upper Pamet River, the resulting base flow would be 3 cfs. This flow is ~ 0.6 cfs lower than the lowest streamflow estimates calculated by Lewis (1989) and ~ 2.6 cfs lower than the 5.65 cfs measured in this study. These disagreements between data sets suggest that additional readings are warranted. The groundwater model developed for this study was used to evaluate these readings (see Groundwater Model section).

Influence of Tides on Water Levels

During the July 15 tidal monitoring round, high tide occurred at 12:09 p.m. at Pamet Harbor. Wilder Dike (PSW-1) experienced a peak level of 5.05 ft NGVD between 12:10 p.m. and 12:37 p.m (Figure 11). These observations indicate an approximate 10 minute lag in the high tide at Cape Cod Bay and at Wilder Dike. These readings also indicate that the clapper valve is closed for approximately 5 hours per tidal cycle and the valve opens approximately 3 hours after peak tidal levels are experienced at Wilder Dike. The tidal range at Wilder Dike was observed to be 4.2 ft, with a low of 0.85 ft NGVD and a high of 5.05 ft NGVD. At monitoring well PR-13, which is 5 ft from the channel bank, the range of groundwater fluctuations was 0.87 ft (see Figure 11). At monitoring wells east of Wilder Dike and west of Route 6 (PR-2s and 2d), the range of groundwater fluctuations were observed to be 0.46 ft in the shallow well and 0.09 ft in the deep well.

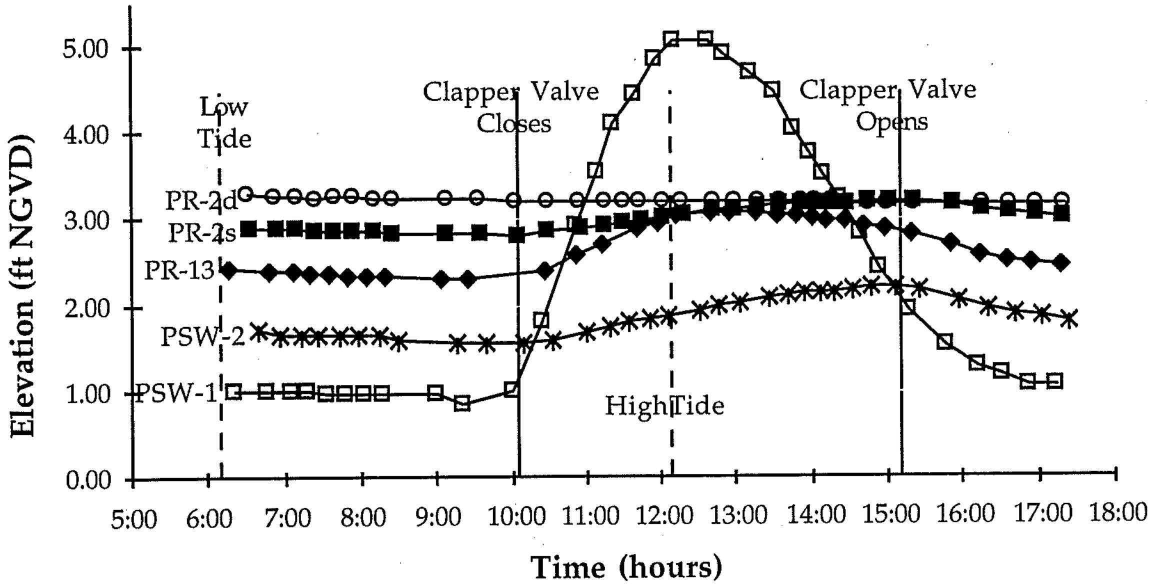


Figure 11. Tidal Influences in Groundwater and Surface-Water in the Vicinity of the Tidal Gate/Wilder Dike (7/15/96).

At the Route 6 culvert (PSW-2), water levels were lowest (1.55 ft NGVD) just before the clapper valve closed (between 9:39 a.m. and 10:09 a.m.); approximately 3 hours after low tide. The highest water levels at PSW-2 were at 3:06 p.m. (2.21 ft NGVD), approximately 3 hours after high tide and just before the clapper valve opened. The range of fluctuations in the river stage was 0.66 ft.

The water level and tidal information near Wilder Dike and Route 6 indicate that groundwater levels on both sides of the Dike are affected by the closing of the clapper valve. The rise in groundwater levels due to the tidal rise (0.87 at PR-13) and ponding of river water (0.46 ft at PR-2s) are notably less than the fluctuations observed in the river (4.2 ft and 0.66 ft, respectively). The groundwater impacts also appear to be most markedly expressed at the water table and are dampened at depth (0.09 ft fluctuation at PR-2d). It is also notable that tidal levels in the river exceed groundwater levels for approximately 3 hours during a complete tidal cycle (see Figure 11).

Tidal fluctuations at Ballston Beach were monitored through the installation of a 1 inch PVC well (PR-Beach) at the upper reach of the high tide mark. During high tide, this well was in 2 inches of water and at low tide, ocean water was approximately 25 ft from the well. The tidal range at this well was 5.43 ft, with a low of -1.05 NGVD and high of 4.38 NGVD (Figure 12). At PR-1, which is approximately 100 ft west of the beach monitoring well, the tidal range was less than 0.01 ft. At monitoring wells southwest of PR-1, tidal fluctuations were 0.5 ft in PW-2d and 0.1 ft at PR-4, a well 400 ft south of PW-2d and 400 ft west of the Atlantic Ocean. PR-12, 247 ft to the west of PR-1, had a tidal range of 0.08 ft. At PR-15, 526 ft to the west of PR-1, tidal fluctuations were negligible (less than 0.01 ft). At PR-7, adjacent to a kettle pond 50 ft north of North Pamet Road, water levels fluctuated 0.12 ft.

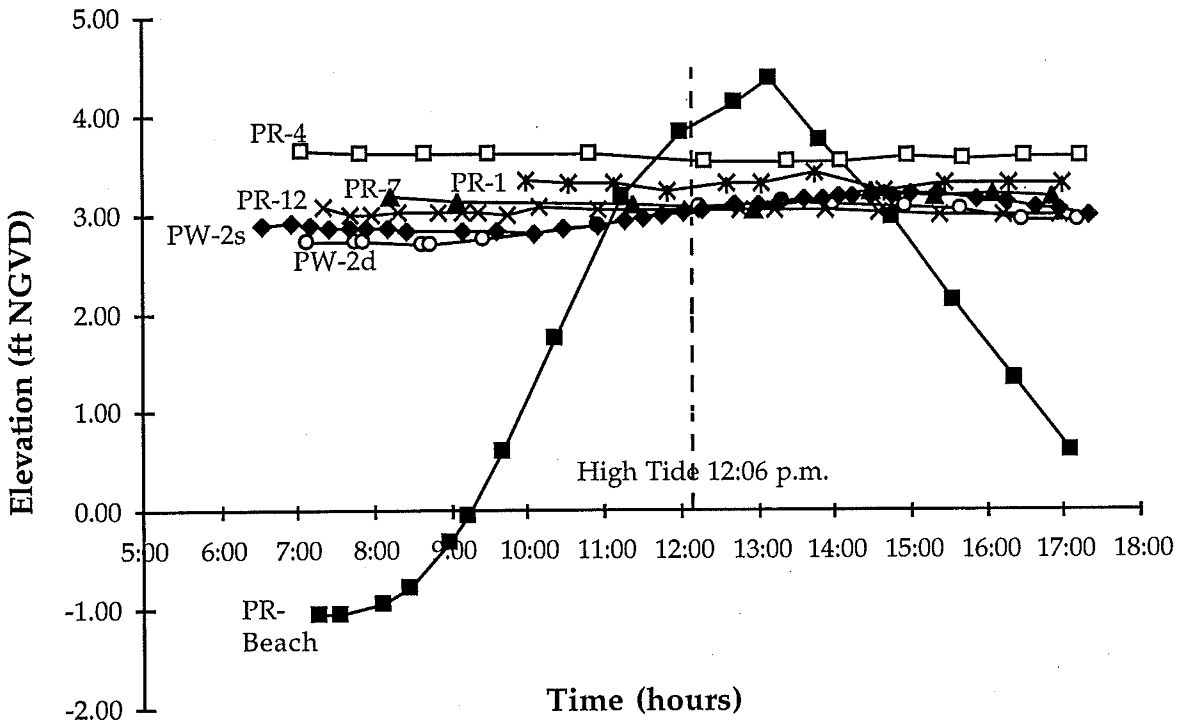


Figure 12. Tidal Influences in groundwater Levels in the Vicinity of Ballston Beach (7/15/96).

These readings indicate that tidal influences on the groundwater levels in the Ballston Beach area are negligible; most of the wells within 500 feet of the ocean had fluctuations of approximately 0.1 ft, which is less than 2% of the range in the ocean (see Figure 12). Of note among the readings is the higher fluctuation (0.5 ft) observed at PW-2d. This well is screened between - 45 and - 50 ft NGVD in an area of highly conductive substrates (see Appendix II). These more permeable materials may allow better transmission of the pressure gradient created by the high tide than the overlying materials. It is also notable that water collected at this depth was green, also possibly indicating a highly permeable connection to the ocean. Ocean tidal levels exceeded water levels in the Ballston Beach area for approximately 2.5 hours (see Figure 12).

On July 15, groundwater levels were also collected at the PW-3 well cluster for 2 hours after high tide in order to assess if tidally induced groundwater fluctuations would be observed in an interior portion of the Upper Pamet study area. No fluctuations were observed in any of the wells in this cluster.

A simplified hydraulic cross-section of the Pamet River was prepared to summarize the observed fluctuations in surface water levels collected during this study (Figure 13). The figure shows the relatively constant water level (~ 3 ft NGVD) at the western side of Ballston Beach (PW-2), the ~ 1 ft range of water levels at Route 6 (PSW-2), the ~ 6 ft tidal range at the Atlantic Ocean (PR-Beach) and the ~ 4 ft tidal range at Wilder Dike (PSW-1). The cross-section shows the relatively constant water level at PW-2 maintaining a gradient of surface water flow at high and low water levels toward Route 6 and the clapper valve. High tides at Ballston Beach exceed the PW-2 water level by approximately 2 ft or a third of the tidal range, while high tide at the Wilder Dike exceeds the PSW-2 high water level by approximately 3 ft or 75% of the tidal range. The difference in the percentage of the tidal range also helps to explain why groundwater levels near Wilder Dike and Route 6 fluctuate much more than those near Ballston Beach (*i.e.*, a greater proportion of the tidal range is above the high groundwater levels causing a more sustained gradient towards the inland portion of the Upper Pamet River). During storm surge conditions at Ballston Beach, the increase in the higher portion of the tidal range likely increases flow from the ocean to the river in this area.

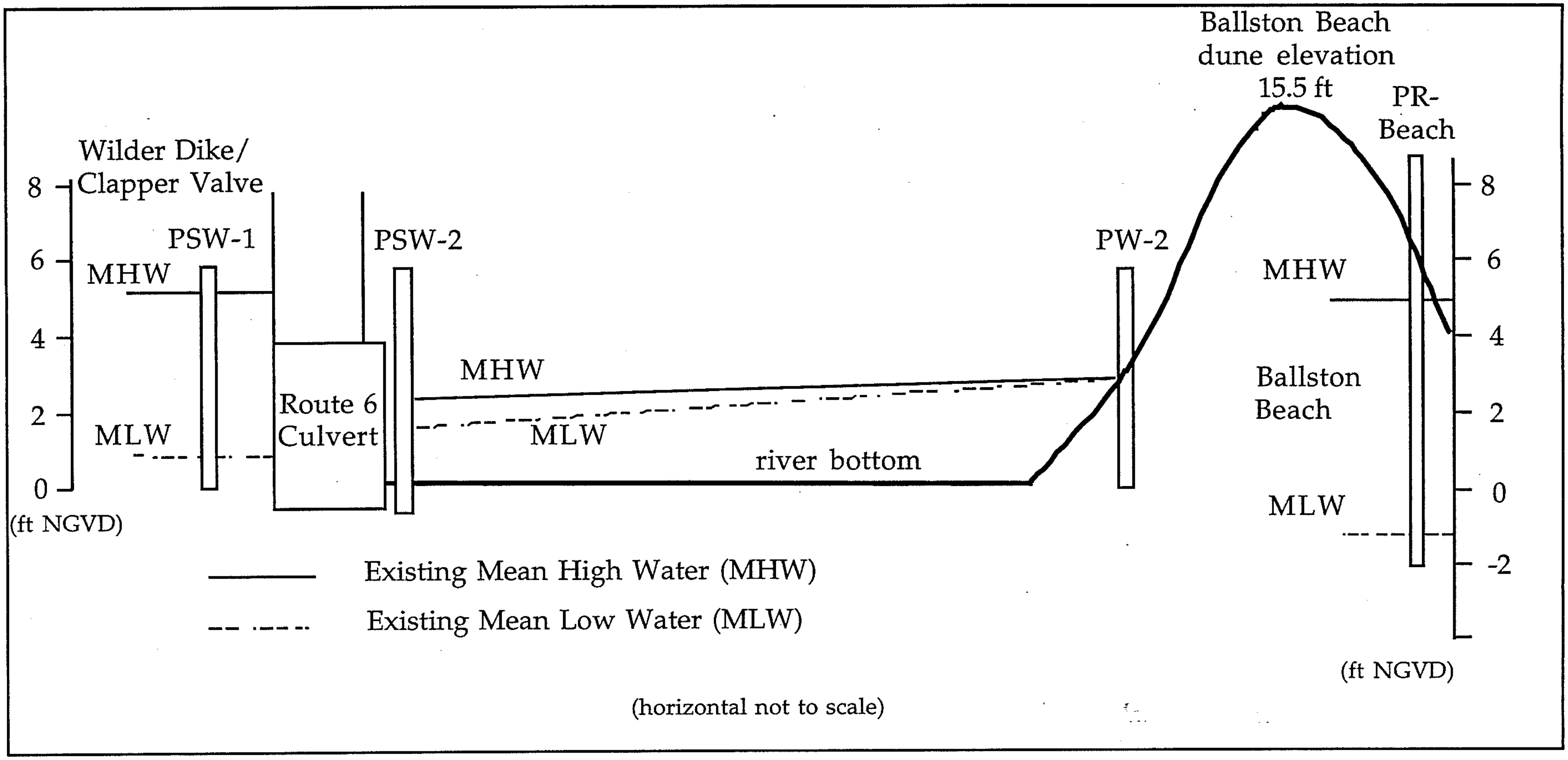


Figure 13. Simplified Hydraulic Cross-Section of the Upper Pamet River

Groundwater Model

The Cape Cod Commission subcontracted the Lower Cape Water Management Task Force to prepare a groundwater flow model for the interlens discharge area of the Pamet River. The objective of the modeling effort was to assist in characterizing the system and to use the model to explore hypotheses about its functions. In addition, development of the model can assist in determining where collection of additional information would be desirable for a more refined characterization. This reconnaissance level model is not intended, nor can it be used, for evaluation of various tidal/clapper valve scenarios. Additional data collection and model enhancements would be necessary to evaluate tidal scenarios.

The model for the Pamet River stream-aquifer system extends from Great Pond in Truro to Pilgrim Lake in Truro and is bounded by Cape Cod Bay and the Atlantic Ocean. The lateral extent of the model was chosen to: 1) include the entire watershed of the Pamet River, 2) incorporate current pumping stresses in the Pamet Lens, and 3) be useful for future modeling work on the Pamet Lens.

Model Structure

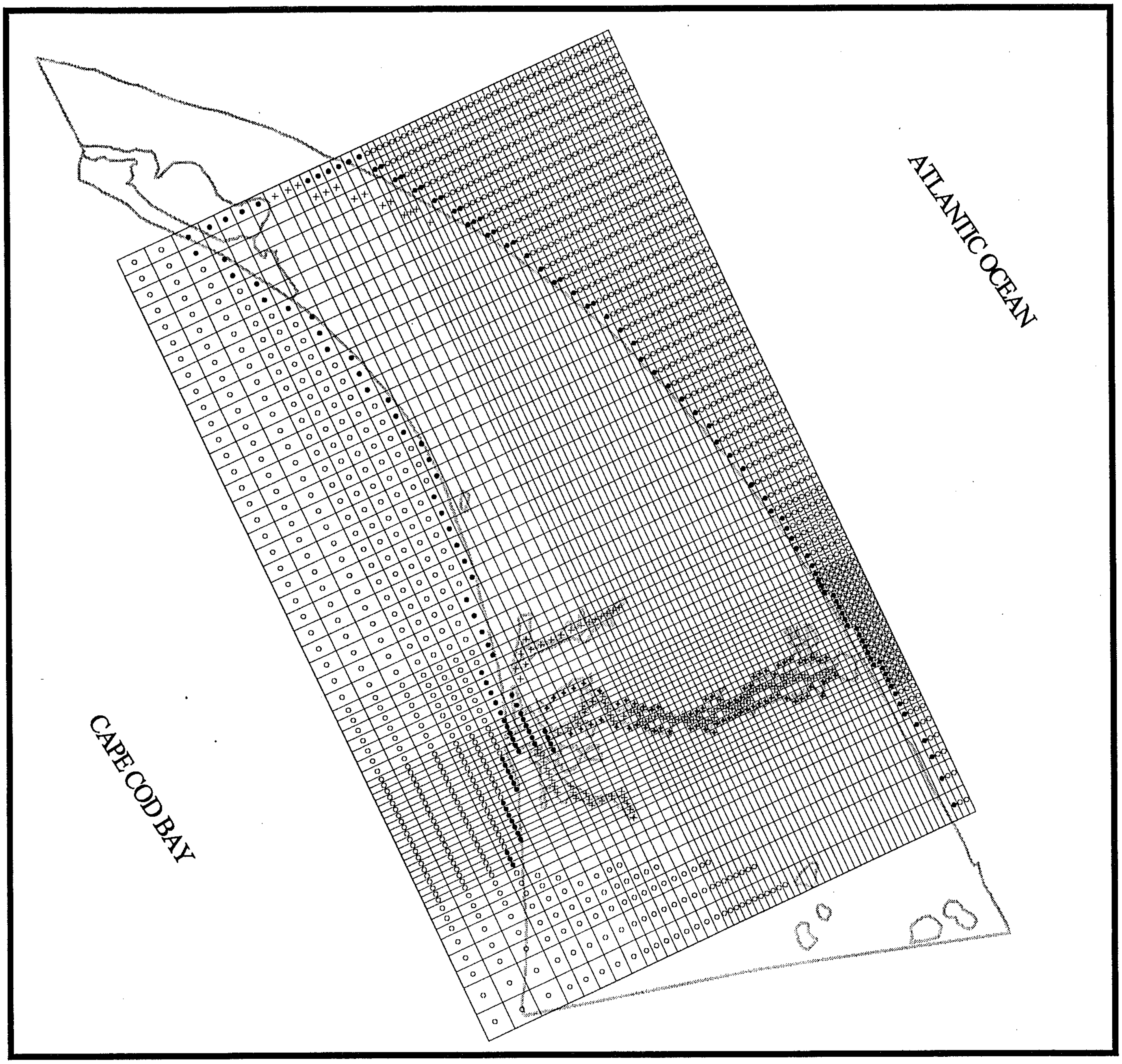
The model consists of 7 vertical layers. The six lower layers generally use elevations and hydraulic parameters developed by the US Geological Survey (USGS) for their regional models of the Pamet and Chequesset Lenses (Guswa and LeBlanc, 1985; Masterson and Barlow, 1994). Modeling information developed by the National Park Service was also considered (Martin, 1993). An additional layer was added to the top of the model to accommodate comparison between simulated and observed vertical gradients beneath the Pamet River.

The 16.5 mi^2 modeled area is subdivided into a grid of rectangular cells arranged in 64 rows and 57 columns (Figure 14). Cell dimensions range from a minimum of 300 by 300 ft to a maximum of 1,250 by 1,250 ft. Grid spacing is smallest near the Pamet River so that the detailed field data collected in this area can be utilized in the calibration of the model and so groundwater interactions in this area can be accurately simulated.

Hydraulic Parameters

Hydraulic conductivity is a parameter that describes the ability of a material to allow water to flow through it. Hydraulic conductivity is expressed in units of length/time (ft/day in the model) and higher values are assigned to sands and gravel and lower values to clays and peat (Freeze and Cherry, 1979). Hydraulic conductivity in the vertical direction is represented in groundwater models by a derivative of hydraulic conductivity called vertical conductance (units of ft^{-1}), which describes the hydraulic conductivity between layers of the model.

Hydraulic conductivities and vertical conductances for the upland portions of the model primarily correspond to values determined in previous investigations by



EXPLANATION

○ inactive area of model

● areas of coastal discharge and constant groundwater level

+ areas of vertical stream seepage underneath streambed

+ areas of horizontal seepage along the perimeter of the marsh

N

⇧

half miles

Cape Cod Commission

Figure 14

Grid Area for Groundwater Flow Model

Guswa and LeBlanc (1985) and Masterson and Barlow (1994). In general, horizontal conductivities in the model range from 350 ft/day for coarse sand to 50 ft/day in areas of fine sand and ratios of vertical to horizontal hydraulic conductivity range from 1:3 for medium sand and gravel to 1:30 for fine sand (Masterson and Barlow, 1994). Horizontal hydraulic conductivities and vertical conductance generally decrease with depth in the model. Marsh sediments were assigned a hydraulic conductivity of 0.5 ft/day to represent the generally low conductivity of clay and peat sediments (Freeze and Cherry, 1979).

Existing Pumping

Groundwater is pumped at the Paul Daley, Knowles Crossing, and North Truro Air Force Base (NTAFB) municipal wells in the northern portion of the Pamet Lens. Pumping rates of 0.6 million gallons per day (Mgal/day) for the Paul Daley well and 0.1 Mgal/day for the NTAFB well were simulated in the fourth layer from the top of the model. A 0.1 Mgal/day pumping rate from Knowles Crossing was simulated in layer 3. Return flow between Route 6 and Route 6A accounts for 16% of the total amount of pumped water. The remaining 84% is transported outside the modeled area to provide drinking water to Provincetown and North Truro. No provision was made in the model to account for the pumping of private wells because on-site septic systems are assumed to return an equivalent volume of water to the same parcel.

Boundary Conditions

In order to run a groundwater model, conditions along the periphery of the modeled area need to be selected. These parameters are called boundary conditions. Poorly chosen boundary conditions can result in the selection of inaccurate aquifer parameters during the calibration of the model and faulty simulation results. The boundary conditions discussed below were chosen to represent average annual conditions within the flow system.

The bottom boundary of the model is defined by the interface between freshwater and saltwater saturated sediments. The depth to the interface was estimated using the Ghyben-Herzberg relationship that each foot of groundwater above mean sea level corresponds to an equivalent 40 feet of groundwater below mean sea level. Flow across the interface is assumed to be insignificant and is modeled as a no-flow boundary.

The southern boundary of the modeled area approximates the top of the groundwater divide on the Chequesset Lens. Groundwater to the north of this divide is assumed to flow toward the Pamet River and groundwater to the south is assumed to flow toward Herring River system in Wellfleet. This is called a no-flow boundary because groundwater never flows across the divide. In the natural system, however, the location of the divide may shift in response to seasonal changes in recharge to the water table.

The model boundaries on the east and west are the Atlantic Ocean and Cape Cod Bay, respectively. Groundwater discharge is assumed to occur along the edge of coastline in the model. Because these coastal discharge areas exhibit only minimal changes in groundwater levels, the cells in the model representing these areas are assigned constant groundwater levels. The assigned water levels have been converted to equivalent freshwater levels because the discharging groundwater is overlain by saltwater. Pilgrim Lake defines the northern boundary of the model and is also modeled as an area of constant water level.

The inland area of the upper surface of the model is bounded by the water table and areas of stream discharge. The modeled area annually receives about forty inches of precipitation, approximately half of which is assumed to reach the water table. The low hydraulic conductivity of marsh sediments, high rates of evapotranspiration from marsh vegetation, and high potential for surface water runoff diminish recharge in marsh areas.

Stream drainage of groundwater within the modeled area occurs at Pamet River, Mill Pond, Little Pamet River, and Salt Meadow. The volume of discharge to these streams depends on the hydraulic gradient between the streams and surrounding aquifer, hydraulic properties of the surrounding sediments, and the elevation and geometry of the stream channel. The hydraulic conductance of streambed sediments is a parameter in the model which represents a wide assortment of stream-aquifer characteristics. Streambed conductance is calculated for each cell containing a reach of stream by the relationship $C = KLW/T$ where K is the hydraulic conductivity of streambed sediments (ft/day), W is the width of the stream channel (ft), L is the length of river in the cell (ft) and T is the thickness of the streambed sediments (ft). The altitude of the streambed of the Pamet River east of Route 6 was assigned a uniform value of 0.2 ft NGVD based on survey information collected by the ACOE. The hydraulic conductivity of streambed sediments were assumed to equal that of the surrounding marsh sediments.

Model Calibration

Calibration is a process in which model parameters are adjusted within reasonable ranges until the simulated results of the model match actual observations made in the field. The study area model was calibrated to water levels taken at 27 observation wells, streamflow in the Pamet River at Route 6, and vertical gradients below the streambed measured near Route 6 and Ballston Beach (see Figures 9 and 10). Because the modeled area combines information from two previous models of the Pamet and Chequesset Lenses and new information collected near the Pamet River, statistical comparisons of simulated and observed water levels were conducted separately for the Pamet Lens, Chequesset Lens, and Pamet River areas of the model (see Appendix III for modeling documentation).

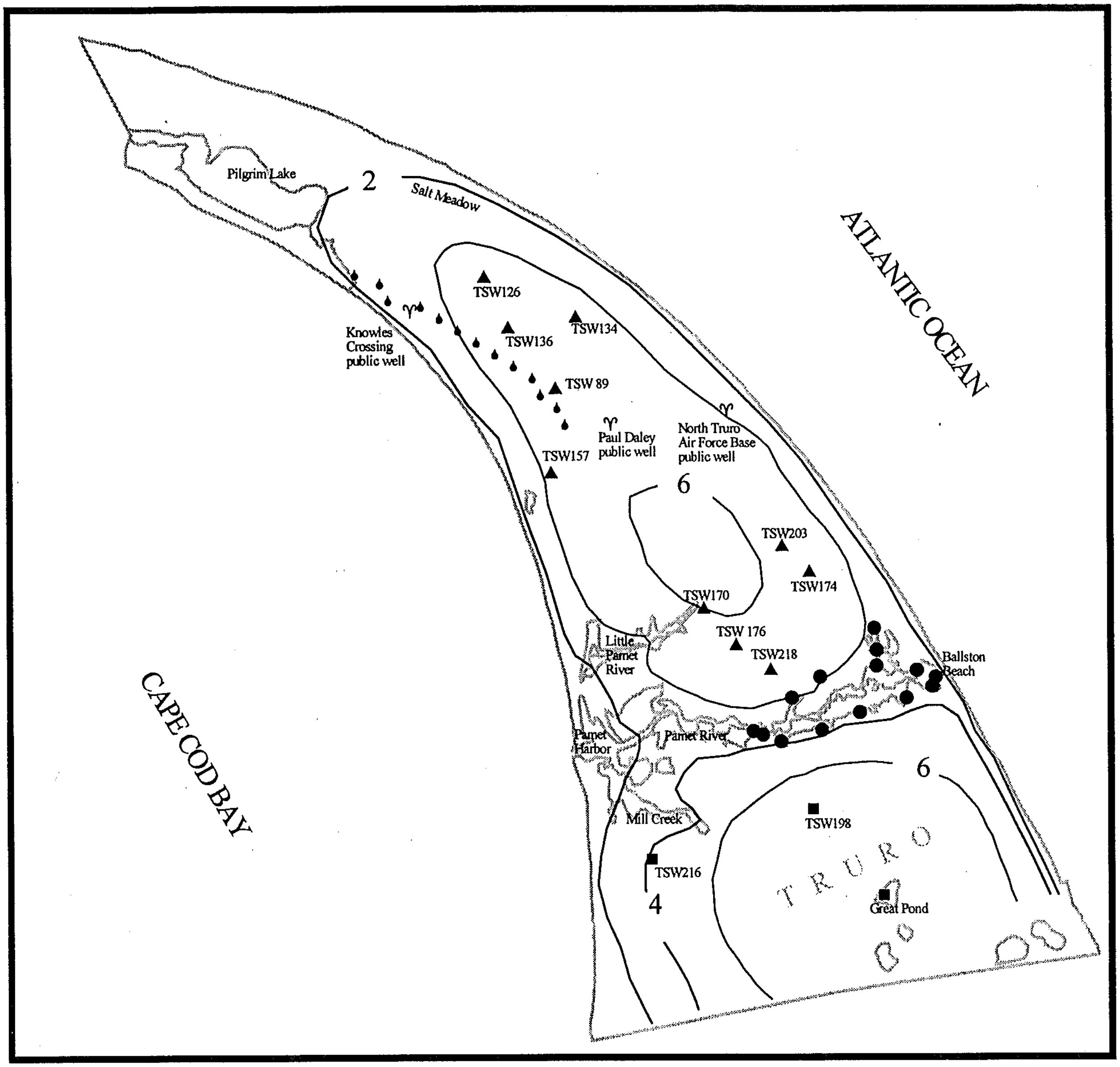
The model was calibrated by adjusting various parameters and boundary conditions. It was initially assumed that groundwater discharge occurred primarily as vertical seepage through the bottom of streambed sediments underlying the Pamet River. However, this conceptual design of the model consistently underestimated streamflow by more than half of observed and historical (Lewis, 1989) values. Review of aerial photographs and visual observation of surface flows entering the river though mosquito ditches and other surface drains suggested that these may be important contributors to the observed streamflows in the river. A random measurement of one seepage ditch on South Pamet Road found flows ranging between 0 and 0.6 cfs.

Based on these observations, a horizontal seepage component along the entire perimeter of the marsh was added to the model at 2.5 ft NGVD. The groundwater which drains off the aquifer as a result of this seepage component was assumed to directly discharge into the river. The ratio of seepage conductance along the marsh perimeter to seepage conductance beneath the river was assumed to be 60:1 to reflect the higher hydraulic conductivity of sandy sediments at the perimeter of the marsh.

Other efforts to calibrate the model to more closely match observed streamflow included increasing the initial estimates of recharge in non-marsh areas of the model from 20 in/yr to 23 in/yr and increasing initial estimates of recharge in marsh areas of the model from 0 in/yr to 8 in/yr. Hydraulic conductivity of the uppermost layer was uniformly increased by thirty percent (30%) and vertical conductances of the lower six layers in the southern portion of the model were reduced by an order of magnitude to more closely match observed water levels. A map of the resulting simulated water table is shown in Figure 15.

There is generally close agreement between observed and calculated water levels, streamflow at Route 6, and vertical gradients below the streambed. The mean error between the absolute value of observed water levels minus simulated water levels in observation wells located in the Pamet and Chequesset Lenses is 0.4 ft, which corresponds to between 5 and 9% of the maximum and minimum water levels in these portions of the modeled area, respectively. The mean error of the observed water levels minus simulated water levels in observation wells located near the Pamet River is 0.6 ft, which corresponds to between 12 and 22% of water levels in this portion of the modeled area. The higher mean error in the Pamet River area is likely due to observed water levels in the area being approximately 0.5 ft above the average annual conditions the model was developed to represent (see Figure 7).

Field measured streamflow at Route 6 range from 4 to 6 cfs in this and previous investigations. The model simulates an annual average streamflow of 3.7 cfs at Route 6 and an annual average streamflow of 5.8 cfs for the entire Pamet River. As discussed above (Stream Flow Measurements section), corresponding estimated streamflows based on 1.5 ft of annual recharge on the Upper Pamet River and whole



EXPLANATION

- model simulated water table
- observation well near Pamet River
- observation well in Pamet Lens
- observation well in Chequesset Lens
- existing public supply wells
- areas of return flow

Figure 15

Simulated Water Table Map

N

half miles

Cape Cod Commission

Pamet River watersheds are 3.0 and 6.3 cfs, respectively. The modeled and recharge method streamflow estimates show good agreement, but they are between 8 and 50% less than the streamflow measurements at Route 6 collected for this study. These differences were examined during the sensitivity analysis of the model.

A water budget of the model was developed to account for the various water flows with the modeled area (Table 6). This analysis in the upper Pamet River also showed that approximately eighty-five percent (85% or 3.1 cfs) of total flow in this portion of the model originates as seepage along the perimeter of the marsh and fifteen percent (15%) originates as vertical seepage through the bottom of the main channel. This difference accentuates the importance of the surface drains along the margins of the marsh to the observed flow within the river.

Table 6. Simulated Water Budget.

Water Budget Item	freshwater flow (cfs)	percentage (%) of total model discharge
MODEL INFLOW		
recharge	26.6	99.4
wastewater return flow	0.2	0.6
MODEL OUTFLOW		
COASTAL DISCHARGE:	18.8	70.1
Pamet Harbor	1.4	5.1
Ballston Beach	0.6	2.1
all other coastal areas	16.8	62.9
STREAM DISCHARGE:	6.8	25.1
Upper Pamet River	3.7	13.8
Lower Pamet River	2.1	7.7
Mill Pond creek	0.4	1.6
Little Pamet	0.4	1.6
Salt Meadow	0.2	0.6
PUBLIC WELLS	1.2	4.6
MODEL ERROR	0.0	-0.1

Sensitivity Analysis

Following calibration of the model, a sensitivity analysis was completed to determine which model parameters and boundary conditions exhibit the greatest control on the response of simulated water levels, streamflow, and vertical gradients below the streambed. This analysis was done because model parameters (such as hydraulic conductivity, vertical conductance, and streambed conductance) and boundary conditions (such as recharge and depth to the saltwater interface) are best estimates of the actual parameters and conditions, but they are still estimates. This type of analysis can also be used as a guide for prioritizing future data collection to improve characterization of the system. Parameters and boundary conditions were uniformly adjusted across the range of values reported below in Table 7 and the model was run a number of times to measure its sensitivity to these adjustments.

Table 7. Parameter Ranges and Boundary Conditions Adjusted in the Sensitivity Analysis of the Groundwater Model.

MODEL PARAMETER	CALIBRATED VALUE	SENSITIVITY RANGE
hydraulic conductivity of wetland	0.5 ft/day	0.005 to 50
vertical conductance of wetland	0.008/day	0.001 to 1
elevation of perimeter of marsh seepage	2.5 ft	0.5 to 4.5
hydraulic conductivity of seepage along marsh perimeter	50 ft/day	0.5 to 500
hydraulic conductivity of layer 1	variable	multiplied by 0.001 to 100
vertical conductance between layers 1 and 2	variable	multiplied by 0.001 to 100
recharge in non-marsh areas	23 in/yr	12 to 35
recharge in marsh areas	8 in/yr	0 to 23
hydraulic conductivity of layer 7	variable	multiplied by 0.01 to 100
vertical conductance between layers 6 and 7	variable	multiplied by 0.01 to 100
depth to saltwater interface	40:1 ratio	30:1 to 50:1

Simulated water levels are most sensitive to removal of horizontal seepage along the perimeter of the marsh. When removed, simulated streamflow at Route 6 decreases to 1.1 cfs. Stream flow increases to 3.5 cfs in this same configuration when areas modeled as marsh are replaced with areas with hydraulic parameters representative of coarse sand. However, this adjustment is contrary to field observations of low permeable sediments throughout the marsh areas and at depth beneath the river.

Water levels in all areas of the model and streamflow are also sensitive to the vertical conductance between layers 1 and 2 in non-marsh areas, recharge to non-marsh areas, the depth of the saltwater interface, and the altitude that seepage occurs along the perimeter of the marsh. Simulated streamflow in the Pamet River increased by 59% (to 5.88 cfs) when recharge was increased by 50% (to 34.5 inches/yr) and increased by 51% (to 5.59 cfs) when the vertical conductance between layers 1 and 2 was reduced by three orders of magnitude. Since groundwater seeps in the river bottom were observed and estimated as approximately 10% of the river bottom, a model configuration assigning 10% of the layer 1 cells a higher streambed conductance was also evaluated. This configuration had negligible effect on the resulting stream flows in the calibrated simulation.

Streamflow increased by 22% (to 4.51 cfs) when the depth of the saltwater interface was reduced by 25% (from 40 ft to 30 ft for every foot of groundwater above NGVD). Streamflow increased 23% (to 4.55 cfs) when the altitude of seepage along the perimeter of the marsh was lowered 2 feet (from 2.5 to 0.5 ft NGVD). The reduction in the depth to the saltwater interface is contrary to the observations at PW-3 and other wells in the Pamet Lens. It should be noted that adjustments in the above parameters to increase stream flow decreased the accuracy of the calibrated simulation considerably by over-predicting the water levels throughout the watershed (*i.e.*, the differences between observed and modeled water levels increased).

Simulated vertical gradients beneath the Pamet River are most sensitive to the altitude that seepage occurs along the perimeter of the marsh, the hydraulic conductivity of the marsh, and the vertical conductance between the marsh sediments and layer 2. All aspects of the model were relatively insensitive to the adjustment of hydraulic properties at depth.

Data Collection Recommendations based on Groundwater Modeling
Since the model predicted flows in the Pamet River lower than observed flows, further characterization of the various aspects of the Pamet River system is warranted to improve the precision of the model. Characterization of freshwater flow to the Pamet River can be improved by measuring the freshwater flow contribution from mosquito ditches and other surface tributaries, the altitude of the tributaries and the thickness of the underlying marsh sediments (if any), and measuring streamflow at several stations along the entire length of the river. Measurement of streamflow along the length would help in characterizing the groundwater interactions along different portions of the river. Further characterization of freshwater discharge from the Pamet River and other streams in the modeled area can also be improved with more precise estimates of the amount and seasonal variability of precipitation and recharge and the depth and thickness of the interface between freshwater and saltwater saturated sediments.

Analytical Tidal Rise Model

In a previous study of the Sagamore Marsh, the USGS assessed the potential impact on groundwater levels resulting from an increase in tidal flow (Walter, *et al.*, 1995). The USGS utilized an analytical model developed by Ferris (1963) to complete this assessment. The analytical model uses the following equation and a known range of surface water levels to predict a range of groundwater levels at a specified distance from a tidal channel:

$$\log \frac{Rgw}{Rsw} = -0.77x\sqrt{\frac{1}{\alpha t}}$$

Rgw is the range (ft) of groundwater levels in an observation well, *Rsw* is the range (ft) of surface water levels in the channel or tidal body, x is the distance (ft) of the groundwater observation well from the tidal channel; t is the period (days) of the tidal cycle; and α is the aquifer diffusivity (ft^2/day). Diffusivity is defined as the transmissivity (T) divided by the storage coefficient (S). The storage coefficient is defined as the volume of water that flows from a volume of an aquifer due to a change in water levels (Freeze and Cherry, 1979). Transmissivity is defined as the hydraulic conductivity times the thickness of the aquifer. Figure 16 presents a schematic representation of the variables involved with the analytical model.

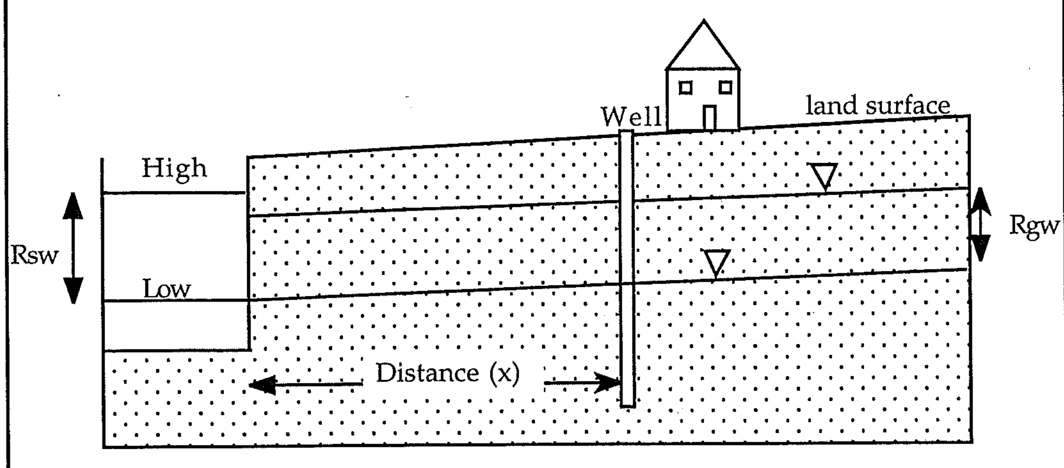


Figure 16. Schematic Explanation of Analytical Tide Rise Model.

To calculate the diffusivity of the Upper Pamet marsh, staff utilized the groundwater and tidal fluctuations measured at monitoring well PR-2s (R*gw* = 0.4 ft) and stream gauge PSW-2 (R*sw* = 0.65 ft), respectively. PR-2s is approximately 5 ft from the tidal channel and the tidal period is 0.51 days. A diffusivity of 654 ft^2/day is calculated using these input parameters in the analytical model. Walter and his coauthors (1996) determined diffusivities of 170 and 380 ft^2/day at two sites in the Sagamore Marsh.

The ACOE has utilized UNET, a one-dimensional, finite-difference model, to conduct a preliminary assessment of the expected tidal ranges within the Pamet River. The ACOE modeled the potential rise in water elevations at Wilder Dike, the east side of Route 6, and at Ballston Beach under existing conditions, with the removal of the tidal gate, and with the tidal gate removed and an open channel through Wilder Dike and Route 6 (Table 8). The model predicts a 0.9 ft increase in the river level at Ballston Beach and a 2.4 ft increase at the Route 6 culvert with the removal of the tidal gate and an opening of a channel under Wilder Dike and Route 6. At Wilder Dike, the mean high water mark is predicted to decrease by 0.4 ft under the same conditions (see Table 8).

Table 8. Predicted Changes in Stage Elevations within the Upper Pamet River.

CONDITION	WATER ELEVATION (FT)			
	PAMET HARBOR	WILDER DIKE	EAST OF ROUTE 6	PAMET RIVER AT BALLSTON BEACH
Existing	5.3	5.2	2.2	3.0
Tidal gate removed	5.3	5.2	2.7	3.2
Tidal gate removed and an open channel through Wilder Dike and route 6	5.3	4.8	4.6	3.9
Note: Elevations are at mean high water mark NGVD.				

Using the calculated diffusivity of 654 ft^2/day, the two increases (0.9 and 2.4 ft) in the range of river water elevations, and the calculated diffusivity of 654 ft^2/day, the analytical model was used to determine the predicted rise in water levels at various distances from the river channel (Figure 17). These results show that at a distance of 46 ft from the river channel at Ballston Beach and 56 ft from the river channel at Route 6, the range of groundwater fluctuations would be 0.01 ft. Thus, the expected rise in river water elevations should have a decreasing impact on groundwater fluctuations as one moves away from the river and as one travels towards the east along the Pamet River. In addition, since the minimum difference between a house and the river channel is 500 ft, the maximum predicted tidal range (2.4 ft) should have no measurable impact at this distance. This attenuation of the tidal range is due to the low permeability peat layer within the marsh, which acts as a buffer to the tidal fluctuations occurring in the river.

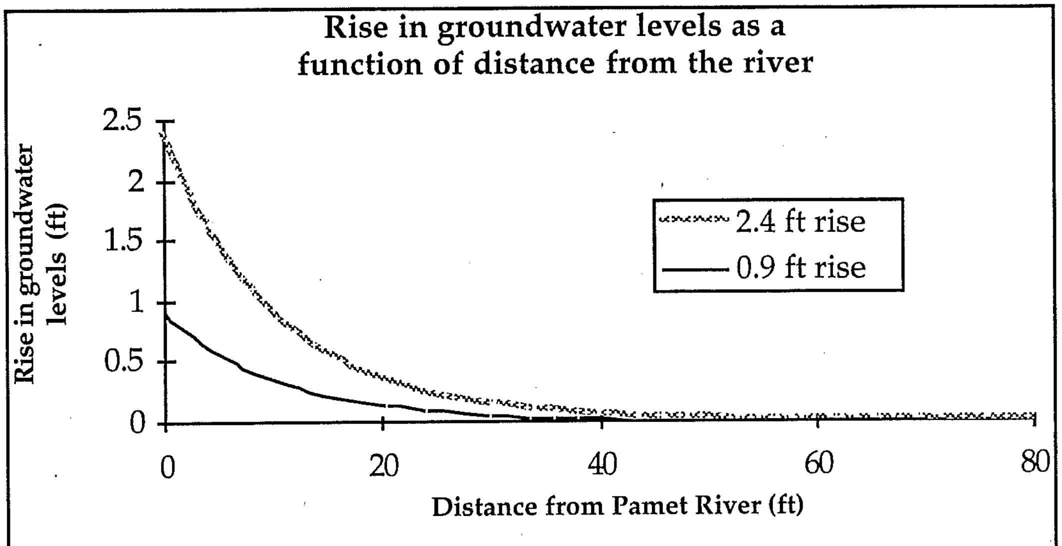


Figure 17. Predicted Rise in Groundwater Levels in Pamet Marsh

The results of the analytical model are dependent on the selection of an appropriate diffusivity of the marsh sediments. Within the Sagamore Marsh study area, diffusivity values ranged from a 275 ft^2/day average for marsh sediments to 2.25 x 10^5 ft^2/day for sand and silt sediments (Walter, *et al.*, 1996). An increase in the diffusivity value corresponds to an increase in the hydraulic conductivity of the sediments. Thus as diffusivity increases, the difference between the tidal fluctuations and the tidal-induced groundwater fluctuations approaches zero.

The calculated diffusivity for the Upper Pamet Marsh was determined to be 654 ft^2/day. Using this diffusivity value and either of the predicted surface water rises (0.9 ft at Ballston Beach and 2.4 ft at Route 6), less than 0.01 ft of groundwater rise is predicted at a distance of 500 ft from the river at either location. If a diffusivity for sand (2.25 x 10^5 ft^2/day) is used, the predicted groundwater rises at a 500 ft distance increase to 0.07 ft and 0.18 ft, respectively (Figure 18). With the higher diffusivity value and the higher surface water, at a distance of 1,000 ft, the rise in groundwater levels is predicted to be 0.01 ft. Thus, even with a much better hydraulic connection between the river and the surrounding materials, the predicted fluctuations in water levels are less than the historic fluctuations (~ 1.8 ft) in groundwater levels in the area (see TSW discussion). Figure 18 presents the predicted impact on groundwater levels at a distance of 500 feet from the river channel with various diffusivity values.

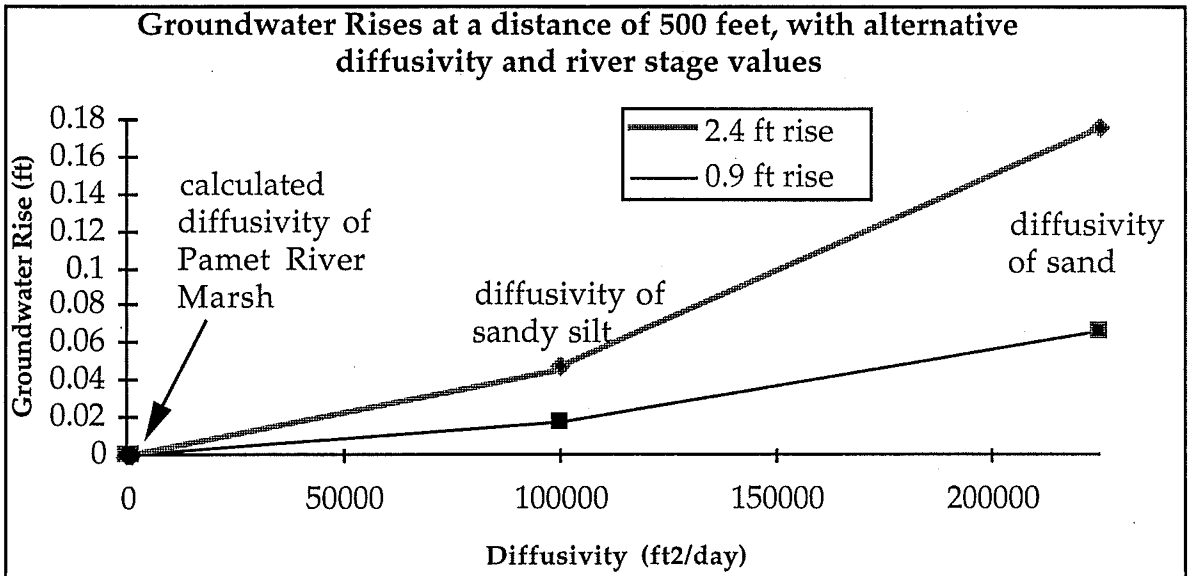


Figure 18. Sensitivity Analysis for Analytical Groundwater Rise Model

V. CONCLUSIONS

Water level measurements in the Pamet River valley indicate that the Pamet River is a discharge area for the Pamet and Chequesset groundwater lenses. Significant upward gradients toward the river have been observed at both local and regional scales. Groundwater modeling based on the collected hydrogeologic information suggest that the marsh surrounding the Pamet River serves to isolate the river from all but limited direct contact with the aquifer underlying the marsh. Modeling results indicate that 85% of the river discharge comes from surface water drains (*i.e.*, mosquito ditches) of the surrounding aquifer that flow across the top of the marsh and discharge into the river. Field observations combined with modeling results suggest that the remaining 15% of the river flow comes from direct groundwater discharge through highly conductive portions of the river bottom.

Analysis of water levels in the river suggest that relatively constant groundwater levels (~ 3 ft NGVD) are maintained at the eastern end of the Pamet River with fluctuations of ~ 1 ft at the Route 6 culvert. The nearly constant water levels near Ballston Beach cause the river to flow toward Route 6 during both high water and low water conditions near Wilder Dike. Tidal modeling of possible water level fluctuations within the river by the ACOE suggest that if the clapper valve at Wilder Dike and flow restrictions under the Route 6 culvert are removed, water levels near Ballston Beach will increase by 0.9 ft, while water levels near Route 6 will increase 2.4 ft.

This study used these modeling results to evaluate the impact of removing the clapper valve on groundwater levels. The analytical model used to evaluate the impact predicted minimal impacts (< 0.01 ft) on the range of groundwater fluctuations at the nearest (~ 500 ft from the river) wells and septic systems. The model suggests that water levels at wells and septic systems greater than 500 ft from the river will experience even less change in groundwater fluctuations.

These results indicate that the limited flow characteristics of the peat in the marsh system surrounding the Upper Pamet River cause tidal ranges within the river to have minimal effect on groundwater levels in the Upper Pamet River valley. In addition, the significant thickness of the aquifer system (greater than 150 ft in the middle portion of the Upper Pamet River valley) and upward groundwater gradients suggest that salt water flow from the river into the surrounding groundwater lenses will be prevented.

VI. RECOMMENDATIONS

Although this report has determined that there will be insignificant impacts on groundwater levels surrounding the Pamet River from increased tidal activity in the Upper Pamet, additional data collection and analyses are necessary to better understand how groundwater flows into the river, to quantify the magnitude of the river/aquifer system interactions with the underlying saltwater interface, and to determine how improvement in tidal interaction in the Upper Pamet might affect draining of salt water from the system during the next overwash of Ballston Beach. The following recommendations address these concerns:

1) Establishment of a long term stream flow monitoring program with a measuring point at Wilder Dike and various points within the river. This data will help to establish the variability of river flows and groundwater discharge along the river.
2) Incorporation of the above recommended data into the groundwater model and introduction of variable density capability into the model to simulate the potential movement of the saltwater interface.
3) Coordination of an iterative design analysis process between the groundwater model and a surface water model, which includes tidal influences, to better understand the impacts of surface water flows on groundwater levels and vice-a-versa.
4) Establishment of an overwash response plan to facilitate the removal of saltwater following the overwash of Ballston Beach. Prior to the establishment of a long term management plan for the Upper Pamet River, a plan should be established to hasten the draining of overwashed saltwater from the Upper Pamet.

REFERENCES

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Fitterman, D.V. and K.F. Dennehy. 1992. Verification of Geophysically Determined Depths to Saltwater Near the Herring River (Cape Cod National Seashore), Wellfleet, Massachusetts. Boston: National Park Service. Technical Report NPS/NAROSS/NRTR-92/05.

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Lewis II, R.G. 1989. A presentation of data collected during the summer of 1988 concerning tidal characteristics and pollution in the Pamet River Basin. Parsons Laboratory, MIT, Cambridge, MA.
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Masterson, J.P. and P.M. Barlow. 1994. Effects of Simulated Ground-Water Pumping and Recharge on Ground-Water Flow in Cape Cod, Martha's Vineyard, and Nantucket Island Basins, Massachusetts. US Geological Survey Open-File Report 94-316. US Geological Survey, Marlborough, MA.
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Appendix I: Annotated Bibliography

Annotated Bibliography of Studies of the Pamet River and associated areas

Cambareri, T.C., G. Belfit, and D.S. Janik. 1989. Hydrogeologic Assessment of the Truro Landfill, Truro, Massachusetts. Cape Cod Planning and Economic Development Commission, Barnstable, MA.

Detailed water-table maps for the Pamet and Chequesset Lenses were completed. The study identified potential municipal supply well sites within the lenses. Additional aspects of the study address zones of contribution for existing municipal supply wells and nitrogen loading analysis for existing wells.

Fitterman, David V., and Kevin F. Dennehy. 1992. Verification of Geophysically Determined Depths to Saltwater Near the Herring River (Cape Cod National Seashore), Wellfleet, Massachusetts. Boston: National Park Service. Technical Report NPS/NAROSS/NRTR-92/05. July.

Identified possible impacts on domestic water wells caused by adjustments to the tidal control structure on the Herring River in Wellfleet, MA. Electromagnetic measurements, water conductivity data, and inductions logs were utilized to predict the location of the saltwater-freshwater interface, which was found approximately 13 to 29 meters below the water table. Adjusting the tidal flow into the upper portions of the Herring River is predicted to have negligible impacts on domestic wells. An increase in tidal flow within the Herring River will cause only a minor rise (~ 0.5 m) in saltwater levels.

Giese, G.S., and C.T. Westcott. 1980. Pamet River: A study of shoaling erosion problems with recommendations for management. Provincetown: Provincetown Center for Costal Studies. No. 80-2.

Report on historical changes within Pamet Harbor. Predicts a 20% increase in the tidal prism with the removal of dike structures in the Lower Pamet. Within the Upper Pamet River, the tidal range was predicted to be 2 feet. Report recommends a management program to increase the navigability of the Harbor and to protect and further develop the barrier beach on the northern edge of the Pamet inlet.

Giese, G.S., C.T. Friedrichs, D.G. Aubrey, and R.G. Lewis, II. 1990. Application and assessment of a shallow-water tide model to Pamet River, Truro, MA.: Woods Hole Oceanographic Institute.

Finite-difference numeric models were used to predict the change in tidal prism after the removal of tidal structures at Wilder's Dike on the Pamet River. Less than a five percent (5%) increase the tidal prism was predicted. Because only the removal of one dike structure was considered, further studies are recommended to predict the impacts of complete removal of all dike structures within the system.

Horsley & Witten. 1994. Final Report: Pamet Harbor management plan. Barnstable: June.

Plan to restore the usefulness of Pamet Harbor as a navigational channel for recreational boats and small commercial fishing boats. The Plan recommends dredging the Harbor to enhance navigation, water quality, and beach replenishment,

while at the same time protecting the natural resources of the harbor.

Lewis II, Richard G. 1989. A presentation of data collected during the summer of 1988 concerning tidal characteristics and pollution in the Pamet River Basin. Cambridge: Parsons Laboratory MIT. February.
Data collected on the Pamet River's hydrology is the first phase of a three year project. Salinity, tidal flow and tidal elevation were taken during the summer of 1989. Data used by Giese *et. al.* (1993) for numeric tidal modeling of the Pamet.

Masterson, John P., and Paul M. Barlow. 1994. Effects of simulated ground-water pumping and recharge on ground-water flow in Cape Cod, Martha's Vineyard, and Nantucket Island Basins, Massachusetts. : U.S. Geological Survey Open-File Report 94-316. U.S. Geological Survey, Marlborough, MA.
The report reviews the regional hydrology, geology, and research work within the Cape Cod Basin. Historic, current, and projected water demand issues are discussed. MODFLOW based models are used to simulate the effects of groundwater pumping on water table elevations, pond elevations, and the saltwater/freshwater interface. The models, which include models of the Chequesset and Pamet lenses, can be customized by users to address specific pumping conditions.

McDonald, M.G., and A.W. Harbaugh. 1988. A modular three-dimensional finite-difference ground-water-flow model. U.S. Geological Survey Techniques of Water Resources Investigations book 6 (Chap. A1): 586.
Outlines the development and operation of MODFLOW, a three-dimensional, finite-difference, single-fluid flow model. MODFLOW is capable of simulating changes in groundwater level and flow under transient and steady state conditions.

Pamet River Workshop. 1993. Discussion for long term management. Proceedings from the Pamet River Workshop, March 18, at Cape Cod National Seashore, Marconi Station Headquarters.
Conference coordinated to address issues related to overwash of Ballston Beach during the winter of 1991. Various scientists and town officials discuss potential impacts and recommended efforts to cope with future overwashes. Conference attendees suggest a detailed hydrogeologic study of the area is necessary to predict possible impacts of overwashes and any mitigative measures that might be taken to reduce flooding to the River system.

Provincetown Center for Coastal Studies. 1979. Summary Report of a Study of Pamet Inlet. Provincetown: July.
A summary of the historical changes that have occurred within the Pamet River system. The study identifies human induced changes to the tidal flow patterns and land formations to the Lower Pamet, specifically the harbor area. Study recommends dredging of the Inner Harbor be undertaken to reduce shoaling. Dredged material should be used to "rebuild" the barrier beach and jetty on the northern side of the Pamet Inlet.

Robinson, Mark H. 1985. Opening Pamet: Possible changes due to reintroduction of tidal flow to Pamet River system.: February.
Discussion paper identifying the range of possible alternatives and consequences that must be addressed when considering the removal of the dike structure and tidal controls on the Pamet River. The paper highlights the need to include National Park Service support for any possible mitigative measures. Possible opponents to the dike removal are proposed to be landowners abutting the river and local officials and taxpayers if changes require an extensive outlay of local money.

Roman, C.T. 1987. A valuation of alternatives for estuarine restoration management: the Herring River ecosystem (Cape Cod National Seashore). New Brunswick, NJ: Center for Costal Studies- Rutgers. October.
Ecological and hydrological report on the Herring River System in Wellfleet, MA. Various research techniques were utilized to assess the current ecological conditions within the saltwater, brackish, and freshwater sections of the Herring River. Hydrological assessments were conducted on salinity levels, tidal flow, and the historical, current, and alternative tidal prisms.

Roman, C.T., R.W. Garvine, and J.W. Portnoy. 1995. Hydrologic modeling as a predictive basis for ecological restoration of salt marshes. *Environmental Management*. 19 (4): 559-566.
Research was conducted on the Herring River, Wellfleet, MA to determine the horizontal and vertical extent of tidal intrusion to a previously diked section of the river. Ecological assessments of the tidal and freshwater section of the river were undertaken to identify differences among vegetation and microinvertebrate populations. An one-dimensional model is presented to simulate the impacts of alternative tidal inflows on flood-prone areas and physical structures.

Truro Conservation Commission. 1993. The Pamet River: What is its future? Truro: February.
A discussion of the consequences related to the overwash at Ballston Beach during a December 1992 storm. The Conservation Commission presents a series of options available to cope with possible future overwashes. The 1992 storm flooded the Upper Pamet River with four feet of saltwater. The clapper valve was not equipped to drain this amount of water, causing extensive week-long floods in the area. The reports suggests more research is needed to identify all possible scenarios, including no future action impacts.

Walter, Donald A., John P. Masterson, and Paul M. Barlow. 1996. Hydrogeology and Analysis of Ground-Water-Flow System, Sagamore Marsh Area, Southeastern Massachusetts. US Geological Survey Water-Resources Investigations Report 96-4200. U.S. Geological Survey, Marlborough, MA.
Report predicting impact to a municipal drinking water supply well from potential increase and restoration of tidal flow within the Sagamore Marsh, Bourne, MA. Tidal flow to the marsh has been artificially restricted to a small culvert from the Cape Cod Canal. A numerical model was used to predict the contributing area to the supply well and the well will not be impacted by an increase in tidal flow to the marsh.

Appendix II. Drilled Well Logs

Boring No. PW-1

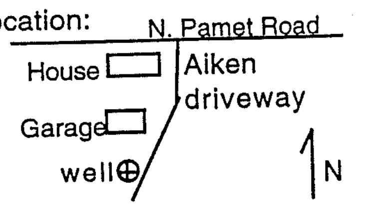
BORING LOG

Sheet 1 of 1

PROJECT	PAMET RIVER PROJECT- CCC/ACOE
LOCATION	Aiken Property
ELEVATION AND DATUM	
BORING CONTRACTOR	T. E. Desmond
DATE	5/20/96
COMPLETION DEPTH	50ft
BORING EQUIPMENT	Hollow Stem Screened Auger
OBSERVED WATER LEVEL DATA	~ 3.5 ft

ELEV.	DESCRIPTION	DEPTH SCALE (ft)	WELL DETAILS	SAMPLE NO.	REMARKS
	dark brown coarse/ medium sand	0		Bentonite Seal	~6 in. above ground, 2". PVC Sch. 40 with flush threaded joints, 5ft section of 10 slot screen, blue locking cover grouted in place with concrete, key # 3476
	tan coarse/medium sand, some gray	5			
	brown coarse/medium sand	10			150 umhos/cm,~10 gpm
		15			140 umhos/cm,~10 gpm
	tan coarse/medium sand, some gravel	20			90 umhos/cm,~10 gpm
		25			90 umhos/cm,~10 gpm
		30			140 umhos/cm,~10 gpm
		35			155 umhos/cm,~10 gpm
		40			165 umhos/cm,~10 gpm, orange water
	some gray mottling then back to tan	45			160 umhos/cm,~8 gpm,
	gray fine sand/silt	50	BOH		165 umhos/cm, ~2 gpm, tan cloudy water

Location:



INSPECTOR: Eichner/ Livingston

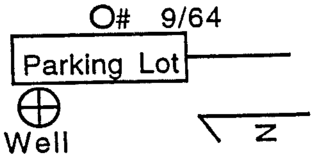
Boring No. PW-2

BORING LOG

Sheet 1 of 1

PROJECT: PAMET RIVER PROJECT- CCC/ACOE	
LOCATION: Ballston Beach Parking Lot	ELEVATION AND DATUM:
BORING CONTRACTOR: T. E. Desmond	DATE: 5/20/96 — COMPLETION DEPTH: 50ft
BORING EQUIPMENT: Hollow Stem Screened Auger	OBSERVED WATER LEVEL DATA: ~ 2 ft

ELEV.	DESCRIPTION	DEPTH SCALE (ft)	WELL DETAILS	SAMPLE NO.	REMARKS
	dark brown medium/ coarse sand	0	Bentonite Seal		~1 ft. above ground, 2" PVC Sch. 40, with flush threaded joints, 5 ft section of 10 slot screen, blue locking cover grouted into place with concrete, key # 3476
		5		no pump	
		10			37,000 umhos/cm, 25% salinity 19 degree C
	dark brown silt/fine sand, H2S smell	15			19,000 umho/cms, 13.5% salinity
		20			no pump
	LOCATION: Telephone Pole O# 9/64	25			600 umhos/cm, 1% salinity
		30			no pump
	dark brown fine/medium sand, gray fine sand in water	35			15,000 umhos/cm, 15% salinity ~15 gpm (good pump)
		40			23,000 umhos/cm, 19% salinity ~15 gpm (good pump)
	green water, brown fine sand gray fine sand in water	45			28,000 umhos/cm, 23.5% salinity ~15 gpm (good pump)
	brown medium/coarse sand some clay /small gravel	50			23,000 umhos/cm, 18% salinity (ok pump)
			BOH		INSPECTOR: Eichner/ Livingston



Boring No. PW-3 s and d

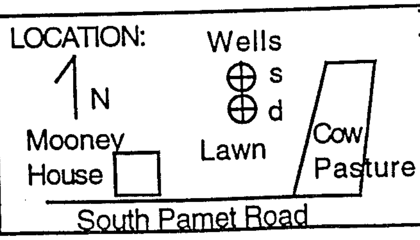
BORING LOG

Sheet 1 of 3

PROJECT	PAMET RIVER PROJECT- CCC/ACOE
LOCATION	Mooney Farm
ELEVATION AND DATUM	
BORING CONTRACTOR	T. E. Desmond
DATE	5/20-5/21
COMPLETION DEPTH	PW-3d 150ft, PW-3s 50 ft
BORING EQUIPMENT	Hollow Stem Auger (3s) Hollow Stem Screened Auger (3d)
OBSERVED WATER LEVEL DATA	~ 4 ft

ELEV.	DESCRIPTION	DEPTH SCALE	WELL DETAILS	SAMPLE NO.	REMARKS
	dark brown peat	0		Bentonite Seal	PW-3s and d: 2" PVC Sch. 40, with flush threaded joints, ~1' above grade, two 5' well screens, 10 slot, green locking covers grouted into place with concrete, key #3476, screened auger used only on 3d drilling
	interbedded peat and sand	5			
	dark brown fine/medium sand	10			
	dark brown medium sand	15			145 umhos/cm, 0% salinity, milky brown water
	brown coarse/medium sand with some gravel	20			140 umhos/cm, 0% salinity, milky orange/brown water, good pump
	tan coarse/medium sand with some gravel	25			118 umhos/cm, 0% salinity, milky orange/brown water, good pump
		30			
		35			90 umhos/cm, 0% salinity good pump, water color same
		40			
		45			90 umhos/cm, 0% salinity good pump, water color same, cleared a bit
		50		BOH	

LOCATION:



INSPECTOR: Eichner/ Livingston

Boring No. PW-3s and d

Sheet 2 of 3

BORING LOG

PROJECT: PAMET RIVER PROJECT- CCC/ACOE	
LOCATION: Mooney Farm	ELEVATION AND DATUM
BORING CONTRACTOR: T. E. Desmond	DATE: 5/20-5/21 — COMPLETION DEPTH: PW-3d 150ft, PW-3s 50 ft
BORING EQUIPMENT: Hollow Stem Screened Auger (3d)	OBSERVED WATER LEVEL DATA: ~ 4 ft

ELEV.	DESCRIPTION	DEPTH SCALE	WELL DETAILS	SAMPLE NO.	REMARKS
		55			90 umhos/cm, 0% salinity good pump, same water color
	tan coarse sand, some gravel	60			
		65			98 umhos/cm, 0% salinity poor pump, same water color
		70			
		75			100 umhos/cm, 0% salinity, poor pump
		80			
		85			95 umhos/cm, 0% salinity ~10 gpm, good pump
		90			
	tan, coarse sand with some gravel	95			88 umhos/cm, 0% salinity ~10 gpm, good pump
		100			
	brown medium/coarse sand, some silt				INSPECTOR: Eichner/ Livingston

Boring No. PW-3s and d

BORING LOG

Sheet 3 of 3

PROJECT: PAMET RIVER PROJECT- CCC/ACOE	
LOCATION: Mooney Farm	ELEVATION AND DATUM:
BORING CONTRACTOR: T. E. Desmond	DATE: 5/20-5/21
COMPLETION DEPTH: PW-3d 150ft, PW-3s 50 ft	
BORING EQUIPMENT: Hollow Stem Screened Auger (3d)	OBSERVED WATER LEVEL DATA: ~ 4 ft

ELEV.	DESCRIPTION	DEPTH SCALE	WELL DETAILS	SAMPLE NO.	REMARKS
	brown medium/coarse sand with some silt	105			85 umhos/cm, 0% salinity ~10 gpm, good pump
	tan coarse/medium sand with some gravel	110			
		115			90 umhos/cm, 0% salinity, ~10 gpm, good pump
		120			
		125			90 umhos/cm, 0% salinity, ~10 gpm, good pump
		130			
		135			99 umhos/cm, 0% salinity, ~10 gpm, good pump
		140			
		145			
		150		BOH	80 umhos/cm, 0% salinity, ~10 gpm, good pump

INSPECTOR: Eichner/ Livingston

BORING NO. TRU-3

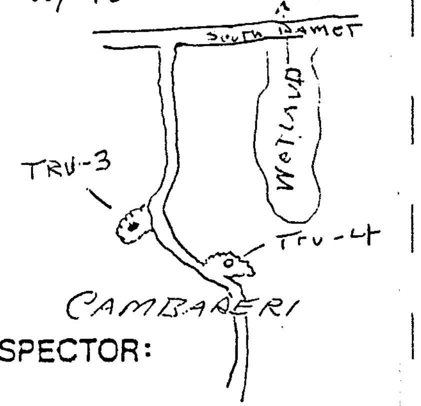
BORING LOG

SHEET 1 OF 1

PROJECT · Truro Landfill	PROJECT
LOCATION Fauk Driveway South off S. Pamet	ELEVATION AND DATUM
BORING CONTRACTOR T. E. Desmond	DATE 4/13/94 — COMPLETION DEPTH
BORING EQUIPMENT Screened Auger w/ Hollow Stem Auger	OBSERVED WATER LEVEL DATA

ELEV.	DESCRIPTION	DEPTH SCALE	WELL DETAILS	SAMPLE NO.	REMARKS
	DARK HUMIC				
	▽ COARSE BRN SAND				
		10			
	COARSE LHT BRN SAND			≈ 80 umho	10gpm
	COARSE-MED BRN SAND			≈ 78 umho	10gpm
		20			
				≈ 92 umho	Slow
		30		≈ 85, 82 umho	10gpm
				≈ 80 umho	5 gpm
		40		≈ 115 umho	3-2 gpm
				≈ 100 umho	5 gpm
		50			
	Very coarse and coarse med sand			≈ 110 umho	10gpm
		60		≈ 150 umho	10gpm
	DARK BRN VC-C SAND some grannuals			≈ 158 umho	3 gpm
		70			
	VC - C - M SAND			≈ 125 umho	3 gpm
	BoH			≈ 130, 115	3 gpm
		80			

One well 2" PVC w/ 10' screen, 10 slot



CAMBARERI

INSPECTOR:

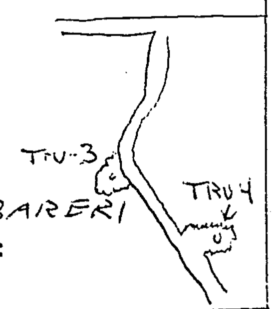
BORING NO. TRV-4

BORING LOG

SHEET 1 OF 1

PROJECT: Truro Landfill	PROJECT
LOCATION: Fauk Driveway South off S. Pamet Rd	ELEVATION AND DATUM
BORING CONTRACTOR: T. E. Desmond	DATE: 4/13/94 — COMPLETION DEPTH
BORING EQUIPMENT: Hollow Stem Auger	OBSERVED WATER LEVEL DATA

ELEV.	DESCRIPTION	DEPTH SCALE	WELL DETAILS	SAMPLE NO.	REMARKS
	DARK HUMIC SOIL				
	COARSE BRN SAND				
	M-C BRN SAND ▽	10	▽		
		20			
		30			
		40			
	C BRN SAND				
		50			
		60			
		70			
		80			
	BOH				
		90			One 2" PVC threaded joint pipe w/ 10' 10 slot screen



INSPECTOR: CAMBARERI

BORING NO. TRU-5

BORING LOG

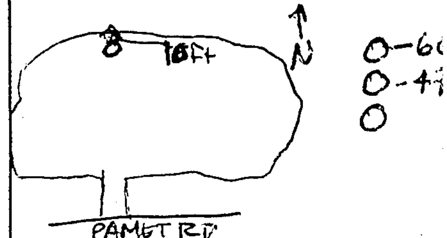
SHEET 1 OF 1

PROJECT: Truro Landfill	PROJECT
LOCATION: John Kelley (South Pamet Rd)	ELEVATION AND DATUM
BORING CONTRACTOR: T. E. Desmond	DATE: 5/13/94 — COMPLETION DEPTH
BORING EQUIPMENT: Screened Auger / Hollow Stem Auger	OBSERVED WATER LEVEL DATA: ~2 Ft

ELEV.	DESCRIPTION	DEPTH SCALE	WELL DETAILS	SAMPLE NO.	REMARKS
	DARK HUMIC SOIL		BENTON.		
	DARK BRN SAND M				
	BRN M SAND SOME FINES	10			≈ 60 μmhos
	GRAY M-F SAND				≈ 60 μmhos
	BRN M AND F SAND SOME C	20			
					≈ 122 μmhos
		30			≈ 122 μmhos
	BRN M-C SAND TRACE VC, F				
					≈ surge developed 15 gpm 1-3 Ft drawdown 122 μmhos
		40			
					155 μmhos ≈ 15 gpm
		50			
					170 μmhos ≈ 15 gpm
		60			
					139 μmhos ≈ 10 gpm
		70			
					106 μmhos
		80	BOH		

3 wells w/ 5 ft screens set @ 60, 47, & 20 Feet

2 inch SCH-40 PVC



INSPECTOR: CAMBARERI & EICHNER

Appendix III. Groundwater Model Documentation

Table A-1. Comparison of observed and simulated measurements for calibrated model

name of monitoring well	model row	model col	average measured water levels, in feet above sea level	Aug-96 measured water levels, in feet above sea level	model simulated water levels, in feet above sea level	residual of observed minus simulated, in feet
Pamet River Observation Wells						
TSW126	56	16	4.2	NA	4.5	-0.3
TSW136	53	16	4.3	NA	5.0	-0.7
TSW134	52	25	4.9	NA	4.6	0.3
TSW89	49	18	4.4	NA	5.1	-0.7
TSW157	45	14	4.4	NA	4.6	-0.2
TSW203	36	38	5.7	NA	5.5	0.2
TSW170	34	24	5.9	NA	6.1	-0.2
TSW174	33	40	5.6	NA	5.1	0.5
TSW176	30	26	5.6	NA	5.7	-0.1
TSW218	25	29	5.2	NA	5.1	0.1
standard error is -0.1 ft, absolute error is 0.3 ft, standard deviation is 0.4 ft						
Chequesset Lens Observation Wells						
TSW216	7	9	4.1	NA	4.9	-0.8
TSW198	6	26	7.6	NA	7.0	0.6
Great Pond	1	31	8.0	NA	8.0	0.0
standard error is -0.1 ft, absolute error is 0.5 ft, standard deviation is 0.6 ft						
Pamet River Observation Wells						
PR13	18	23	NA	2.7	2.0	0.7
PR2S	16	24	NA	3.1	2.6	0.5
PR17	15	26	NA	3.2	2.6	0.6
PR18	20	30	NA	5.0	4.1	0.9
TLF007	14	32	NA	4.3	3.9	0.4
TSW181	21	35	NA	4.8	4.3	0.5
PW3S	14	38	NA	4.5	3.5	1.0
PW1D	19	43	NA	4.0	3.2	0.8
TSW182	24	45	NA	4.9	3.9	1.0
PR8S	13	45	NA	4.2	3.4	0.8
PR10S	16	48	NA	3.1	3.0	0.1
PR4	13	49	NA	3.6	3.4	0.2
PR13	14	50	NA	3.3	3.0	0.3
standard error is 0.6 ft, absolute error is 0.6 ft, standard deviation is 0.3 ft						
Entire Set of Observation Wells						
standard error is 0.3 ft, absolute error is 0.5 ft, standard deviation is 0.5 ft						

NA - not available

Figure A-1. Graphical comparison of observed and measured groundwater levels

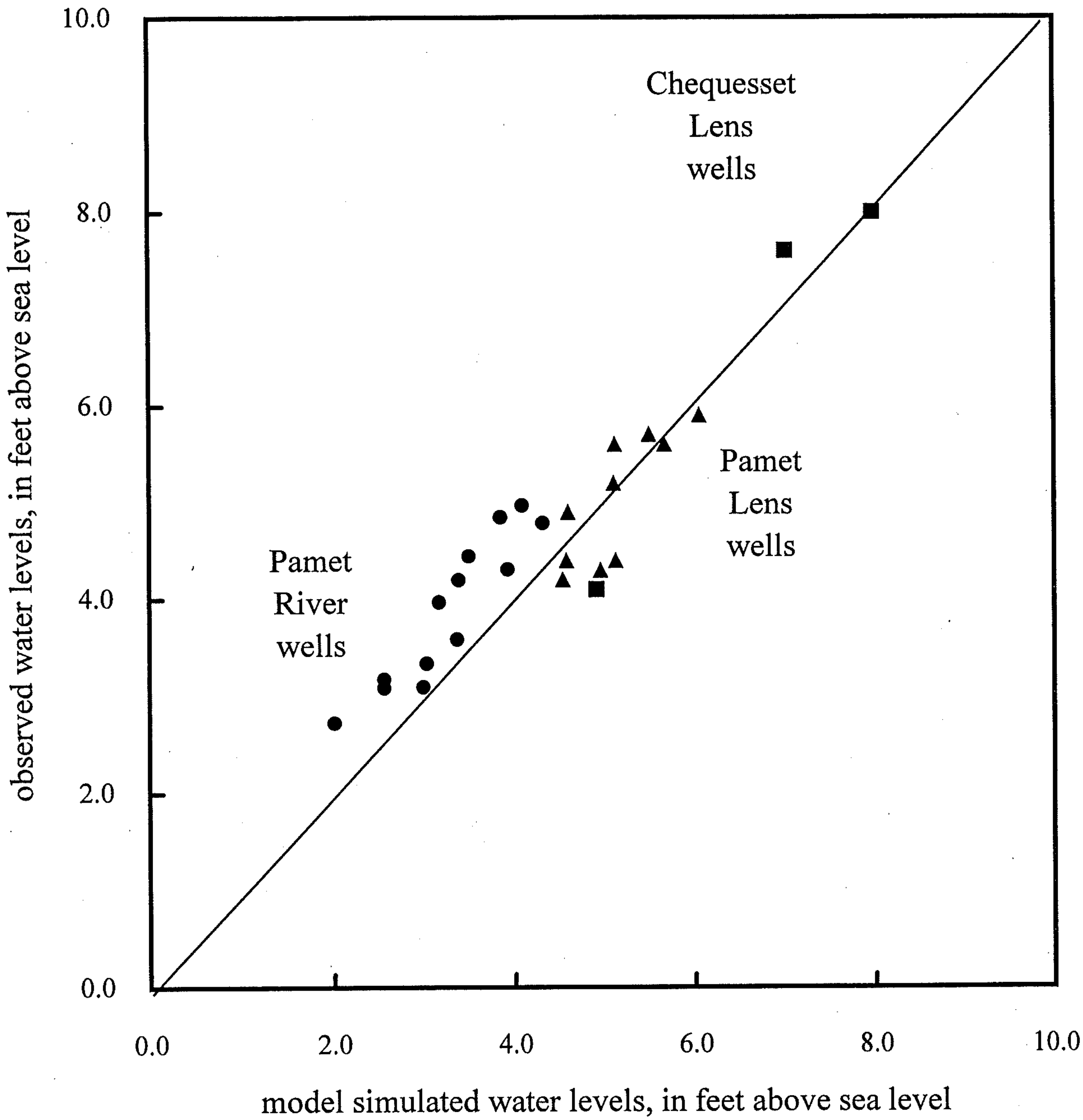


Table A-2. Sensitivity analysis of calibrated model

brief descriptions of how model was adjusted	statistical comparison of observed and simulated heads (observed - simulated)												flow at Rt 6 (cfs)	vertical gradient (ft/25 ft)
	Pamet Lens			Chequesset Lens			Pamet River			All				
	SE	AE	SD	SE	AE	SD	SE	AE	SD	SE	AE	SD		
calibrated model														
	-0.11	0.32	0.37	-0.07	0.47	0.57	0.60	0.60	0.28	0.25	0.48	0.50	3.68	1.49
hydraulic conductivity of wetland is fluctuated, calibrated value is .5 ft/d														
.005 ft/d	-0.24	0.37	0.36	-0.37	0.59	0.68	0.31	0.60	0.68	0.02	0.51	0.64	3.73	-0.34
.05 ft/d	-0.21	0.36	0.36	-0.31	0.57	0.66	0.37	0.57	0.56	0.06	0.49	0.59	3.72	0.03
.5 ft/d	0.00	0.35	0.40	0.19	0.45	0.48	0.81	0.81	0.43	0.43	0.59	0.58	3.58	2.49
50 ft/d	0.05	0.38	0.42	0.28	0.44	0.46	0.87	0.87	0.47	0.49	0.63	0.59	3.54	2.62
vertical conductance of wetland is fluctuated, calibrated value is .008 /d														
.001/d	-0.18	0.34	0.36	-0.23	0.53	0.63	0.63	0.63	0.42	0.22	0.51	0.59	3.70	2.70
.01/d	-0.10	0.32	0.37	-0.05	0.47	0.57	0.60	0.60	0.28	0.26	0.48	0.50	3.68	1.32
.1/d	-0.05	0.32	0.39	0.06	0.48	0.54	0.57	0.62	0.38	0.27	0.49	0.50	3.69	0.22
1/d	-0.04	0.33	0.40	0.08	0.48	0.54	0.56	0.63	0.41	0.27	0.50	0.51	3.69	0.02
elevation of overland seepage is fluctuated, calibrated value is 2.5 ft above sea level														
.5 ft	0.30	0.64	0.65	0.78	0.89	0.74	1.87	1.87	0.55	1.14	1.28	0.96	4.55	0.66
1.5 ft	0.10	0.46	0.49	0.36	0.68	0.66	1.25	1.25	0.38	0.70	0.88	0.72	4.12	1.07
3.5 ft	-0.32	0.41	0.34	-0.50	0.53	0.48	-0.06	0.27	0.31	-0.21	0.35	0.38	3.22	1.92
4.5 ft	-0.52	0.57	0.42	-0.94	0.94	0.38	-0.73	0.77	0.46	-0.68	0.71	0.46	2.73	2.34
hydraulic conductivity of overland seepage is fluctuated, calibrated value is 50 ft/d														
.5 ft/d	-0.57	0.63	0.47	-1.09	1.09	0.33	-0.94	0.95	0.69	-0.82	0.84	0.61	2.62	2.47
5 ft/d	-0.18	0.34	0.35	-0.23	0.48	0.54	0.37	0.37	0.28	0.09	0.37	0.45	3.54	1.64
250 ft/d	-0.10	0.32	0.38	-0.05	0.48	0.58	0.62	0.62	0.28	0.27	0.49	0.51	3.70	1.48
500 ft/d	-0.10	0.32	0.38	-0.05	0.48	0.58	0.63	0.63	0.28	0.27	0.49	0.51	3.70	1.48

Table A-2. Sensitivity analysis of calibrated model

brief descriptions of how model was adjusted	statistical comparison of observed and simulated heads (observed - simulated)												flow at Rt 6	vertical gradient
	Pamet Lens			Chequesset Lens			Pamet River			All				
	SE	AE	SD	SE	AE	SD	SE	AE	SD	SE	AE	SD	(cfs)	(ft/25 ft)
hydraulic conductivity of layer 1 (not including wetland areas) is multiplied by:														
0.001	-0.40	0.44	0.39	-0.42	0.55	0.51	0.43	0.43	0.28	0.01	0.45	0.55	3.67	1.56
0.01	-0.40	0.44	0.39	-0.42	0.55	0.51	0.43	0.44	0.28	0.01	0.45	0.55	3.67	1.56
0.1	-0.37	0.42	0.39	-0.38	0.54	0.51	0.45	0.45	0.28	0.04	0.45	0.54	3.67	1.55
1	1.17	1.17	0.33	1.45	1.45	0.87	1.15	1.15	0.40	1.19	1.19	0.47	3.50	1.28
10	2.96	2.96	0.35	3.67	3.67	1.28	1.76	1.76	0.64	2.44	2.44	0.98	1.66	1.01
100	4.10	4.10	0.49	5.31	5.31	1.57	2.84	2.84	0.72	3.61	3.61	1.17	0.20	0.36
vertical conductance between layers 1 and 2 (not including wetland areas) is multiplied by:														
0.001	-17.41	17.41	2.70	-17.29	17.29	1.82	-4.75	4.92	3.21	-11.06	11.15	6.94	5.59	5.33
0.01	-9.07	9.07	1.04	-7.90	7.90	0.71	-3.36	3.54	2.39	-6.08	6.17	3.30	4.93	4.83
0.1	-1.93	1.93	0.31	-1.77	1.77	0.44	-0.61	0.81	0.74	-1.25	1.35	0.87	3.99	2.35
1	0.13	0.35	0.39	0.18	0.57	0.59	0.78	0.78	0.29	0.46	0.59	0.49	3.64	1.38
10	0.15	0.36	0.40	0.21	0.58	0.59	0.79	0.79	0.29	0.48	0.60	0.49	3.63	1.36
100	0.16	0.36	0.40	0.21	0.59	0.59	0.80	0.80	0.29	0.48	0.61	0.49	3.63	1.36
upland recharge is fluctuated, calibrated values are 23.2 ft/yr and 22.7 ft/yr for the Chequesset and Pamet Lenses, respectively														
-50%	2.05	2.05	0.33	2.44	2.44	1.05	1.28	1.28	0.45	1.71	1.71	0.68	1.47	1.20
-25%	0.96	0.96	0.33	1.18	1.18	0.80	0.94	0.94	0.33	0.97	0.97	0.42	2.58	1.35
25%	-1.15	1.15	0.44	-1.29	1.29	0.44	0.27	0.37	0.33	-0.46	0.78	0.82	4.79	1.64
50%	-2.18	2.18	0.52	-2.50	2.50	0.47	-0.07	0.42	0.45	-1.16	1.34	1.20	5.89	1.78
wetland recharge is fluctuated, calibrated value is 13.1 ft/yr														
0 ft/yr	-0.05	0.31	0.38	0.02	0.46	0.54	0.64	0.64	0.29	0.30	0.49	0.50	3.46	1.62
23.2 ft/yr	-0.15	0.33	0.37	-0.14	0.49	0.60	0.57	0.57	0.27	0.21	0.47	0.51	3.85	1.40

Table A-2. Sensitivity analysis of calibrated model

brief descriptions of how model was adjusted	statistical comparison of observed and simulated heads (observed - simulated)												flow at Rt 6 (cfs)	vertical gradient (ft/25 ft)
	Pamet Lens			Chequesset Lens			Pamet River			All				
	SE	AE	SD	SE	AE	SD	SE	AE	SD	SE	AE	SD		
hydraulic conductivity of layer 7 is multiplied by:														
0.01	-0.11	0.32	0.37	-0.13	0.49	0.56	0.60	0.60	0.28	0.24	0.48	0.50	3.69	1.49
100	-0.11	0.32	0.37	0.08	0.60	0.62	0.60	0.60	0.28	0.27	0.49	0.50	3.67	1.49
vertical conductance between layers 6 and 7 is multiplied by:														
0.01	-0.11	0.32	0.37	-0.07	0.47	0.57	0.60	0.60	0.28	0.25	0.48	0.50	3.68	1.49
100	-0.11	0.32	0.37	-0.07	0.47	0.57	0.60	0.60	0.28	0.25	0.48	0.50	3.68	1.49
Perimeter seeps is removed and marsh sediments is modeled as sand/gravel sediments														
	0.69	0.91	0.86	1.83	1.83	0.48	1.36	1.36	0.40	1.15	1.24	0.74	3.46	0.12
Depth of interface is reduced by twenty-five percent (25%)														
	-2.06	2.06	0.78	-1.44	1.44	0.63	0.28	0.37	0.34	-0.82	1.14	1.26	4.50	1.60

SE - standard error, AE - absolute error, SD - standard deviation

Table A-3. Calibration adjustments made to model without seepage along the perimeter of the marsh

brief descriptions of how model was adjusted	statistical comparison of simulated vs observed water levels												stream flow at Rt 6 (cfs)	gradient below stream (ft)
	Pamet Lens			Chequesset Lens			Pamet River			All				
	SE (ft)	AE (ft)	SD (ft)	SE (ft)	AE (ft)	SD (ft)	SE (ft)	AE (ft)	SD (ft)	SE (ft)	AE (ft)	SD (ft)		
vertical conductance between wetland and underlying model layer is adjusted (1/day) to:														
0.001	-1.17	1.26	1.27	-1.46	1.46	0.42	-2.45	2.55	2.10	-1.85	1.93	1.77	0.23	6.91
0.005	-0.77	0.87	0.91	-0.85	0.85	0.46	-1.68	1.88	1.75	-1.23	1.37	1.42	0.81	4.85
0.01	-0.54	0.64	0.70	-0.49	0.49	0.51	-1.21	1.52	1.55	-0.87	1.06	1.22	1.19	3.56
0.05	-0.13	0.36	0.40	0.13	0.55	0.65	-0.35	1.03	1.21	-0.21	0.72	0.90	1.90	1.14
0.1	-0.04	0.31	0.37	0.26	0.62	0.69	-0.18	0.95	1.14	-0.08	0.66	0.85	2.06	0.62
0.5	0.03	0.28	0.35	0.38	0.68	0.73	-0.01	0.90	1.08	0.05	0.63	0.81	2.21	0.13
horizontal hydraulic conductivity of wetland is adjusted (ft/day) to:														
0.001	-0.13	0.36	0.40	0.13	0.55	0.65	-0.35	1.03	1.21	-0.21	0.72	0.91	1.90	1.14
0.01	-0.13	0.36	0.40	0.13	0.55	0.65	-0.35	1.03	1.21	-0.21	0.72	0.91	1.90	1.14
0.1	-0.13	0.36	0.40	0.13	0.55	0.65	-0.35	1.03	1.21	-0.21	0.72	0.91	1.90	1.14
1	-0.13	0.36	0.40	0.13	0.55	0.65	-0.35	1.03	1.21	-0.21	0.72	0.90	1.90	1.14
10	-0.13	0.36	0.40	0.13	0.55	0.65	-0.35	1.03	1.21	-0.21	0.72	0.90	1.91	1.13
100	-0.11	0.35	0.40	0.16	0.57	0.67	-0.32	1.02	1.20	-0.19	0.71	0.90	1.94	1.05
streambed conductance is adjusted (sq ft/day) to:														
0.001	-1.35	1.43	1.43	-1.74	1.74	0.42	-2.78	2.84	2.25	-2.11	2.17	1.92	0.01	0.00
0.01	-1.32	1.40	1.41	-1.69	1.69	0.42	-2.72	2.78	2.22	-2.06	2.12	1.89	0.05	0.03
0.1	-1.06	1.15	1.17	-1.30	1.30	0.44	-2.21	2.33	2.00	-1.66	1.76	1.66	0.44	0.26
1	-0.13	0.36	0.40	0.13	0.55	0.65	-0.35	1.03	1.21	-0.21	0.72	0.90	1.90	1.14
10	0.47	0.60	0.51	1.09	1.09	0.82	0.83	0.93	0.79	0.72	0.82	0.70	2.87	1.72
100	0.57	0.69	0.58	1.25	1.25	0.85	1.02	1.02	0.74	0.87	0.92	0.71	3.02	1.81

Table A-3. Calibration adjustments made to model without seepage along the perimeter of the marsh

brief descriptions of how model was adjusted	statistical comparison of simulated vs observed water levels: Pamet Lens SE (ft)	Pamet Lens AE (ft)	Pamet Lens SD (ft)	Chequesset Lens SE (ft)	Chequesset Lens AE (ft)	Chequesset Lens SD (ft)	Pamet River SE (ft)	Pamet River AE (ft)	Pamet River SD (ft)	All SE (ft)	All AE (ft)	All SD (ft)	stream flow at Rt 6 (cfs)	gradient below stream (ft)
stream bottom elevation for the Pamet River is adjusted as follows:														
subtract 0.5 ft	-0.08	0.33	0.38	0.20	0.59	0.69	-0.23	0.99	1.18	-0.13	0.69	0.88	2.05	1.23
add 0.5 ft	-0.17	0.39	0.43	0.07	0.50	0.62	-0.48	1.08	1.24	-0.30	0.74	0.93	1.76	1.05
wetland is shrunk to include only stream cells, hydraulic conductivity of the rest of layer 1 is multiplied:														
by 1	-0.12	0.36	0.40	0.14	0.55	0.66	-0.35	1.03	1.20	-0.21	0.71	0.90	1.90	1.14
by 10	-0.12	0.36	0.40	0.14	0.55	0.66	-0.35	1.03	1.20	-0.21	0.71	0.90	1.91	1.12
by 100	-0.10	0.34	0.39	0.17	0.57	0.67	-0.30	1.01	1.19	-0.17	0.70	0.89	1.96	1.01
wetland properties of layer 1 are replaced with layer 2 properties, streambed conductance is multiplied:														
by 0.01	-1.29	1.38	1.38	-1.65	1.65	0.42	-2.69	2.75	2.18	-2.03	2.09	1.87	0.05	0.01
by 1	0.02	0.28	0.35	0.36	0.67	0.72	-0.05	0.91	1.09	0.02	0.63	0.82	2.18	0.28
by 100	0.92	1.02	0.89	1.81	1.81	1.01	1.82	1.82	0.59	1.47	1.51	0.86	3.79	0.55

SE - standard error, AE - absolute error, SD - standard deviation