Hydrologic Report
Hyannis Ponds Project

Richard McHorney
Biohydrology Project Coordinator
The Nature Conservancy

September, 1997

This report was produced with support from

Table of Contents

Summary

•The Hyannis Ponds area of Barnstable, Massachusetts includes several coastal plain ponds hosting a rare pond-shore plant community. The Hyannis Ponds Biohydrology Project was initiated to elucidate the relationship between ground-water and surface-water flow systems and pond-shore community dynamics. The hydrologic phase of this project was carried out to determine the dynamics of the ground-water flow system, its relationship with surface-water bodies and the influence of water supply pumping of ground water on the movement of water between the two systems.

• The hydrology of the area is dominated by the geologic materials comprising the aquifer, sands and gravels deposited in the waning stages of the Wisconsinan glaciation. Within these deposits are a series of ponds, occupying old ice-collapse features. These ponds contain some fine-grained deposits which may influence the movement of water between the ponds and the surrounding aquifer.

• The Nature Conservancy has installed a network of wells, piezometers and staff gages to determine water levels, map the water table and measure vertical hydraulic gradients between the ponds and the surrounding aquifer. Ground-water flow in the aquifer is generally from the northwest to southeast, with some localized exceptions. Vertical gradients are found primarily under the pond or in the pond margins, and not in the surrounding aquifer. Higher vertical gradients are associated with shallow ponds with primarily fine-grained substrates. Lower vertical gradients are found at Mary Dunn Pond, indicating less resistance to flow between the surface and ground-water systems.

• In June and July of 1995, a pumping test of a well adjacent to Mary Dunn Pond (MD#2) allowed TNC to establish for the first time a firm relationship between water supply pumping of ground-water and decline in the level of the pond. This was accomplished using several types of data.

- Water table measurements showed the intersection of the cone of depression with the pond bottom. Large downward vertical gradients developed between the pond bottom and the aquifer in the area of the pond adjacent to the pumping well.

- Temperature measurements in the pond and aquifer under the pond shore demonstrated the movement of water from the pond into the aquifer during the pumping test. These same measurements may also be used to trace the movement of water under normal flow conditions.

- Comparison of drawdowns in Mary Dunn Pond and other ponds away from the influence of pumping indicate that pumping strongly affected the level of Mary Dunn Pond. Changes in the levels of the surrounding ponds were consistent with evaporation, but Mary Dunn Pond was lowered at about three times the rate of evaporation.

- A water budget was calculated for Mary Dunn Pond using an evaporation method likely to provide a conservative estimate of the effect of pumping. The budget indicated that at least 27 % of the water pumped from MD#2 was derived from the pond.

- Seepage meter measurements of water flow through the pond bottom showed an area of greatly enhanced seepage from the pond to the aquifer in the area of the pond near the pumping well.

• Water level changes in the summer of 1996 indicated the influence of pumping on Mary Dunn Pond under non-pumping test conditions. Mary Dunn Pond levels fell more than the surrounding ponds during a relatively cool, wet summer. Similar patterns of pond level decline occurred in 1993 and 1994. Pumping rates of the two water supply wells nearest the pond were highly correlated to the short-term rate of pond level decline between May and August of 1996.

• In the fall of 1996, abnormally high rainfall raised the levels of the ponds and aquifer abruptly. During several periods of little or no rainfall, pond levels continued to rise indicating ground-water inflow. This effect was most pronounced at Mary Dunn Pond, where pond levels increased at rates, and in a pattern, very similar to the surrounding aquifer. During this period it appears that ground-water levels were the dominant factor determining the level of Mary Dunn Pond.

• During the spring of 1997 a series of three pumping tests were performed to determine the effects of pumping under conditions differing from those of the 1995 test. Additional wells were also tested. The results were similar to those obtained in 1995 despite lower temperatures and, presumably, lower rates of evaporation. In all of the tests, a distinct effect of pumping was apparent, including the test of the Airport well, located about 1000 feet from the pond shore. Pumping in July, after cessation of the tests, also appears to have had an effect on the level of Mary Dunn Pond.

• The overall conclusion of the hydrologic study is that the ponds within the study area all interact to some degree with the surrounding aquifer. The greatest degree of interaction is seen at Mary Dunn Pond, as indicated by pumping tests and recharge behavior.

Hydrologic Report

Project Status

The primary purpose of the hydrologic study phase of the Hyannis Ponds Project is to produce an understanding of the hydrologic factors controlling the water level fluctuations of the coastal plain ponds within the study area. To accomplish this goal, it is necessary to elucidate the nature of the hydraulic interaction betweeen ponds and the surrounding aquifer and determine what, if any, influence water supply pumping has on this interaction.

The primary tasks of the hydrologic study as proposed were; installation of observation wells and piezometers, mapping the water table configuration of the study area in detail, pond and well water-level monitoring on a monthly or bi-weekly basis, monitoring of rainfall and snowmelt events, installation and measurement of seepage meters, and complilation of a computer ground-water numerical model. In addition, four pumping tests and measurement and analysis of ground-water temperature patterns have been added to the project tasks. Also, during the spring, summer and fall, monitoring has been performed on a weekly (and at times more frequent) basis to match the variablilty of pumping rates and other hydrologic factors. All of the additional tasks have greatly added to the resolution of the study. The intensive phase of hydrologic data collection is complete and analysis of much of the data has been performed.

The time frame of the study has been extended through an additional grant, primarily to allow gathering additional biological data. Detailed hydrologic data, specifically pumping test data from the spring of 1997, has also been collected within this extended time frame. This report presents hydrologic data gathered as of July 23rd, 1997 and analysis of that data. Analysis of the data collected during the Spring of 1997 is not complete at this time. The final project report will be completed on December 31, 1997 and will include some additional analysis of the field hydrologic data as well as a completed numerical ground-water model. Preliminary modelling results are not included in this report.

Introduction

The study area consists of about 1000 acres of undeveloped or partially developed land in Barnstable, Massachusetts. Figure 1 shows the placement of the larger ponds, water supply wells, and roads. The three primary land owners within the study area are the Barnstable Water Company (watershed lands), the Commonwealth of Masssachusetts (Hyannnis Ponds Widlife Management Area) and the Town of Barstable (Barnstable Municipal Airport).

Geology

The geology of the study area has been characterized by previous studies including Oldale (1974), Oldale and O'Hara (1984) and IEP (1990). The project area straddles the border of the late Wisconsinan glacial moraine. Most of the sediments in the study area are comprised of outwash sands and gravels extending south of the morainal deposits. Some area of likely ice-contact deposits are also evident near the moraine border. (see Figure 2)

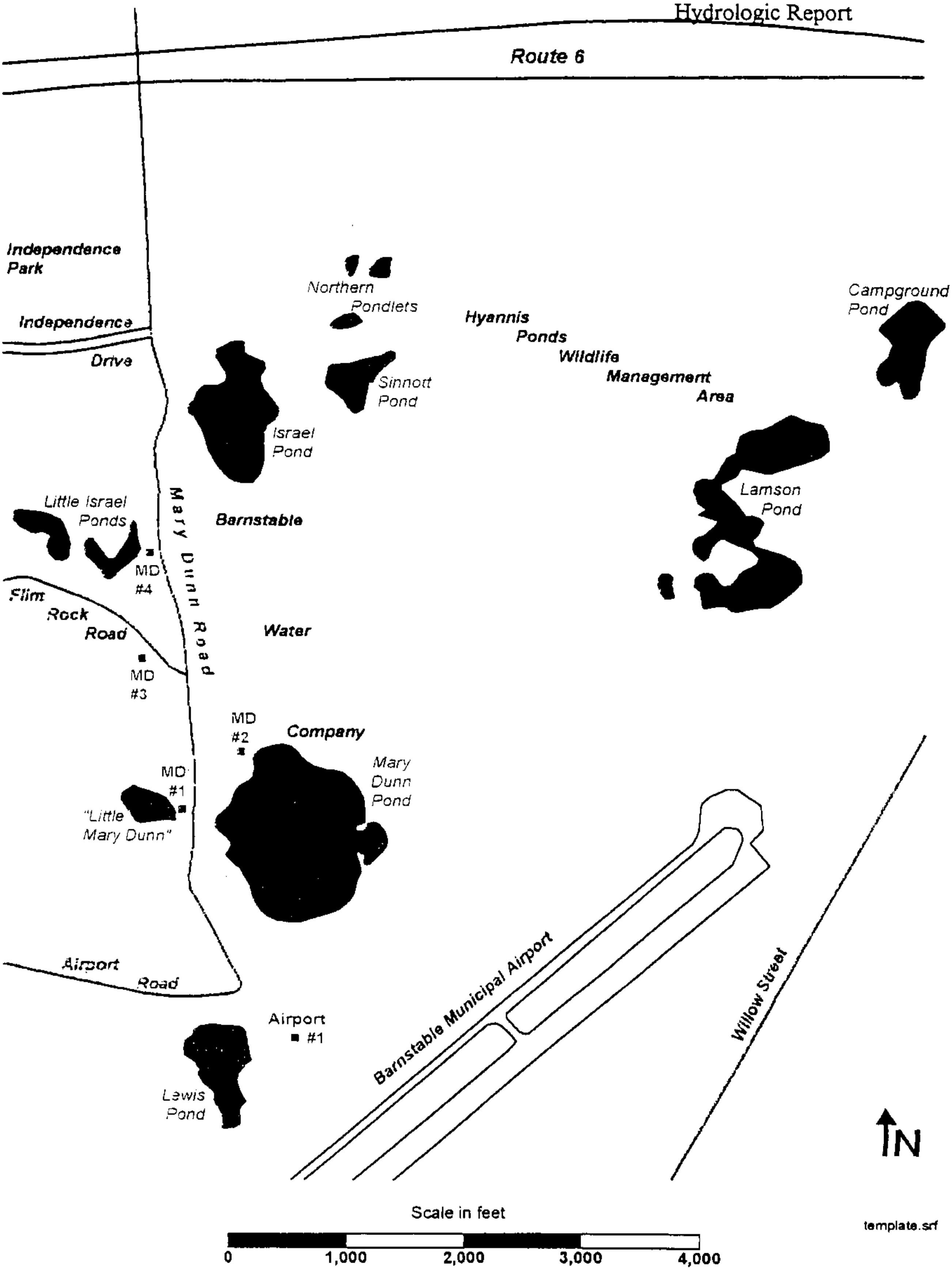


Figure 1. Study Area Map. Source: Town of Barnstable GIS data. Red blocks denote water supply wells. Smaller ephemeral ponds are not shown.

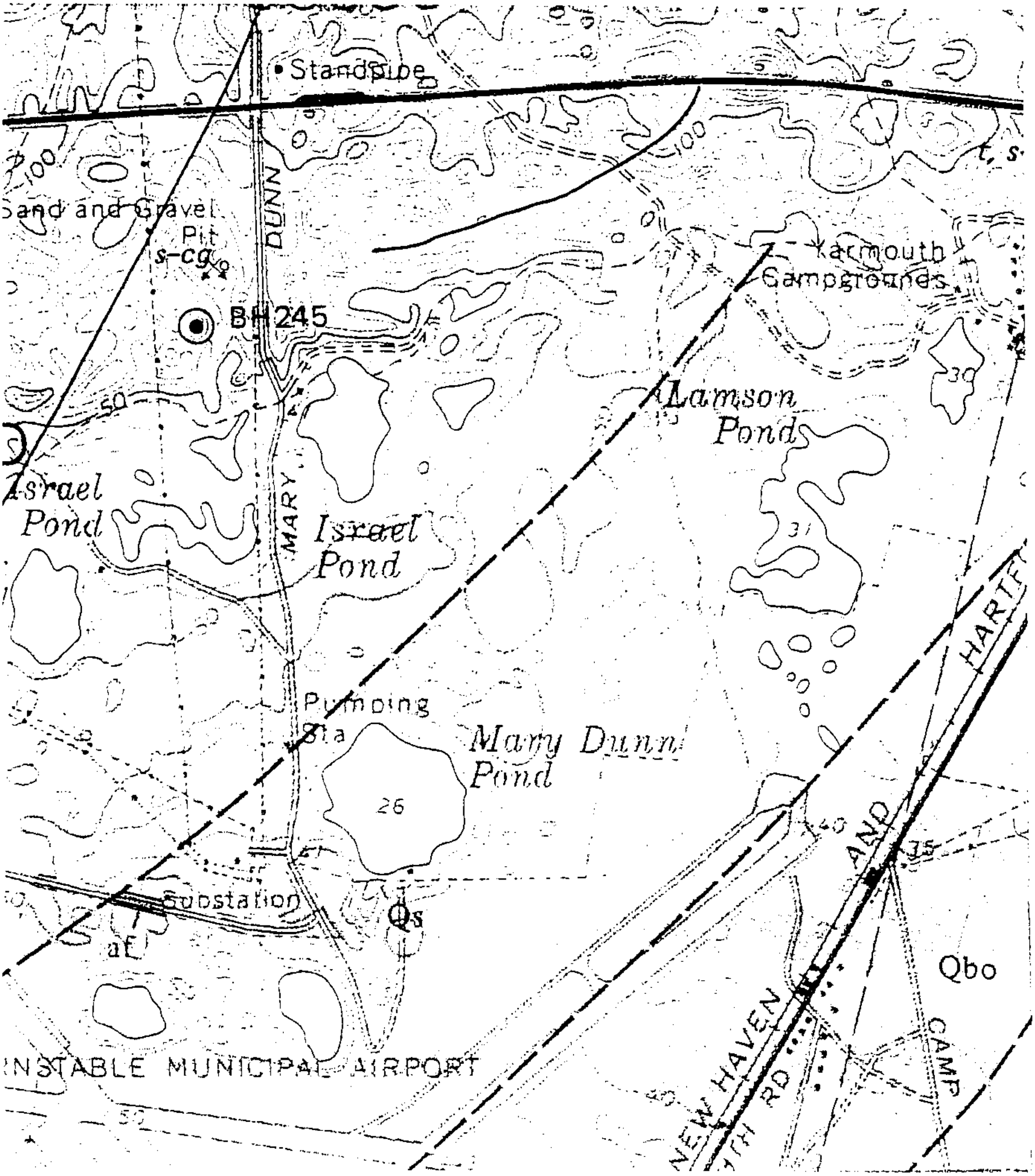


Figure 2. Geologic map of the study area, from Oldale, 1974. Scale:1" = 12,000ft. Units are Sandwich moraine (no symbol shown, tan, at north), Barnstable outwash (Qbo, mustard, most of map) and swamp deposits (Qs, light yellow, small area south of Mary Dunn Pond). Short red line is a moraine lineament, indicative of thrusting, longer red line is bedrock elevation contour (-300 feet), dashed lines are inferred pre-collapse and pre-erosion outwash plain elevation (60 ft to left, 50 ft to right). All elevations are w/r/t NGVD 1929.

Moraine and Ice-Contact Deposits

Approximately one-quarter of the study area is underlain by thrusted morainal deposits. This is the topographically highest portion of the study area, forming a broad ridge along the nothern border of the WMA. Well logs from this area indicate that the primary sediment type consist of medium to coarse sand with traces of gravel . Fine sands and fine to medium sands are also present (HMM Assoc, unpublished data). There are two types of geologic evidence for thrusting as a significant feature in moraine development. First, some road cuts in the Hyannis Ponds Wildlife Management Area (WMA) and nearby excavated area contain well-bedded medium to coarse sands interbedded with fine sands. The layering is tilted, dipping toward the north-northwest at about 20°. The general topography of this section consists of small hills elongated along the moraine edge and transverse to the direction of ice movement (Oldale, 1974). These hills appear to be the forward edges of thrust sheets. Second, in one well log in the moraine, OW 4 (installed in 1989), the presence of organic rich sediments was noted at a depth of about 40 feet below grade. These sediments probably represent proglacial sediments caught up in thrust movement. The presence of thrusting zones may have hydrologic implications; thrust faults within the moraine disrupt layering and may act as conduits for rapid vertical transmission of water. Some evidence of rapid vertical water movement in the moraine was seen in this study. (See later section on Fall 1996.)

No significant wetlands are developed in the depressions in the topographically higher portions of the morainal deposits. In these areas the water table is at least 40 feet below the ground surface and the morainal deposits are apparently too permeable to support perched ponds. The depressions appear to be formed along the upper and lower bounding faults of thrust packages, likely areas of enhanced permeability.

Some wetlands are formed at the edge of the moraine; Israel Pond abuts the southern edge. The "northern pondlets" are formed in a depression in an area which may be at the edge of or within the moraine. The ground surface of the ridge between the northern pondlets and Sinnott Pond contains large boulders similar to those found areas that are clearly moraine, however these boulders may be the coarsest constituents of ice-contact deposits. Large boulders along the eastern shore of Israel Pond also appear to be part of an ice-contact deposit.

Outwash Plain

The majority of the study area is underlain by deposits of the Barnstable outwash plain. The topographic surface of the outwash plain is relatively level, but punctuated with depressions of varying size and depth. Most of the deeper depressions in the outwash plain contain a seasonal or permanent wetland. Some of the depressions are quite large(>50 acres) and contain multiple wetlands. The predominant view of these depressions is that they are ice-melt structures or "kettles" (Oldale, 1974).

The outwash consists of a wide variety of interbedded sediments, the majority of which are medium to coarse subangular sands with some pebbles. There are also fairly abundant layers consisting of a mixture of sands and cobbles at various poportions. Some of the cobble layers are very difficult (or impossible) to drill through with a 6" hollow stem auger. In some areas, the sands and gravels are arranged in fining-upward sequences consistent with deposition in a fluvial environment. In the WMA, preliminary excavation for roads has exposed the sediments below the soil layers. In one of these road scrapes, the exposed surface contains fairly abundant cobbles in a broad stripe oriented obliquely with respect to the road. This appears to be the remains of a stream channel active during the closing stages of glaciation. Coarse-grained channels may provide local higher permeability areas within the outwash sediments. Generally, the outwash deposits appear finer grained with increasing distance from the moraine.

At shallow levels, fine sands, silts and clays are uncommon; layers consisting of these materials increase in abundance at depths greater than 40 feet below grade. At an elevation of about sea level, about 50 feet below grade in most of the study area, there is a layer consisting of fine sand grading downward to brown, then blue-gray silty clay. This material is very firm and of apparently extremely low permeability. One split-spoon sample from this layer was varved indicating in a very low energy depositional environment subject to seasonal variations in sediment influx. In this study no wells were emplaced below this layer, however, three piezometers were driven through it. Previous studies drilled through (or used drive and wash techniques) this layer and found sands and gravels below it.

This fine-grained clay layer, referred to herein as the "basal" clay, functions as an effective seal between the surficial aquifer and deeper sand layers except in areas where it is thin or breached. This may be the case within some of the collapse zones within the topographic depressions in the outwash plain. The clay layer appears to dip down to lower elevations within the collapse zones, reflecting the variations in surface topography. This implies that the ice blocks, the melting of which formed the kettles were emplaced prior to the sedimentation of the basal clay. When the ice blocks melted, the overlying clay collapsed along with the sands and gravels. It may also be possible that the ice blocks were grounded in and protruded from the sediments underlying the basal clay. If this is the case the basal clay would have been laid down around the margins of the ice blocks, and these marginal areas would have also been caught up in the collapse due to melting.

The hydrologic significance of these hypotheses is that the clay could have been breached in both scenarios, allowing movement of water between the surficial and lower aquifers. The head difference between these two zones is strongly downward in some portions of the study area. In the collapse zone around Mary Dunn Pond head differences are less pronounced, indicating greater hydraulic communication between the upper and lower zones. In one well pair, the vertical head difference across the basal clay reverses direction seasonally near an apparent closed depression in the water table. This may represent an area where due to a breach in the basal clay vertical leakage from the upper to lower aquifer occurs. During times of high water levels in the surficial aquifer, this area becomes a local-discharge zone for the upper aquifer. As water levels in the upper aquifer fall, the lower aquifer may provide recharge to the upper aquifer.

Soils

The soils within the study area belong to three soil series, the Barnstable, Carver and Plymouth series. The Barnstable and Plymouth Series soils are lumped into a single mapping unit, the Plymouth-Barnstable Complex which occurs on the morainal deposits within the study area. The Carver soils are developed on the outwash plain deposits. All of the soils are characterized by a relatively low degree of pedogenic development as would be expected due to their relative youth and high permeability (Fletcher, 1993).

Carver soils have low clay contents (less than five per cent) throughout the soil profile and are extremely permeable. Permeability is listed in the Barnstable County Soil Survey (Fletcher , 1993)) as greater than 20 inches per hour (the highest category) at all levels in the soil profile. Plymouth-Barnstable soils also have low (less than six per cent) clay contents, with permeabilities listed at 2.0 to 6.0 inches/hour (Barnstable) and 6.0 to 20 inches/hour (Plymouth) in b-horizon and above and >6.0 inches/hour (Barnstable) and >20 inches/hour (Plymouth) in the c-horizon. All of these soils are characterized as having severe limitations for sanitary facility use due to high seepage rates and poor filtration characteristics. (Soil Survey) Some of the soils observed in areas mapped as Carver soils differ to some degree from the typical Carver soils. In particular, some soils contain a Bhs horizon or similar stratum within or below the solum. At a few locations, this horizon forms a thin iron "pan" requiring considerable effort to dig or drive wells through. Where this layer is below the solum, it is also well above the highest observed position of the water table. This layer does not appear to impede the vertical movement of water. When one location with a particularly dense iron-rich layer was excavated during a fairly rainy period in the Spring of 1997, no accumulation of water or moist zone was found above it.

The information cited above indicates that the soils within the project area should have very high infiltration rates. There are no natural surface water channels in the study area, also indicating that precipitated water infiltrates into rather than runs off of the soil surface. In over two years of field observations, including periods during rainfall events, I have not observed surface runoff from any natural undisturbed surface in the field area. Evidence of surface runoff in the Hyannis Ponds area is found only in areas where human activities have produced low permeability surfaces such as roads and compacted soils on trails and dirt roads. There is very little area (I estimate less than two per cent) of low permeability ground surface in the study area.

Ponds

Lamson and Israel Ponds are in relatively flat basins and fine-grained, organic-rich sediments form much of the pond bottom. The sandy pond margin in Lamson and Israel Ponds is relatively narrow, extending less than 20 feet horizontally and 3 feet vertically from the shrubby margin of the shoreline. In some sections of the shoreline of these ponds, there is very little sandy margin, the organic-rich pond bottom sediments extend nearly to the shrubby margin.

In Mary Dunn Pond, the shoreline zone is much more distinct, forming a slope extending about six feet vertically and 40 to 100 feet horizontally from the shrubby margin. (Eagle Surveying, 9/6/1991). In the upper parts of this zone, the substrate is predominantly sand, pebbles and cobbles and becomes finer-grained lower down and farther from the shrub margin. However , in some sections of the shoreline the substrate is coarse-grained well down the shoreline slope. Below the bottom of the shoreline slope, the substrate is predominantly an organic, peaty muck.

Below this muck, the sediments may be sandy, clay-rich or include a mixture of grain sizes. I have not been able to core the deeper sections of the pond, as was originally intended. I have, however, driven piezometers into the pond bottom at several locations within Mary Dunn Pond at one location in each of Lamson , Israel , Little Israel, and Sinnott Ponds and two locations in Little Mary Dunn Pond. While driving the piezometers, the sound the tip makes when rotated can be used as a test for the presence of sand. Also, when the piezometers are developed, a washed sediment sample is recovered. The piezometers were slotted within six-inches of the tip and the slot size was about 0.03 inches, allowing passage of grain sizes up to medium sand. Medium and fine sands, organic muck and clay have all been recovered from washed samples from below the deeper portions of the pond bottom. In some locations organic sediments and sand were recovered as washed samples from the same interval . During driving, the tip sounded "sandy" at some levels and not at others, indicating layering. While driving piezometers along the mid to lower marginal slope of the pond, both sand-dominated and organic-dominated sediments were encountered. Piezometers on the upper pond margin were installed during low water conditions by augering four to five feet and driving. The sediments encountered in excavating and as washed samples were predominantly coarse-grained. Some mid-pond piezometers such as P21 and P22 in Mary Dunn Pond were completed in muddy sediments at depths of about 7 and 12 feet below the pond bottom.

Water Table Configuration

Method

For the purpose of detailed water table mapping, we have installed 14 wells and 88 piezometers. Figure 3 shows the location of all measurement points. We installed three well/piezometer triplets near pond margins, and one well pair in an upland area. On the pond margins, we installed piezometer pairs, with a shallow piezometer installed about 4.5 feet below grade and a deep piezometer installed about 14.5 feet below grade. When pond levels are up to the ground surface elevation at these piezometer pairs, vertical gradients between the pond and the aquifer as well as within the aquifer can be measured. Piezometer triplets in Israel and Lamson have been installed at 1.8, 11.8 and 21.8 feet below the pond bottom. At Mary Dunn Pond two piezometer pairs (P19/20 and P21/22) were installed at depths of 7 and 12 feet below the pond bottom.

Deeper piezometers (> 5 feet long) are slotted over the bottom 12 inches while the shallow piezometers (five feet long or less) are slotted over the bottom six inches. All piezometers were completed by pumping and surging following installation. Prior to the inception of this study, hydrologic investigations were performed in the study area by the Barnstable Water Company, Independence Park Inc, and the Town of Barnstable. Some of the hydrologic measurement points installed as part of these sturies have been used in the current investigation. The total number of available water level measurement points used in this study is 140.

Water measurements were taken with two instruments. The first instrument used was a Solinst® water tape with a "P2" probe. The P2 probe reads water level from a needle tip located halfway up the probe. Although this instrument is standard for most well applications, in narrow wells and piezometers the length of the tip results in some initial upward displacement of water. This water can be allowed to leak out of the piezometer and measurements taken when the water level in the piezometer has equilibrated with the surrounding aquifer. For some piezometers, this process is essentially instantaneous, but for those in low permeability materials it can take a few minutes. In

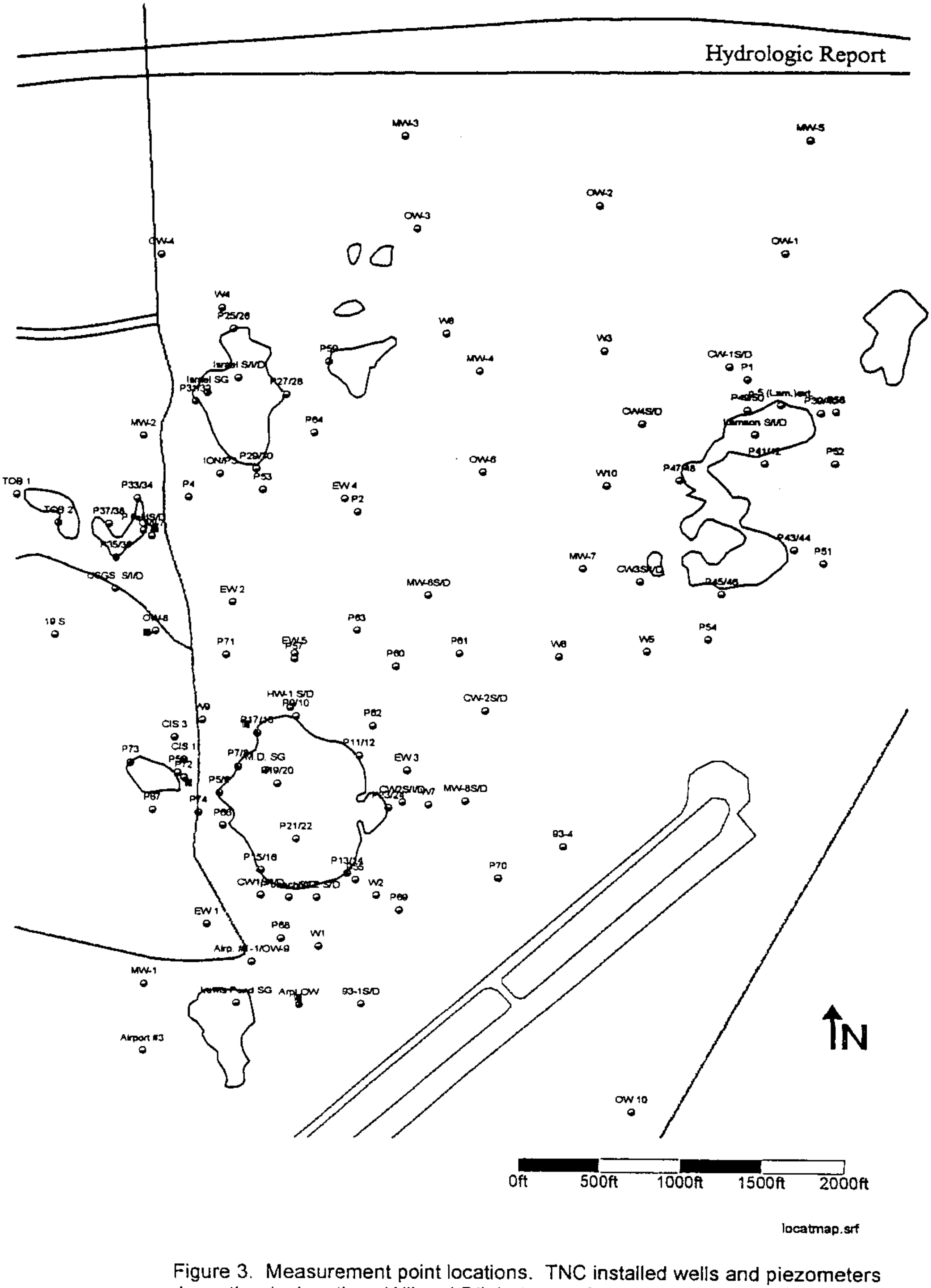
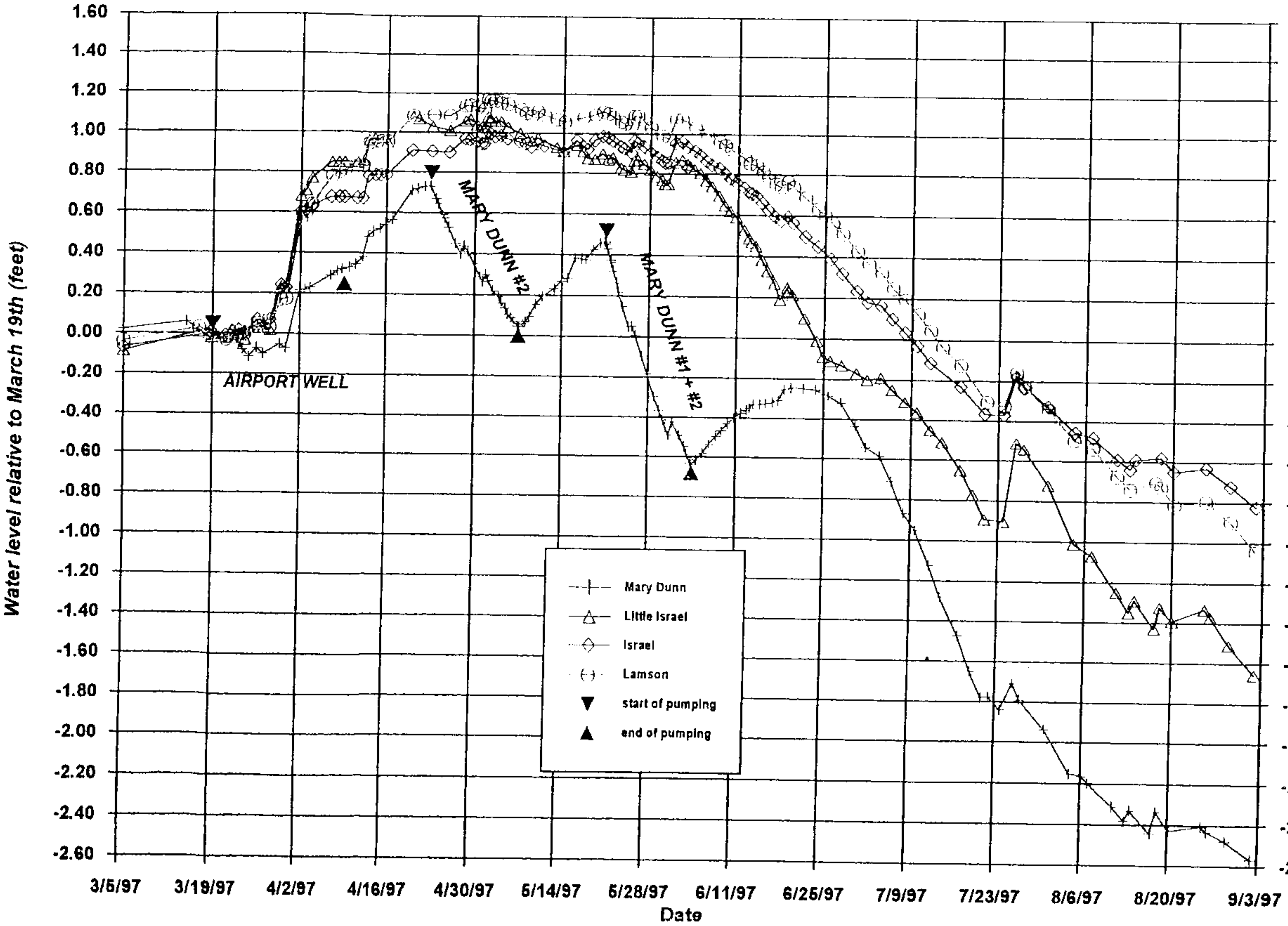


Figure 3. Measurement point locations. TNC installed wells and piezometers have the designations W# and P#, but are referred to in the text as TNC W# etc. Wells installed prior to this study are designated OW#, EW# or MW#. Red blocks are water supply wells.



Water level relative to March 19th (feet)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
-1.60
-1.80
-2.00
-2.20
-2.40
-2.60
AIRPORT WELL
MARY DUNN #2
MARY DUNN #1 + #2
Mary Dunn
Little Israel
Israel
Lamson
start of pumping
end of pumping
3/5/97
3/19/97
4/2/97
4/16/97
4/30/97
5/14/97
5/28/97
6/11/97
6/25/97
7/9/97
7/23/97
8/6/97
8/20/97
9/3/97
Date

order to get more rapid and accurate readings, an inexpensive tip-reading instrument was designed and built for use in piezometers when depth-to-water does not exceed 2.6 feet. Longer versions can be built, but are more awkward to handle in the field.

Water levels have been measured in these points on a weekly basis, when possible, to build a data base and establish statistical relationships among them, as well as to examine short-term changes in the water table. Water table maps have been compiled from water elevations in the wells, piezometers and staff gages using Surfer®, a software contouring package widely used in the geological sciences. All of the contouring grids were generated using Kriging with a linear variogram amd linear drift. For some maps, water levels in a small number of wells have been estimated using a statistical relationship with the nearest well. In all of these cases the correlation coefficient of the regression equation was greater than 0.980. In all such cases, the well locations are indicated with a distinct symbol on the map.

Results-General Water Table Features

Figure 4 shows the water table confguration on March 18, 1997 during a period of relatively high water levels, following several months of low ground-water withdrawal. Figure 5 shows the water table configuration on September 1, 1996 under relatively low water level conditions, following relatively moderate summer water withdrawals. These two figures demonstrate the general water table features characteristic of this area. The general direction of water flow is from the northwest to the southeast. A localized ground-water mound in the area of Lamson Pond is the major exception to this pattern. Water flow in the vicinity of Mary Dunn Pond follows the general flow direction, but ground-water contours mimic the pond shore on the up- and down-gradient sides of the pond. To the northeast of the pond there is an area of relatively flat contours. A small cone of depression in the area of MD#1 is evident on the September 1 map as well as a closed depression in the water table to the northeast of Mary Dunn Pond.

Results-Vertical Gradients

The purpose of the nested pairs and triplets was to determine what, if any, vertical gradients were present in the study area, particularly at the pond margins and below the pond bottoms. We found no significant vertical gradients in the surficial aquifer in upland areas. Where deep wells and piezometers penetrated the basal clay layer, however, downward vertical gradients across the clay layer were found under most circumstances. The largest values of downward vertical gradients across the clay were found at TNC CW 3 near the southeast margin of Lamson Pond, where we have measured vertical gradients as high as -1.18 ft/ft under high water conditions in the surficial aquifer. In CW2, installed in 1989 to the east of Mary Dunn Pond, the gradient reversed direction from downward to upward during periods of low elevation of the surficial aquifer. Similar gradient reversals were also found in well pairs in the proximity of heavily pumped wells.

Both upward and downward vertical gradients characterized the shorelines of all of the ponds. When pond water levels are high enough, internal and external water level measurements may be taken on the pond margin piezometers, allowing determination of the gradient between the pond

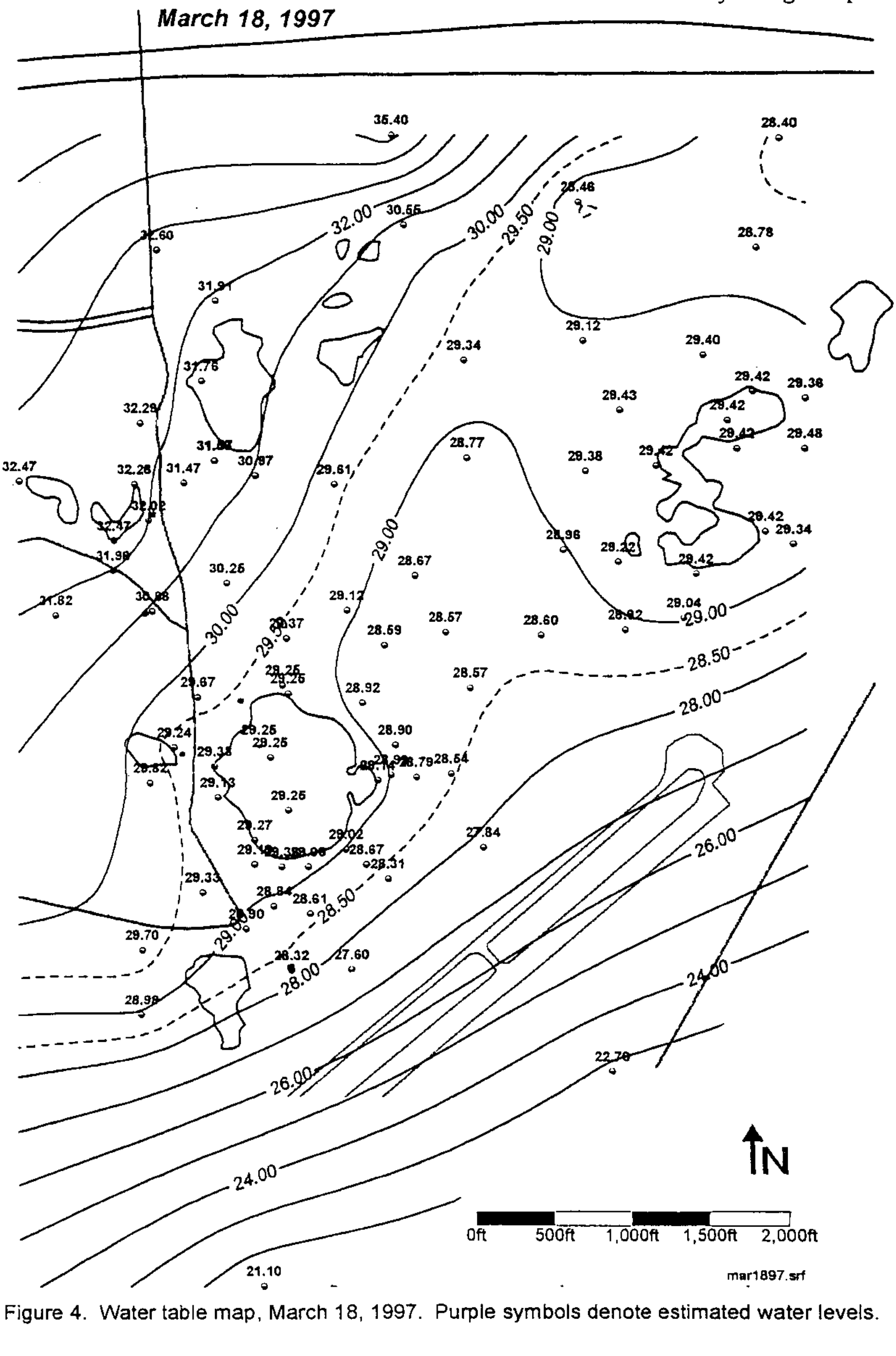


Figure 4. Water table map, March 18, 1997. Purple symbols denote estimated water levels.

September 1, 1996

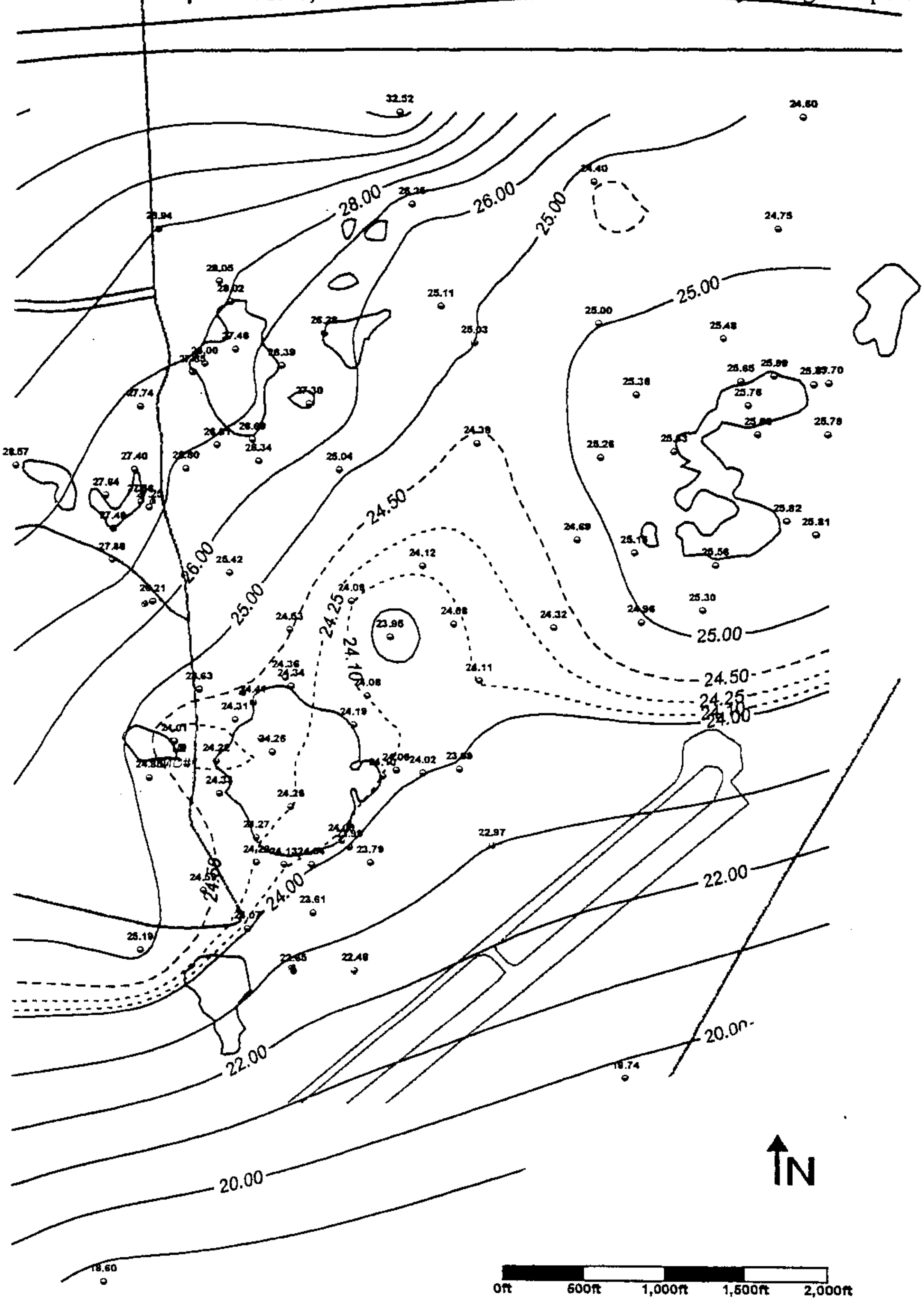


Figure 5. Water table map, September 1, 1996. Purple symbols denote estimated water levels.

and ground water. Where nested piezometers are in use it is also possible to determine the vertical gradients within the upper level (down to the depth of the deeper piezometer) of the surficial aquifer. In general we found that vertical gradients are most pronounced between the pond and the shallow piezometers, but are also reflected in the surficial aquifer below the pond bottom. The largest pond margin vertical gradients were found at Israel Pond and in areas of Mary Dunn Pond near wells during heavy pumping. In Israel Pond the upward gradients developed along the upgradient areas of the pond were much lower in absolute value than the downward gradients on the downgradient areas of the pond. In general, the direction of the vertical gradients agreed with the relationship between the pond and the aquifer as determined from observation wells surrounding the pond. That is, where water table mapping showed the upgradient side of a pond, upward vertical gradients were present along the pond margin.

Vertical gradients were also measured in piezometers installed well out into the pond. The largest values of vertical gradient were measured in Israel Pond in 1995, prior to the pond drying out in late August. At this time a downward vertical gradient of about 0.218 ft/ft was measured in the north-central portion of the pond. At the same time the vertical gradient in the nothern portion of Lamson Pond was .028ft/ft downward. In Mary Dunn Pond, two piezometer pairs were installed mid-pond, P19/20 in the north-central portion of the pond and P21/22 in the south-central portion of the pond. In both of these pairs measured vertical gradients were insignificant (less than 0.001 ft/ft) except during the pumping test of MD#2 in 1995. (See later discussion.)

Discussion

The general direction of ground-water flow is in agreement with published reports on the configuration of the water table of the Sandwich lens (LeBlanc et. al., 1986). Previous studies of the local water table were based on fewer measurement points and could not demonstrate the details of the water table (IEP Inc., 1990; Mass. DEM, unpublished data; Horsley&Witten Inc., 1994, 1995 & 1996). The most significant departure from the general northwest to southeast flow direction is the ground-water mound in the vicinity of Lamson Pond. It is unclear at this time why this feature exists. One possibility is that the water table is elevated on a local high in the deep clay layer which forms the lower bound of the surficial aquifer. The elevation of the basal clay is higher in the area around Lamson Pond than over most of the rest of the study area. An alternative explanation is that the area is a local focused recharge zone. In models of focused recharge, areas in which ground water is reached at relatively shallow depths receive focused recharge as a transient phenomenon following rainfall and snowmelt. While the depth to ground water in this portion of the study area is relatively shallow, the ground-water mound near Lamson Pond persists throughout the year under different water table conditions and does not, therefore, appear to be due to focused recharge.

The pond-bottom vertical gradients encountered in this study are consistent with varying degrees of interaction between the pond and the surrounding aquifer. At one end of the spectrum are readings from Israel Pond during the summer of 1995. During late summer, high downward vertical gradients in the center of the pond indicated an essentially perched condition as Israel Pond dried out except for a few scattered shallow pools. At the same time, piezometers in the middle of Mary Dunn Pond had almost no vertical gradient, indicating no significant perching.

The consistent pattern of vertical gradients along the pond shore does show that there is some impediment to flow between all of the ponds and the aquifer under a variety of conditions. The high downward vertical gradients in the pond shore around Israel Pond again are indicative of a relatively low permeability of the pond bottom sediments. Israel Pond is also located across a relatively steep section of the water table. At Mary Dunn Pond, the lower gradients along the pond shore are consistent with a higher permeability pond bottom and less sloped water table. At Mary Dunn Pond, high vertical pond shore gradients are apparently only developed under highly stressed, pumped conditions.

Conclusions

The general direction of ground-water movement is from the nothwest to southeast in the study area. The largest departure from this pattern is seen around Lamson Pond, but the cause of this feature is problematic. In the vicinity of Mary Dunn Pond flow is generally west to east during periods of relatively low impact from ground-water-supply pumping.

Vertical hydraulic gradients measured within the study area, indicate significant head differences across the "basal clay" layer separating the surficial aquifer from lower levels. In some areas, lower gradients may indicate discontinuities in the clay. Gradients at the pond shores and within the ponds indicate varying degrees of hydraulic interaction between the ponds and the surrounding aquifer.

1995 Pumping Test - Mary Dunn #2

Introduction

In June of 1995, BWC initiated a pumping test to determine the percentage of water flowing from Mary Dunn Pond to supply well MD#2 under continuous pumping conditions. The Horsley &Witten (H&W) protocol for the test was to sample water temperatures in the well water prior to, during and after the pumping period and analyze the results with a mixing equation. (Horsley and Witten Inc, 1996) A prior attempt of the same protocol in 1994 had been rendered ineffective by a discontinous pumping schedule. The pumping schedule for this test, as set by BWC, was continuous, 24-hours per day for four weeks. The average rate of pumping was 514 gpm, 73 per cent of the permitted rate for MD#2. Figure 6 shows the daily pumping levels on all wells within the wellfield. Note that MD#2 was pumped prior to the test at rates about 1/4 of the test rate and that MD#1 was also pumped prior to the test.

During this test The Nature Conservancy collected data on pond and aquifer levels, seepage at Mary Dunn Pond, water temperatures at Mary Dunn Pond and in the aquifer at the pond margin, and precipitation. We have also obtained air temperature and precipitation, collected at the NOAA weather station at the Hyannis waste water treatment plant.

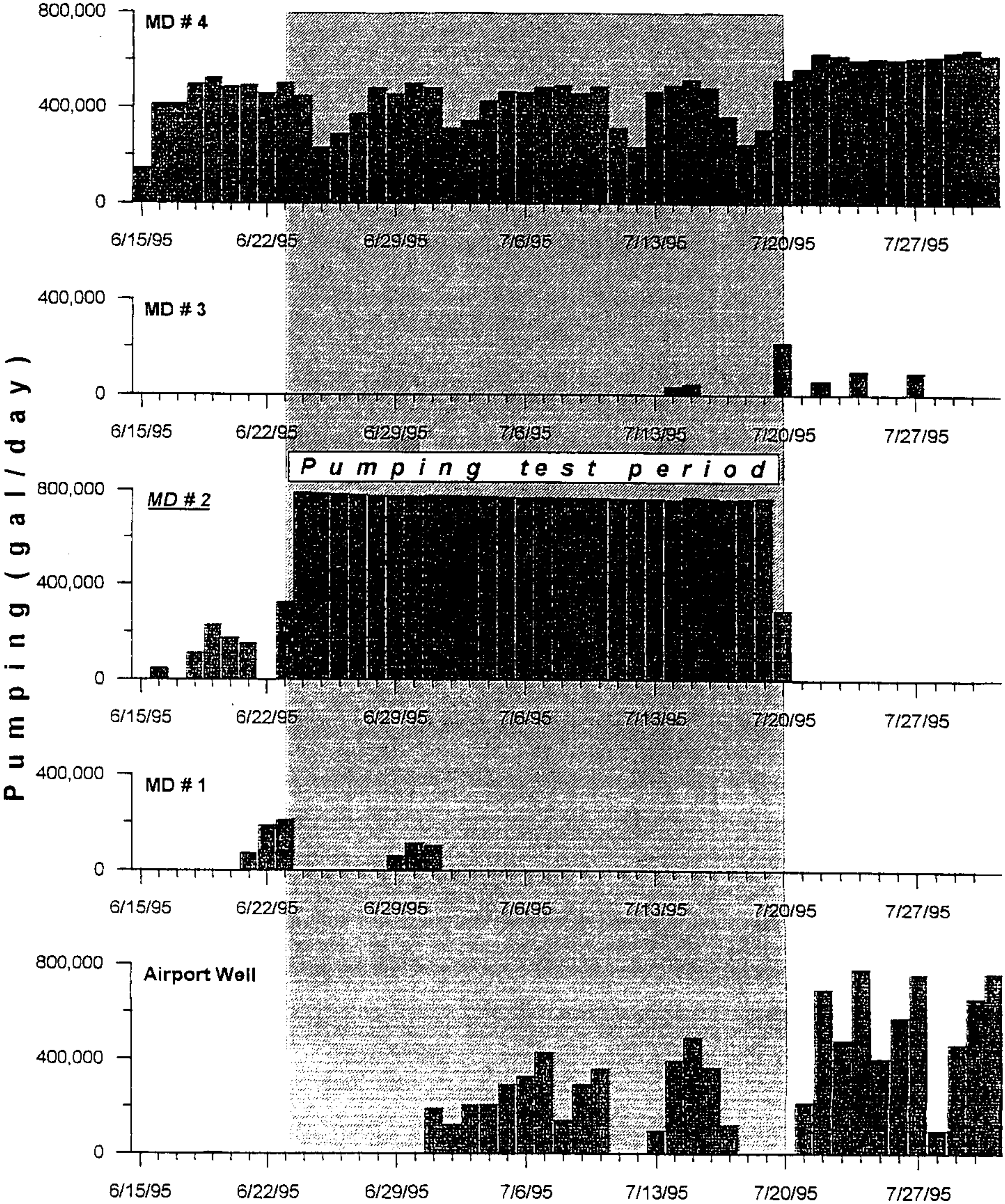


Figure 6. Mary Dunn Wellfield pumping from June 15 through July 31st, 1995. The box encloses the period of the pumping test of MD#2. All y-axes are at the same scale.

Water Table Changes and Vertical Hydraulic Gradients

Method

Water levels were measured in piezometers and wells in and around Mary Dunn Pond throughout the pumping test and afterward. Measurements in paired piezometers were also taken.

Results

During the pumping test, significant changes occurred in water table levels in the area surrounding the pumping well. Figure 7 shows the water table configuration on June 23, 1995 at the beginning of the test. (Please note that the measurements used for areas away from the pumping test were taken on June 24 and adjusted for the average daily ground water decline rate, about 0.02 ft per day, during this period.) Figure 8 shows the water table configuration at the end of the test on July 20, 1995. Please note that the points with the red symbols to the southeast of Mary Dunn were not installed at the time of the test and that water elevations are estimated based on linear regression to the closest monitoring well using 1997 data. Correlation coefficients for both of these relationships are greater than 0.980.

Figure 9 shows the differences in water table elevations between the beginning and end of the test. The influence of pumping is clearly seen around MD#2; the drawdown zone is centered on this map around P17/18, the measurement point nearest the pumping well.

The pond shore piezometers at Mary Dunn Pond were installed shortly before the onset of the pumping test, on exposed areas of the shoreline. Therefore, it was not possible to measure gradients between the pond and the shallow aquifer from these points during the test. There were, however four piezometers installed adjacent to seepage meters in standing water. There were also two piezometer pairs installed about 300 feet from the shoreline two days into the test. Figure 10 shows the values of vertical hydraulic gradient at MDSM#1P, located near the pumping well, adjacent to seepage meter # 1, and MDSM#2P located on the west side of the pond. (Locations of these piezometers are given in Figure 11.) In MDSM#1P, a strong downward gradient developed shortly after the beginning of the test which reversed rapidly after the end of the test. In MDSM#2P, the upward gradient increased during the test and fell afterward. Please note that there are no prior measurements available for these meters as they were installed shortly before the pumping test.

Figure 12 shows the drawdowns as well as the development of a distinct vertical gradient within the aquifer in the pondshore area adjacent to the pumping well. The gradient in the piezometer pair P17/18 very quickly rose to a value of -.30ft over the 13.5 foot interval between the two screened sections of the piezometers (-0.022ft/ft). Following the test, the vertical hydraulic gradient dissapated rapidly.

At deeper levels in the pond, a downward vertical gradient developed on the north side of the pond during the test, but not on the south side. Figure 13 displays the gradients in TNC P19 and P21. Both of these piezometers were screeened about six feet below the pond bottom.. P19 and 21 were installed on June 26th and the first measurements were taken on June 28th.

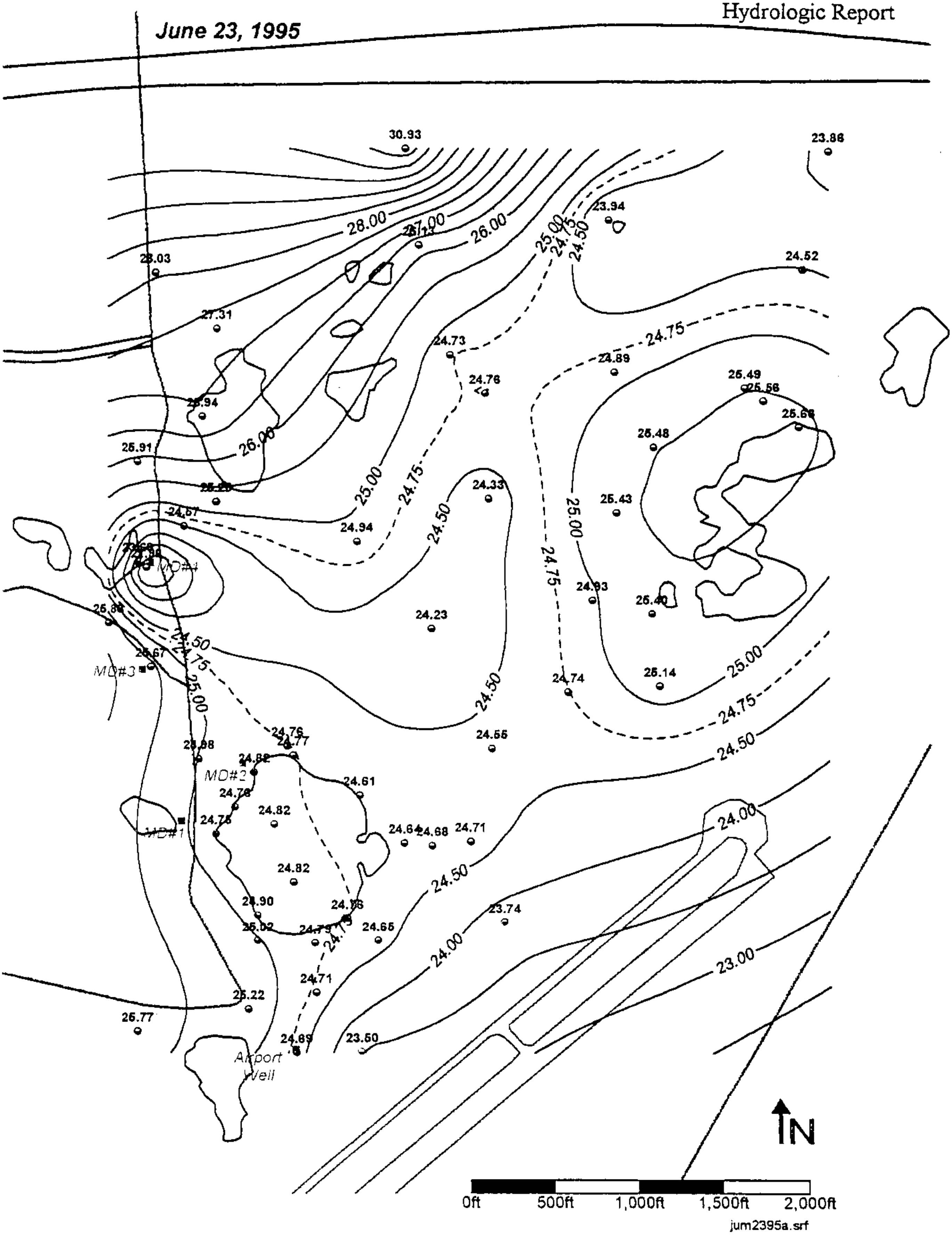


Figure 7. Water table map, June 23, 1995, at start of pumping test. Purple symbols denote estimated water levels.

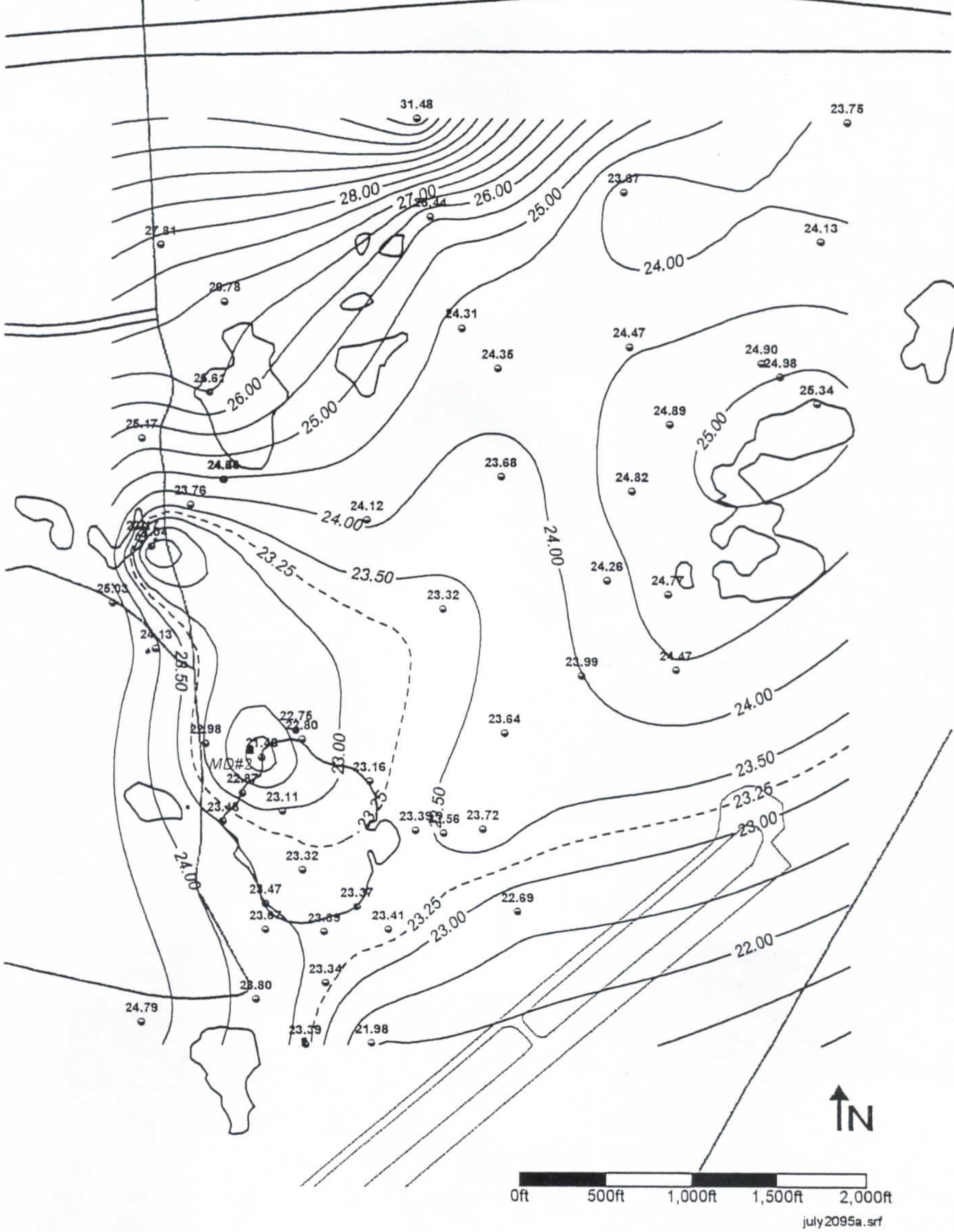


Figure 8. Water table map, July 20, 1995, at end of pumping test. Purple symbols denote estimated water levels.

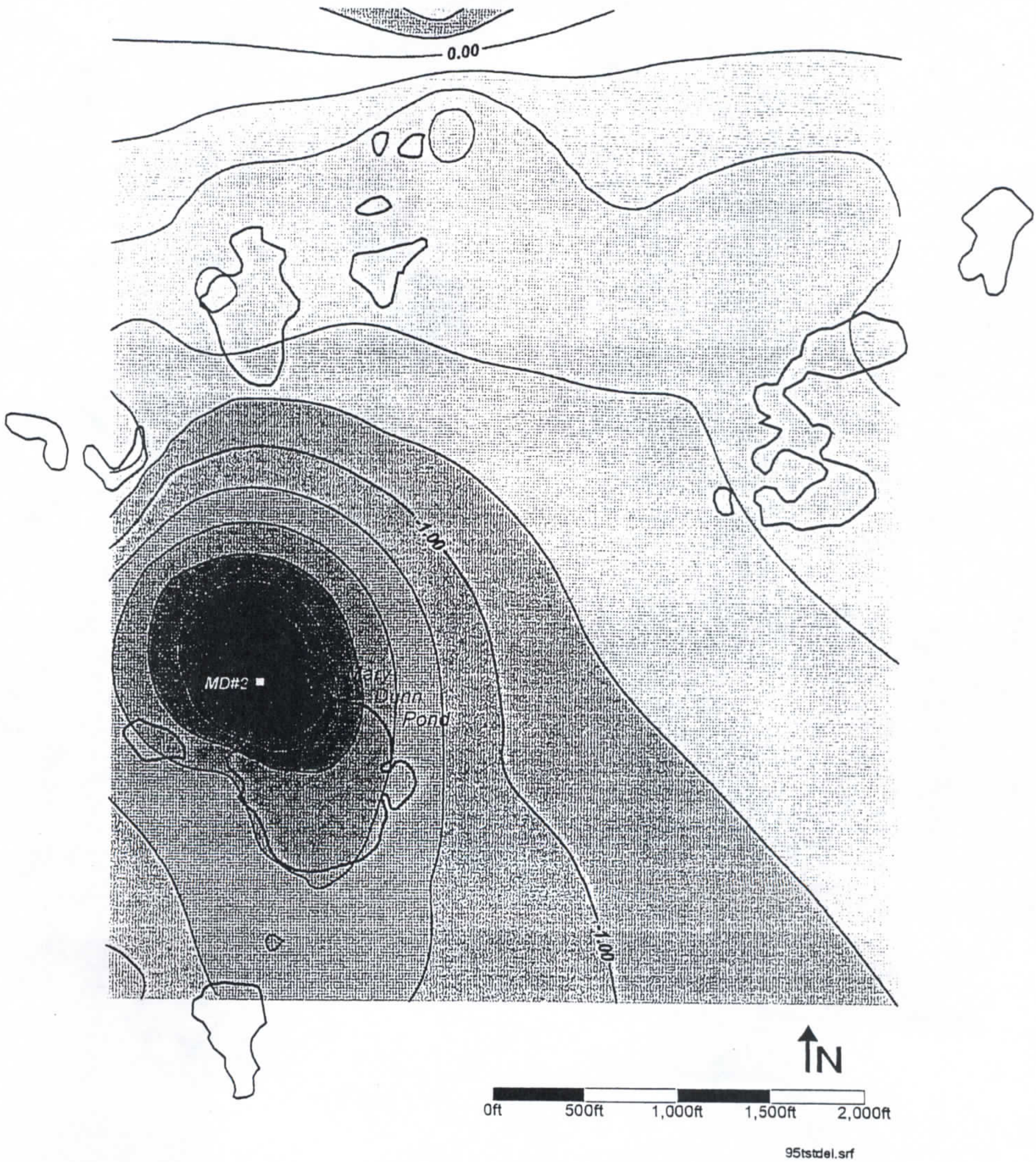


Figure 9. Water table change, June 23 to July 20, 1995. Contour interval is 0.20 feet, blue shading indicates negative change, green shading indicates positive change, red lines indicate whole numbers. Greatest change was 3.36 feet at P17.

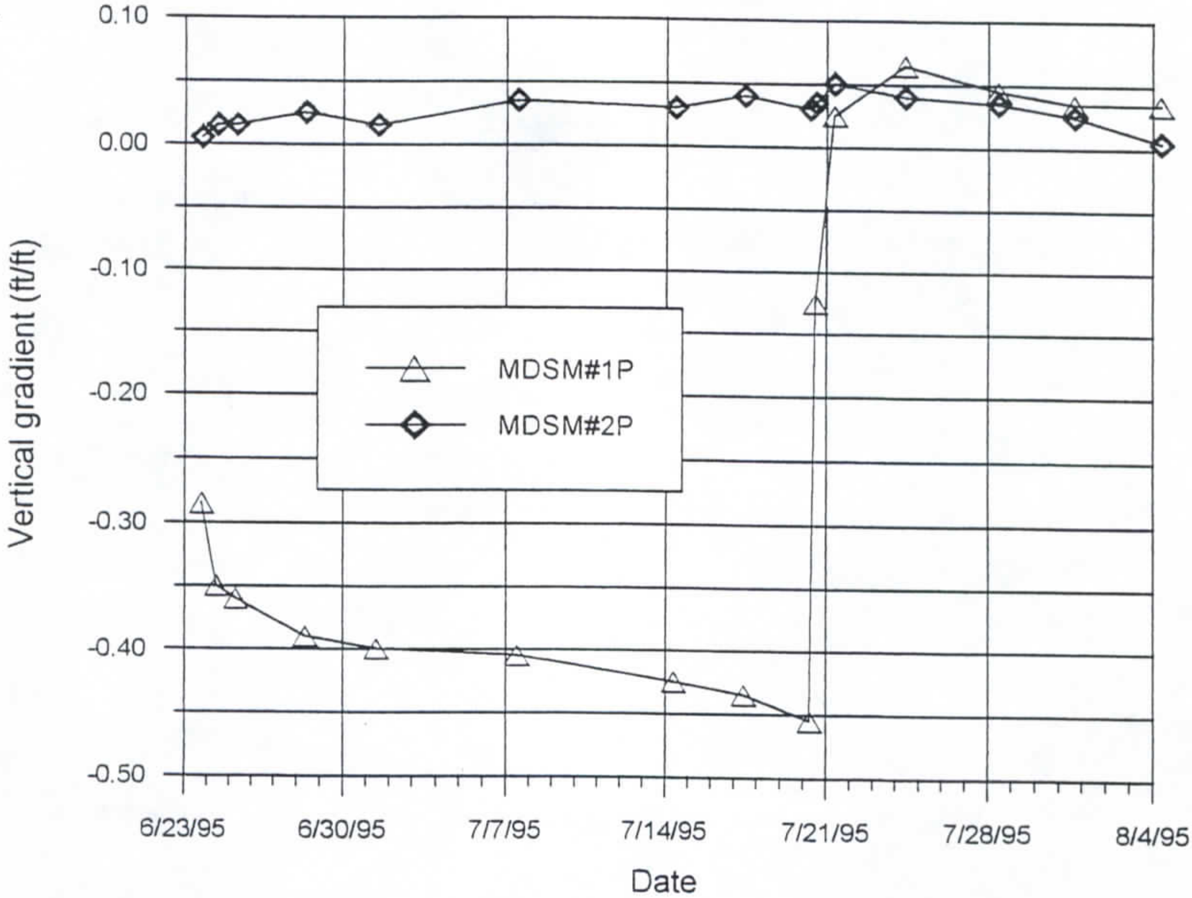
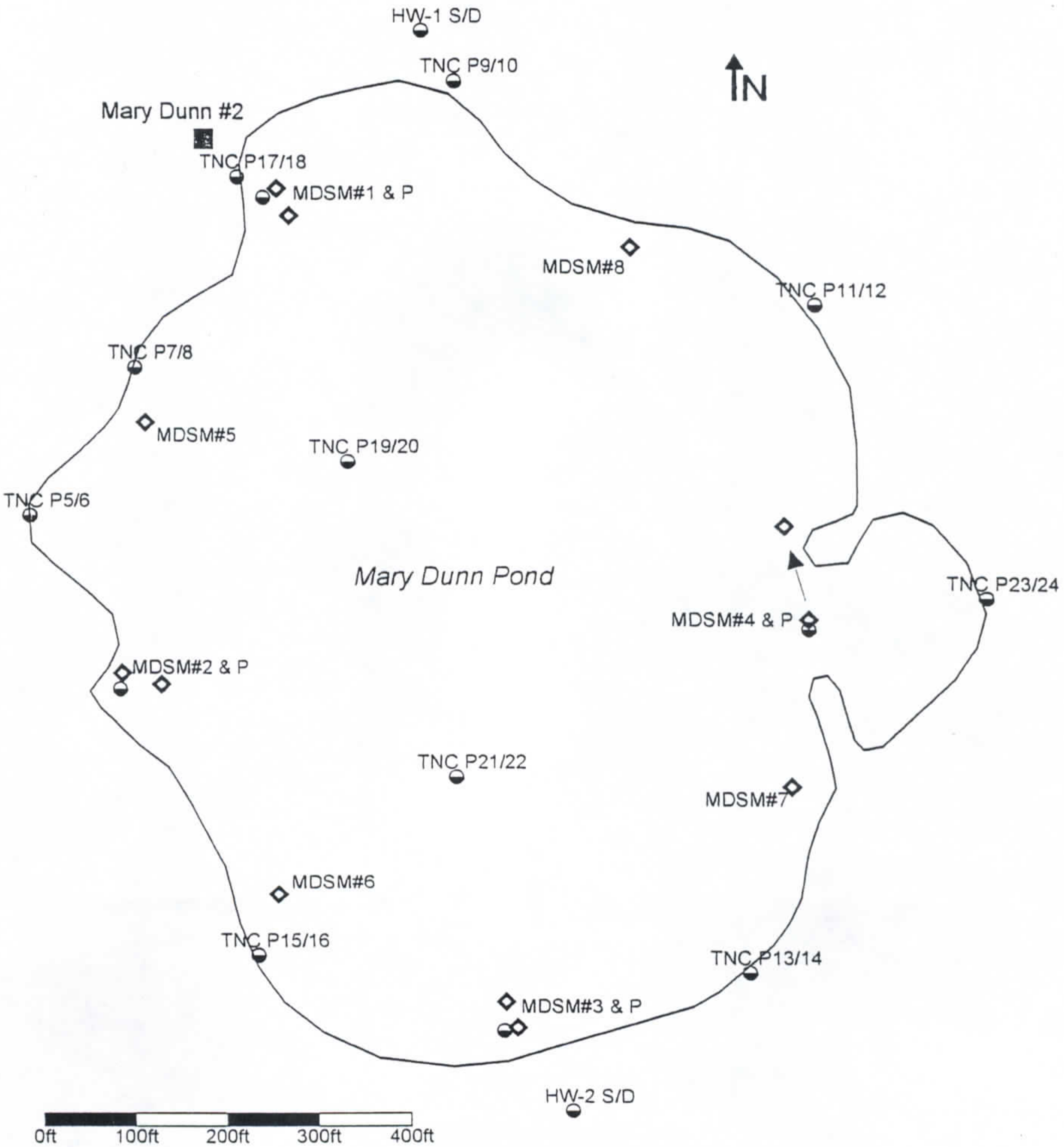


Figure 10. Development of vertical gradients in piezometers MDSM#1P and MDSM#2P. Ticks on the x-axis are at 00:00 on the indicated date. The first measurement is at 18:30 on June 23, 4.5 hours after the test start.

Figure 11. Location of piezometers and seepage meters around Mary Dunn Pond. Paired piezometers are indicated by two numbers eg. P17/18. Seepage meter locations are shown as diamonds. Seepage meters 1-4 were moved to deeper levels midway through the 1995 test (adjacent symbols). The arrow shows the movement of meter #4.



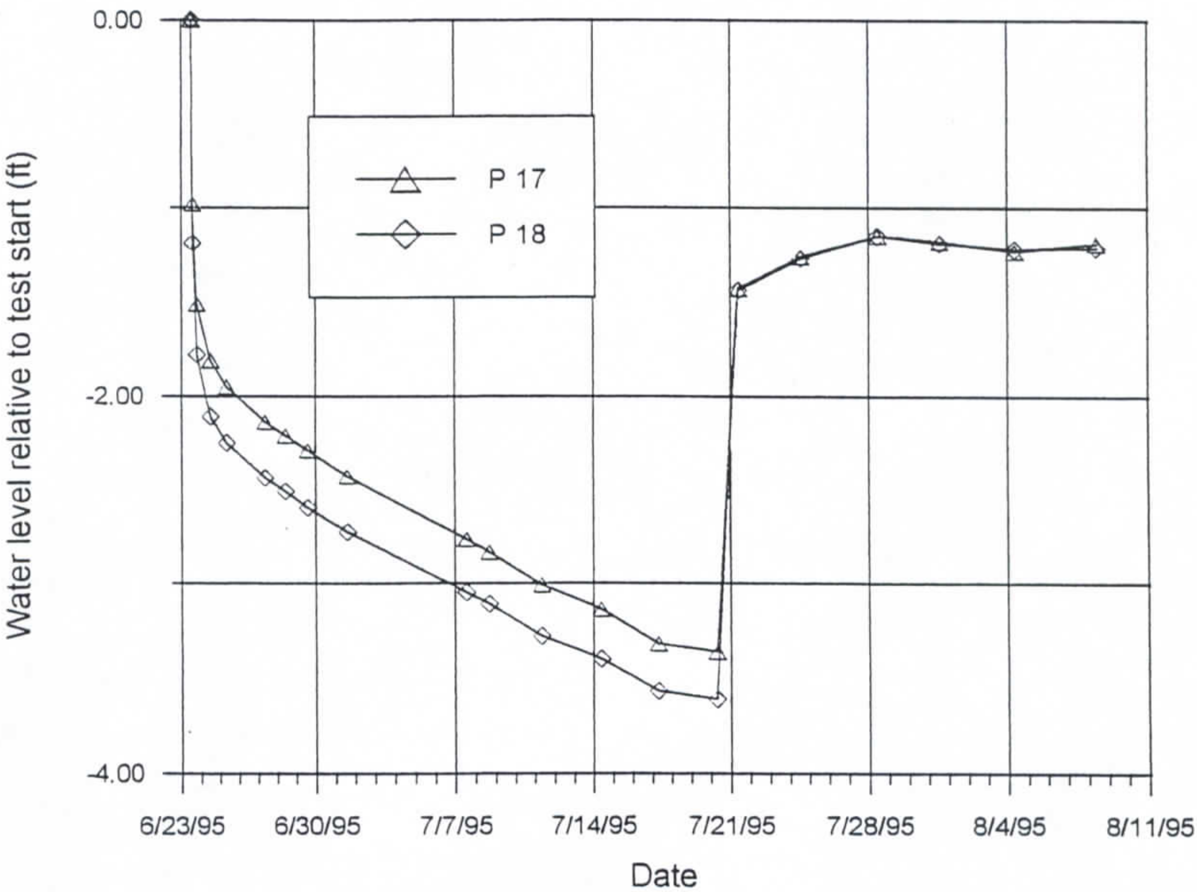


Figure 12. Water level changes in piezometer pair P17/18 during and following MD#2 pumping test June-July, 1995.

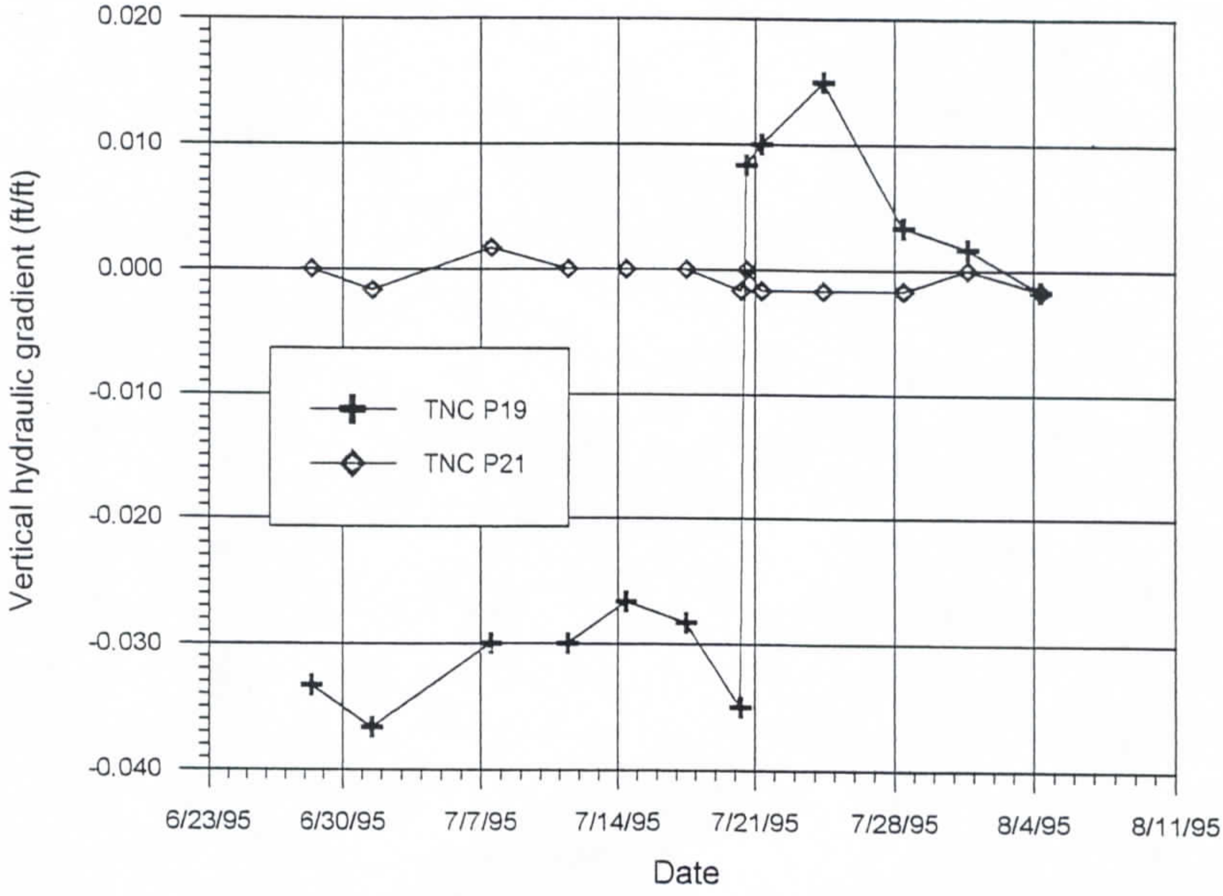


Figure 13. Vertical hydraulic gradients in pond piezometers P19 and P21. Date ticks are at 00:00 on the indicated date. Measurements on 7/20 are about five hours before and one hour after the end of the test at 12:00.

Discussion

The water table configuration shown in Figure 7 (June 23) is similar to the maps previously presented with one significant exception. A distinct cone of depression is present near MD#4. The apparent eastward extension of the cone of depression, joining with the trough to the west of Lamson Pond may be an artifact of the Kriging variogram used by Surfer. At this point, relatively early in the study, we had not installed monitoring points to the north of Mary Dunn and were not aware of the wells installed earlier by BWC as part of their exploration program in the 1970's. Later maps, utilizing these monitoring points, do not have the same degree of uncertainty in this area. Linear regression to nearby wells, as was done for the area south of Mary Dunn Pond, was not performed for this area. In 1995, MD#4 had been pumped for an extended period of time and flow patterns differed significantly from 1996 and 1997 in the area near this well. It was therfore felt that estimation of water levels in this area would yield possibly erroneous results for the period of the pumping test.

Prior to the test, flow in the area of Mary Dunn Pond is generally west to east as with previously given maps. By the end of the test this pattern has been altered and much of the flow is now directed toward the pumping well on the north shore of Mary Dunn Pond.

In Figure 8 (July20) the effect of pumping MD#2 is shown as a cone of depression surrounding the well. It apparently joins with the cone of depression associated with MD#4, however there is insufficient data from the area north of Mary Dunn Pond to draw firm conclusions about the exact configuration of the water table in this area. (The effect of pumping MD#2 on this area will be analyzed using the 1997 pumping test data.)

Lowered pond levels have altered the relationship between the aquifer and the pond by the end of the test. In areas to the east and southeast of the pond, the horizontal gradients had been from the pond into the aquifer at the beginning of the test. By the end of the test, these gradients had reversed, creating the potential for flow from the aquifer into the pond. To the southwest of the pond, horizontal gradients were from the aquifer into the pond throughout the test period, but were enhanced by the lowering of the pond during the test. In the northern section of the pond, gentle gradients from the pond to the aquifer at the beginning of the test became strong gradients from the pond into the aquifer at the end of the test.

The area of lowered water levels in Figure 9 extends around the pumping well but also extends around Mary Dunn Pond. It appears that the lowering of water levels in the pond extends the cone of depression to areas of the aquifer which interact hydraulically with the pond. Therefore, when pumping lowers pond levels, areas of the aquifer adjacent to the pond experience water level declines also. At any particular point, at some distance from the pumping well, these declines may be greater than would be expected based on a typical distance-drawdown relationship in an unconfined aquifer with similar hydraulic characteristics but no pond between the pumping well and the monitoring point. In essence, the pond extends the cone of depression to more distant parts of the aquifer, acting as if it were a large pumped well.

Vertical hydraulic gradients developed during the test within the cone of depression and dissapated after the end of the test. The gradients between the pond and the aquifer were large in the area near the well and decreased farther into the pond. The *pattern* of vertical gradient development was similar for MDSM#1 P, located about 100 feet south of the pumping well and for P19, about 400 feet south of the pumping well. For both piezometers downward gradients, present during pumping, rapidly reversed following the sessation of pumping. The post-test upward gradient in MDSM#1P lessened but remained positive, while in P19 the gradient returned to zero or slightly downward.

Conclusions

The pumping test produced clear effects on the water table surrounding Mary Dunn Pond as well as propogating drawdowns under the pond. These drawdowns resulted in the development of downward vertical gradients in the vicinity of the pumped well and extending at least 300 feet out under the pond. Duing the pumping test, the hydraulic relationship between the pond and the aquifer was altered so that some areas which were down-gradient to the pond at the beginning of the test became up-gradient by the end of the test. The mechanism for accomplishing this reversal was removal of pond water in the vicinity of the pumping well in areas of strong downward vertical gradients. Following the test the vertical gradients in the vicinity of the pumping well reversed.

Temperature Measurements

Methods

In conjunction with H&W, TNC installed a piezometer pair between the pond and MD#2; the shallow piezometer (P 17) was installed to a depth of about eight feet below grade, the deep piezometer (P 18) was installed to a depth of about 24 feet below grade. The intent was to use an H&W temperature probe to measure water temperatures in the deeper piezometer, however the probe would not fit into the narrow piezometer opening. In order to obtain measurements without delay, a temperature meter was constructed using a Radio Shack indoor-outdoor thermometer, a thermistor-based instrument. Rated accuracy of the thermometer was +/- 2°F, reading to 0.1°F. The thermometer was calibrated against a mercury thermometer on several occasions to guard against significant drift, but was not calibrated against a lab or calibration grade thermometer to assure absolute accuracy of the readings. After completion of the pumping test this thermometer eventually wore out under the rigors of field work and was replaced in early September. The new electronic thermometer was calibrated against the mercury and original electronic thermometers. All of the temperatures given in this section of the report should be considered to be accurate relative to one another, but their accuracy relative to a fixed standard is only within the product specifications.

Due to the delay in constructing a useable thermometer while monitoring the beginning of the test, the initial temperature measurements did not take place until June 27, four days into the test. The initial measurement of temperature in P18 was 58.5°F at a depth of 12 feet below TOC and decreased above and below this level. Since the temperature was well above the expected temperature of about 50°F at this level, temperature measurements were taken at six other deep (≈14 feet below grade) piezometers which were in place around the pond at that time, to establish a "background" temperature level. Temperatures were measured at depths of 6, 9 , 12 and 15 feet below TOC (also 18 feet in P18). The results of these measurements indicated that there was no single background temperature at the twelve-foot depth, but instead, that temperatures varied with position around the pond. The twelve foot depth was chosen as the standard for comparison as it was the depth with the highest temperatures in P18. Temperatures were subsequently measured in all of the piezometers around the pond shore and several nearby wells thoughout the course of the pumping test and into and through the fall of 1995.

Results

Figure 14 show the temperature levels in the piezometers at a depth of twelve feet below top of casing (TOC), please refer to figure 11 for the piezometer locations.

Discussion

There are several significant patterns evident in this graph. First, significant increases in temperature are evident in the vicinity of the pumping well, MD#2. The largest increases in temperature during the pumping test occurred in the three piezometers closest to the pumping well. Temperatures rapidly increased in P 18, reaching a peak of 77.1°F on July 17th, three days before the end of the test. The highest temperatures reached in P 18 are similar to the pond water temperatures during the latter portion of the test. Pond water temperatures were measured on July 14th at a location about 50 feet from the shoreline near the pumping well. The temperature varied from 75°F in the morning (09:00) to 84°F in the late afternoon (17:30). In piezometer P8 about 200 feet to the south-southwest of P18 ground-water temperatures at the 12 foot depth rose to 63.5°F by the end of the test. The shape of the temperature change curve (Figure 14) indicates that the temperatures in P8 had achieved or were nearing an equilibrium state at this time. The piezometer with the third highest temperature increase during the test was P10 located about 270 feet to the east-northeast of P18.

Following the test, temperatures in P8 decreased while those on P18 did not. In fact, ground-water temperatures in P18 remained at nearly the same high level (>75°F) into September and did not return to normal levels until January of 1996. Temperatures in P10 continued to rise after the end of the test.

The second pattern is one of overall ground-water temperature increase through the course of the test, evident in the temperatures in the other piezometers. There are several exception to this pattern. Piezometers P16, P14 and P24 show little temperature increase during the test. Following the test temperatures in these piezometers rose in a similar fashion to the other wells.

The third pattern evident in the temperature data is that, when the effect of pumping is removed, the upgradient areas of the pond have lower ground-water temperatures than the down-gradient areas. The up- and down-gradient areas of the pond have been determined by water table mapping and vertical gradients in the pond-shore piezometer pairs.

The fourth pattern seen in some wells is typified by P16 and P24. In these piezometers, water temperatures were fairly static during the test and began to rise, in a pattern similar to other

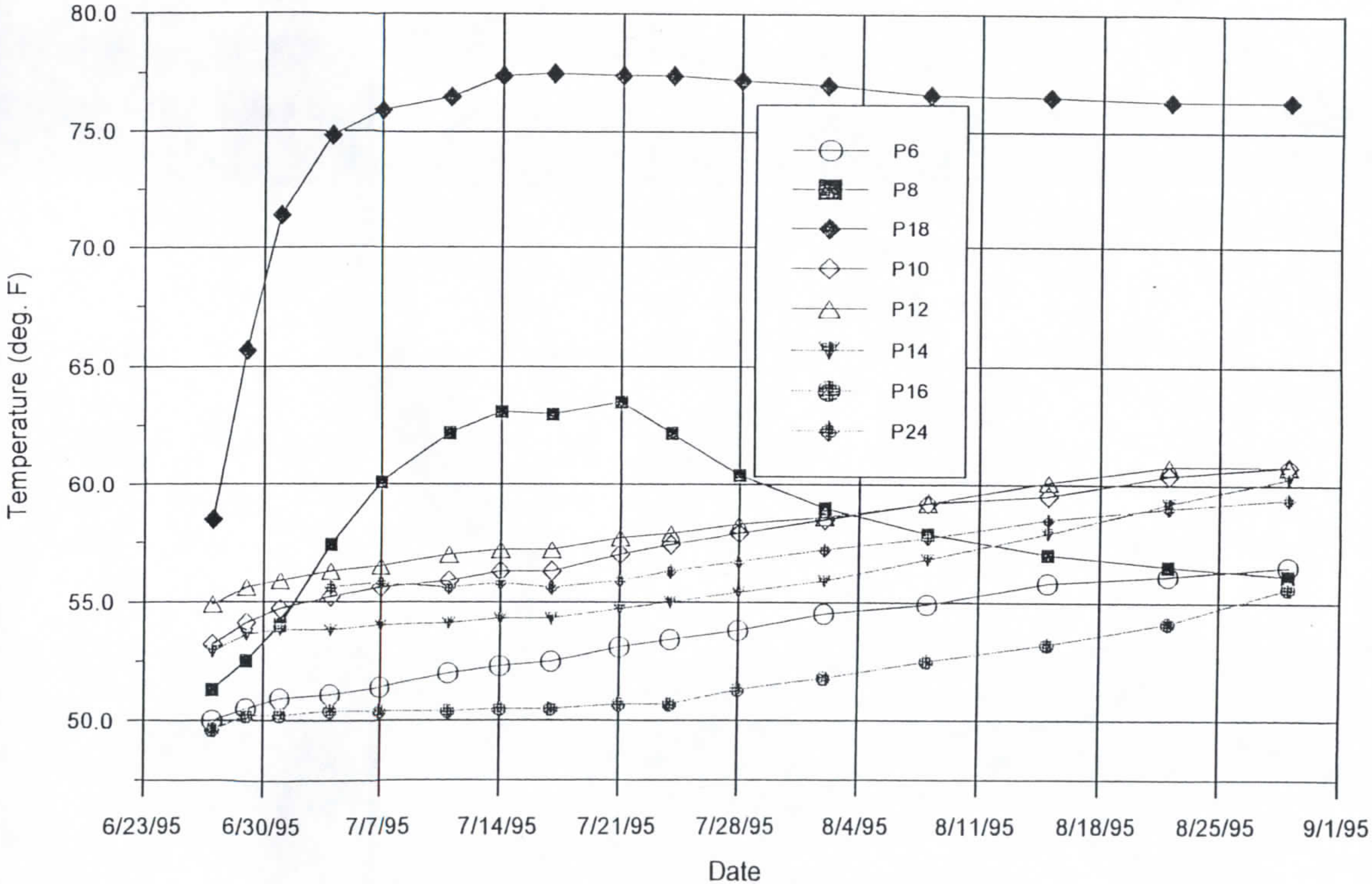


Figure 14. Temperatures in Mary Dunn piezometers during and following MD#2 pumping test, June-July, 1995. Locations strongly affected by movement of pond water into the aquifer are indicated in red, those affected by movement of ground water into the pond by blue, others by green.

Heat in ground water moves by conduction, convection and radiation as in any other physical setting where a fluid phase is present. Radiative heat transfer is considered to be minimal by most workers in this field (Barlow, 1987). Conduction takes place both within and between the fluid and solid phases of the aquifer. Conductive heat movement under a temperature gradient is similar to the diffusion of solutes under a chemical concentration gradient and can be described with similar mathematical treatment. Also heat, like solutes, moves with movement of ground-water mass. This process is referred to as forced convection, and is similar to advective transport of solutes (Freeze and Cherry, 1979). Under free convection, water movement is controlled by density differences. In any flow system, all of these mechanisms may operate.

Annual ground-water temperature fluctuations are commonly observed in areas with seasonal air temperature variations due to the addition and subtraction of heat from the land surface. Downward conduction of heat and forced convection with infiltrating rainwater produce a near-surface zone of temperature fluctuation. At some depth, usually about 20 feet below grade, these fluctuations are damped by the thermal mass of the aquifer materials and intergranular water.

In addition, local sources and sinks of heat can influence ground-water temperatures through conductive and convective heat transfer. In the summer, Mary Dunn Pond is just such a source of heat. Solar heating of the pond water proceeds rapidly, outpacing the seasonal vertical transfer of heat through the unsaturated zone into the relatively cool surrounding aquifer. Under these conditions, all areas of the pond margin receive some heat from the pond water by conductive transfer. Downgradient areas will also receive heat by forced convection, by one of two methods. First, water may flow directly from the pond through an area of the pond shore, heating that area. Second, water underflowing the pond may pick up heat conducted from the overlying waters through the pond bottom, move though a down-gradient section of the pond shore, and transfer that heat by conduction.

The movement of heat by underflowing water is somewhat problematic in the hydrologic setting of most coastal plain ponds. Horizontal flow velocities are likely to be low in close proximity to the deeper areas of the pond due to the accumulation of fine-grained sediments in those areas. Underflowing water may flow at velocities high enough to transfer significant heat to the pond margin, but not through the fine-grained sediments in close proximity to the heat source, ie. the pond water. High flow velocities will only be produced at deeper, cooler levels where heat conducted downward from the pond bottom will be minimal. It is therefore unlikely that underflow of the pond produces any significant heat transfer to the pond margin.

Efficient forced convective transfer of heat may take place due to flow of water from the pond through the marginal or bottom sediments. In areas which recieve copious quantities of warm pond water, the temperature rise may be dramatic.

In upgradient areas of the pond, heat may be *lost* from the pond shore by forced conduction as cooler aquifer water flows into the pond. This will be particularly true in those areas where ground water moves upward toward the pond. If flow rates are low or nil, heat may be gained by conduction of heat from the pond and vertical heating from the surface (for exposed areas of shoreline). Some areas of the pond may have a delicate balance of vertical heating, conductive heating from the pond and forced convective cooling from ground-water flow.

These types of effects are evident in the temperature measurements from Mary Dunn Pond. Clear forced convective movement of heat is seen in the area near the pumping well, MD#2, producing profound changes in temperature. Other downgradient area of the pond also recieved a combination of vertically transferred heat and heat convected from the pond, however in lower amounts due to the lower volumes of outseepage from the pond. Some areas of the pond, such as near P16, display a balance of convective cooling and diffusive heating which may be upset by changes in the pattern of ground-water flow.

The persistence of high ground water temperatures in P18 may also be evidence of free convective heat movement following the cessation of the test. The temperature measurements in this piezometer were taken at depths down to 18 feet below grade, but the pumping well is screened at an interval from 40 to 60 feet below grade. Temperatures in water taken from the pumping well indicated that warm pond water flowed to the well screen (Horsley and Witten, 1996). A large volume of warm water therefore was emplaced under P18 as well as near the surface. Under lower horizontal ground-water velocities following the test, free convection may have dominated the heat transfer process continually moving high-temperature water up from deeper levels.

An interesting implication of the results presented above is that K, hydraulic conductivity of the area between the pond and the pumping well varies as a function of temperature. Hydraulic conductivity may be expressed as:

$$K = \frac{k \bullet \rho_w \bullet g}{\mu}$$

where: k = intrinsic permeability, a function of aquifer properties only,
ρ_w = density of water,
g = the acceleration of gravity, and
μ = dynamic viscosity (Domenico and Schwartz, 1990)

Since $\mu / \rho_w = \nu$, where ν = kinematic viscosity,

$$K = \frac{k \bullet g}{\nu}$$

A change in water temperature from 10°C to 25°C results in a dynamic viscosity reduction from 1.307 centipoise (cp) to 0.8904 cp and a density reduction from 0.99973 to 0.99707 gm/cm^3 (Weast, 1977). Kinematic viscosity therefore changes from 1.787 to 0.8930 centistokes or a reduction of 31.7%. Since the intrinsic permeability and acceleration of gravity do not vary, hydraulic conductivity should rise by about 32 % in any aquifer volume which experiences this change in temperature. Movement of heated pond water through the aquifer should result in the creation of a temporary zone of enhanced hydraulic conductivity between the pumping well and the pond.

Conclusions

The temperature changes that took place during and after the pumping test clearly indicate that pond water was flowing though a portion of the shoreline near Mary Dunn #2 and toward the well during the pumping phase of the test. During recovery, temperature reversals in P8 indicate a reversal of flow and ground water flow was toward the pond, however, ground-water temperature closer to MD#2 remained very high for an extended period of time. In addition, the overall pattern of ground water temperature indicates that the areas of the pond shore on the wast and north side are upgradient from the pond. The patterns of temperature changes in some of the piezometers also indicate that during the test, ground water was flowing toward some areas of the pond margin at higher rates than after the test. This indicates the potential for change in the balance between inseepage and outseepage in areas of the pond away from the pumping well.

Area Pond Level Changes/Water Balance

Method

During the pumping test, water level measurements were performed throughout the TNC wellfield weekly, with more frequent measurements in the area around Mary Dunn Pond. Pond water level measurements were also performed before and after rainfall events. Pond level measurements at Mary Dunn Pond were taken by dropping a water tape to the pond surface from the top of the BWC staff gage and are accurate to 0.01 feet. Lamson and Israel Ponds were measured to the same accuracy.

Results

Figure 15 shows pond levels in Mary Dunn and two other ponds as well as two wells in areas away from the pumping well. The time interval of this graph also includes early June when tropical storm Alison dropped about three inches of water on June 7th and 8th. Tropical storm Alison provided some recharge to the water table after which ground-water levels fell steadily with no apparent significant recharge during the test and into the Fall of that year. During the pumping test and recovery period, ground-water levels, as indicated by the reference wells, fell at a rate averaging 0.023 feet per day.

Pond levels in Israel and Lamson Ponds also fell during the period of the test. During the initial stages of the test, these ponds fell at rates similar to, but slightly lower than ground-water loss rates of 0.023 feet per day. Between July 14th and July 17th, near the end of the test, Israel and Lamson Ponds both fell at an average rate of 0.027 feet per day. Daily high (air) temperatures were 86°F and 91°F for the 15th and 16th of July respectively. For the period from July 19th through July 24th, both ponds fell at an average rate of 0.022 feet per day as temperatures cooled somewhat following rain on the 18th and 19th.

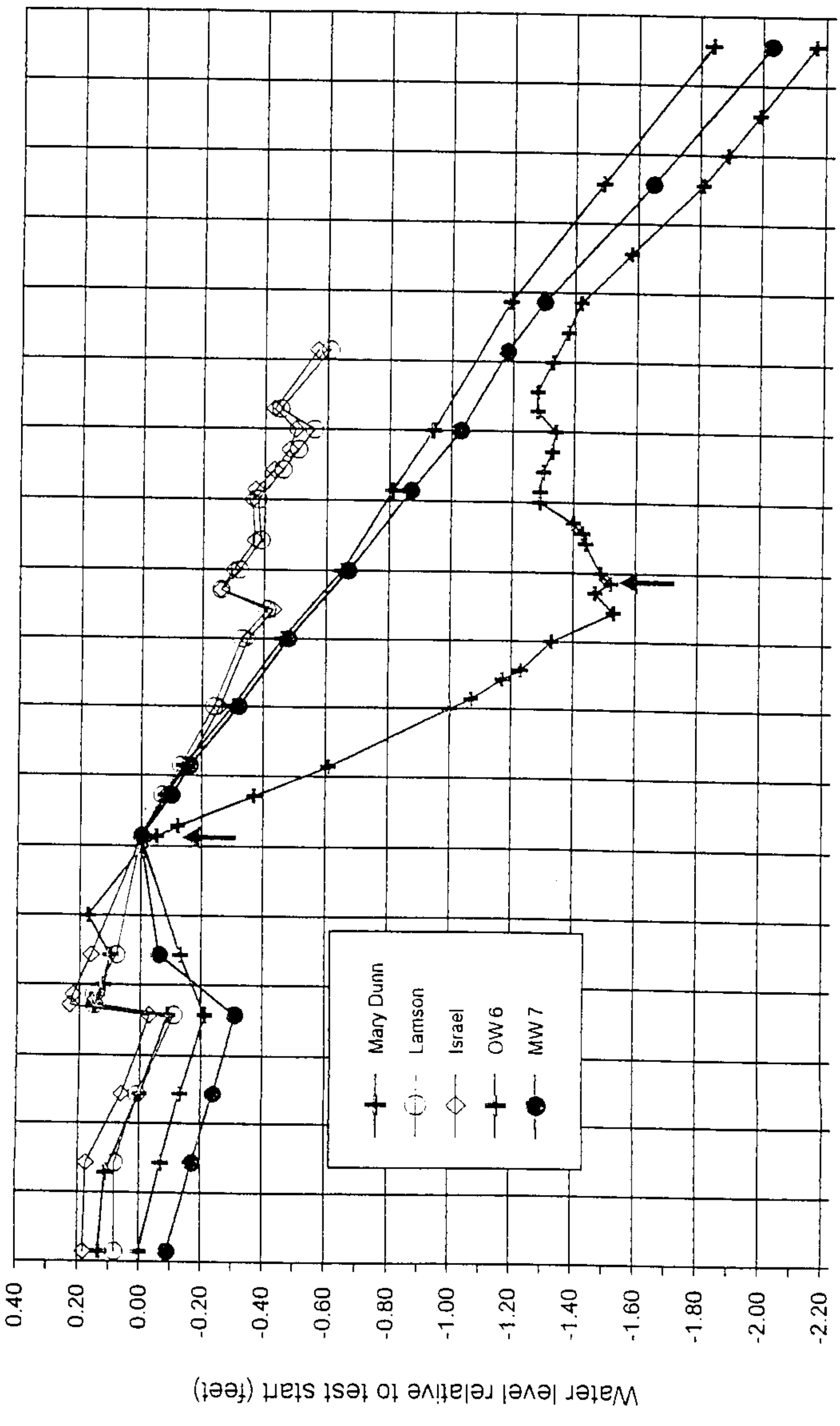


Figure 15. Water level changes May to August, 1995. Water levels are relative to the start of MD#2 pumping test on June 23rd. Green arrow indicates start of pumping test, red arrow indicates end of test.

Discussion

On July 14th, water temperatures were measured in Israel and Lamson Ponds in mid-afternoon at 96.1°F and 99.9°F respectively. These measurements were taken in locations well out into the ponds, at depths typical for the ponds at this time. Average daily air temperatures for July and August were 72.0 and 70.2°F respectively. Daily highs were in the upper 70's and 80's. After the test, Israel and Lamson ponds dried out except for deep holes in the center of the pond basins. In early August, as these ponds dried out, water levels fell at rates as high as about 0.027 feet per day (as calculated during rain-free periods). At this stage, water was present only in the portions of the ponds underlain by fine-grained, highly organic rich, low-permeability sediments. All of the vertical hydraulic gradients, measured in Israel Pond and on the pond shore were downward through this period. (Lamson piezometer pairs were not yet installed.) It is likely under these conditions that most of the water loss from Israel and Lamson Ponds was due to evaporation, although some downward leakeage of pond water may also have occurred.

Under these conditions of high air and water temperatures and very shallow pond depth, the water loss rates that occurred from July 14th to 17th and after the test represent the extreme upper limits of evaporation rates for this area, corresponding to about 0.8 feet or 9.7 inches per month, assuming negligible leakage of pond water to the water table. These evaporation rates occurred at the end of the pumping test and for about a month afterward and would only occur as a pond is close to drying out completely and are therefore not valid for comparison to Mary Dunn Pond during the pumping test.

It is likely that evaporation rates in Mary Dunn Pond during the pumping test were considerably lower. During the test both Lamson and Israel Ponds were shallow averaging about two feet over their entire area, while Mary Dunn was about five feet deep in the middle of the pond. Mid-pond temperatures in Mary Dunn were in the upper 70's through the latter part of the test. Mid-pond temperatures are relatively stable and integrate the effects of diurnal variation due to solar heating during the day and radiative and evaporative cooling at night. The shallow waters of the shoreline and near-shore zones heat up to a greater extent during the day than do the deeper waters in the mid-pond. Shoreline and near shore water surface temperatures in Mary Dunn Pond reached 85.8 and 83.7°F respectively in the late afternoon of July 14th (as compared to 99.9°F in Lamson Pond and 96.1°F in Israel in mid-afternoon). These temperature represent the upper end of the diurnal fluctuation in temperatures in Mary Dunn Pond. Due to the lower temperatures, Mary Dunn Pond would not be expected to experience evaporation rates as high as those in Lamson and Israel Ponds under these conditions.

Conclusions

Despite lower expected evaporation rates, Mary Dunn Pond fell at a rate averaging 0.063 feet per day during the test (after adjustment for rainfall). This rate is three times the overall rate of ground-water decline during the same period and over three times the rate of decline in Lamson and Israel Ponds (after adjustment for rainfall). The difference is attributable to the effects of pumping.

Mary Dunn Pond Water Budget

Method

I have prepared a water budget for Mary Dunn Pond for the pumping test period by the following method. A water budget equation may be written as:

PPTN + RO,in + GW,in = E + RO,out + GW,out + ΔS Where:

PPTN = precipitation; RO,in = streamflow into the pond; GW,in = ground-water input to the pond; E= evaporation from the pond surface; RO,out = streamflow from the pond; GW,out = ground-water output from the pond and ΔS = the change in storage within the pond.
The water budget for this test treats the pond as a system with boundaries equivalent to the top and bottom surfaces of the pond. There are no surface water inputs to or outputs from the pond, therefore the runoff terms drop from the equation. The ground-water term has been lumped to give total ground-water exchange. The resulting equation is:

PPTN = E + GW,exch + ΔS.

During the pumping test Mary Dunn Pond fell a total of 1.52 feet over 27 days, while Lamson Pond fell 0.32 feet and Israel Pond fell 0.30 feet. The NOAA weather station in Hyannis reported 2.02 inches (0.17 feet) of rain, most of which fell on the 17th and 18th of July.

I have estimated evaporation during this period based on three methods. First, evaporation may be estimated using the Thornthwaite (1948) method. The Thornthwaite method is meant to estimate potential evapotranspiration, and is commonly used to estimate evaporation under the assumption that evaporation from a free surface will be similar to evapotranspiration (ET) under conditions of unlimited water supply. The calculations estimate ET at 4.36 inches (0.36 feet) for June and 5.45 inches (0.45 feet) for July. I have estimated ET for the pumping period by applying the June rate to the first quarter of the test period and the July rate to the last three quarters of the test period and adjusting for the duration of the test (27 days). The calculated Thornthwaite ET for this period is thus 4.53 inches, equivalent to 0.38 feet or about 0.014 feet per day averaged over the test.

Evaporation may also be estimated by an energy-balance method such as Penman-Montieth, however, this requires collection of data on solar radiation, relative humidity and windspeed as well as air temperature. Fennessey and Vogel (1996) have developed a regional model for the northeastern U.S. to emulate the Penman-Montieth evaporation calculation based on air temperature, elevation and longitude. This allows calculation of evaporation in areas not served by first-order climate stations. I have calculated evaporation by their method as 6.60 inches (0.55 feet) for June and 7.25 inches (0.60 feet) for July. I have estimated evaporation for the testing period, as indicated above, to be 6.22 inches, equivalent to 0.52 feet or 0.019 feet per day.

Evaporation may also be estimated based on the water loss rates in reference ponds (presumably unaffected by pumping), recognizing that some percentage of water loss from any pond under conditions of a falling water table may be due to leakeage to the surrounding aquifer through the pond bottom. For this study, the only ponds available for comparison are Lamson and Israel. As stated above, these ponds experienced higher temperatures than Mary Dunn during the pumping test. Therefore, any estimate of evaporation based on water loss rates from these pond should be considered as overly high. Using the average water loss (0.31feet) and reported rainfall (0.17 feet), the resulting evaporation for the duration of the test is 0.48 feet or an average of 0.018 feet/day, similar to the result given by the method of Fennessey and Vogel (1996).

Given the results above, it is likely that the method employed by Fennessey and Vogel (1996) somewhat over-estimates evaporation, especially for Mary Dunn Pond. It predicts greater water loss than was observed at Israel and Lamson Ponds. It is unlikely that *all* of the water lost from these ponds was due to evaporation; some small portion of the water loss was probably due to leakage though the pond bottom. Use of this Fennessey and Vogel's method in calculating a water budget will result in an apparently *lower* effect of pumping, than using either of the two other methods. However, I prefer to use this method calculation of the water budget for this test as it will *conservatively* estimate the effect of pumping.

Results

The resulting equation is:

$PPTN = E + GW,exch + \Delta S,$

$0.17\ ft = 0.52\ ft + GW,exch + (-1.52\ ft) \therefore$

$GW,exch = 1.17\ ft$

This ground-water exchange represents the balance of ground water gains and losses during the test, not just the amount of ground water lost. It is therefore, a minimum estimate of the amount of water lost from the pond to the pumping well. This linear measurement may be converted to a volume if the area of the pond is known. As the pond margin is a sloping surface, a reasonable estimate of the area over which this water loss occurred may be made by averaging the upper surface area of the pond at the beginning and end of the test. The entire pond margin and parts of the pond bottom have been professionally surveyed during a period of very low water. (Eagle Surveying, 1991, unpublished) I entered this data into a Surfer® file and produced a contour map of the pond margin slope. From this map I determined the areal extent of the pond at the beginning of the test (pond elev. ≅ 25 feet, area = 15.9 acres) and at the end of the test (pond elev. ≅ 23.5 feet, area = 13.8 acres). The average of the two areas, 14.85 acres is the area over which the pond lost water for purposes of this calculation. A depth of 1.17 feet over 14.85 acres is equivalent to 5.66 million gallons or 27% of the 20.724 million gallons pumped during the test.

Conclusion
The test period water budget indicates that during the pumping test of Mary Dunn #2, the net loss of water from Mary Dunn Pond to the surrounding aquifer was 5.66 million gallons. This number represents 27% of the volume pumped by Mary Dunn #2 during the test period. This is a *minimum* estimate of the actual percentage flowing to the well for two reasons. First, it is a calculation of net pond and groundwater exchange and neglects ground water inflows in areas distant from the pumping well. Second, the method used to calculate from the pond evaporation (Fennessey and Vogel, 1996) produced the highest estimate of evaporation of the three methods proposed for use in the water budget.

Seepage Meter Measurements

Introduction
Although vertical gradients demonstrate the potential (in the strict sense) for water movement between the pond and the aquifer, they do not demonstrate actual movement. The actual movement of water between the pond and the aquifer may be measured using seepage meters. Seepage meters isolate a section of pond bottom and measure the flow of water through that section. Using measured flow rates and vertical gradients across the pond bottom, pond bottom conductance may be measured.

Method
Seepage meters for this study were constructed in a manner similar to that outlines in Lee (1977) and other publications. The basis design is half of a 55-gallon plastic drum fitted with tubing ports to allow water to flow in and out of the meter. Each meter was fitted with two ports to allow any accumulated gasses to be exhausted easily. The cut edge of the meter was serrated to facilitate driving the meter into the pond sediments. Handles glued and rivetted on the upper rim of the meter provided a grip. All of the rivet holes were sealed with silicone aquarium sealant.

The meters were driven into the pond bottom by rotating them by hand while applying downward pressure. They were driven to the final depth by walking on top of the meter, while being careful not to touch the tubing ports. Each meter was emplaced to a depth of at least six inches. The method of emplacement limited the depth of water in which the meters could be placed to about three feet. During periods of rapid drawdown it became necessary to move and re-emplace the meters.

Four meters were placed prior to the start of the pumping test and four additional meters were added during the test. Additional meters, added after the test, are not included in this section of the report. The locations of the meters used during the pumping test are given in Figure 11.

Each meter had 1/2 inch tubing attached to the tubing port. This tubing terminated in a "quick connect" (purchased from Fischer Scientific Inc.), which allowed it to be connected to tubing on the measurement bag. For measurement bags, I used Baxter Inc. urine collection bags. These clear plastic bags come with tubing with installed clamps, have about a 2.5 liter capacity and have a blowout valve which prevents catastrophic loss of fluids (of any variety) during overfilling.

Prior to installation, each bag was pre-filled with 1000ml of water, emptied of air and sealed using tubing clamps. Bags were installed by connecting to the meter tubing and opening the clamps at a known time. Following a time period determined by the filling or emptying rate, the bags were retrieved after closing the clamps at an observed time. Seepage rates were calculated based on the elapsed time, change in bag volume and the cross-sectional area of the meter.

Results

Seepage rates for late June, July and August, 1995 are given as Table 1. Several seepage rates calculated from the measurements of the meter adjacent to the pumping well may be too low. Outseepage rates from this meter were very high and on two occasions the final bag volume fell below 150 ml. When this occurred, collapse of the bag prevented easy passage of water.

The most obvious feature of the seepage results is the large rate of outseepage at meter #1, located adjacent to the pumping well. Following the test, this pattern reversed and the area was dominated by inseepage at much lower rates. Meter #2 experienced inseepage throughout the summer. Seepage rates increased for meter # 2 at the original location, as the test proceded. The seepage rates at the other locations are considerably lower. In some cases, these readings were obtained after the bag was left on the meter for two days. Rates below +/- 10ml/sq. meter/hour probably signify insignificant or no seepage at these locations. At several locations, both inseepage and out seepage were observed

Discussion

The high rates of outseepage at meter #1 very clearly indicate the influence of pumping on the pond. The adjacent meter to the west (meter #5) also experience outseepage during the test and inseepage after the test, although the rates were much lower.

There is some indication of an increase of inseepage as the test proceeded. Meter # 2 located on the east side of the pond experienced inseepage thoughout the test. At the first placement of this meter, inseepage increased in the first three measurements. At meter #3, the test period was characterized by inseepage, but after the test this location experienced both inseepage and out seepage.

For the other meters, there is not a clear pattern of seepage related to the test of MD#2. The somewhat ambiguous results from these other meters are also significant when considered in the context of the areas of distinct inseepage and out seepage. The materials of the pond bottom are highly variable, ranging from a mix of silt and organic materials to a mix of cobbles and sand. Some of the areas of coarse-grained substrate extend well out into the pond. A recent attempt to emplace a piezometer adjacent to the deeper placement of meter #2 (inseepage zone)was thwarted by a large rock about two feet below the pond bottom. Note also that seepage rates are *higher* for the deeper locations of meters #1 and #2, than for their shallower locations. There appear to be some areas, well out into the pond, capable of allowing fairly rapid movement of water across the pond bottom. There are also areas, extending up fairly high up on the shoreline, which do not allow much water movement. Thus the pond bottom appears to be a mosaic of sediment types and permeabilities.

Table 1. Seepage Meter Readings for Mary Dunn Pond

All readings are in liters per square meter per hour. Negative readings indicate outflow, positive readings indicate inflow

Seepage Meter Number

Date	1	2	3	4	5	6	7	8	9
06/25/95	-6620	1.2	57.9	-21.9					
06/27/95	-6950	37.8	56.7	-29.9					
	-6690								
06/29/95	-6200	95.5	1.7	-19.6					
	-6720								
	-6750								
07/03/95			127	-2.9					

Note: Meters 1,2,3 & 4 were moved into deeper water in this interval due to pond drawdown and meters 5,6,7,& 8 were installed.

07/09/95	-7130								
	-7980								
07/10/95		381	0	56.8	-43.3	-66.5	39.3	-4.3	

Note: Readings for meter #1on 7/9 and 7/12 should be considered too low since the final bag volume was below 150 ml.

07/12/95	-10410								
07/13/95		391							
07/14/95			63.2	9.3	-16.2	-5.9	-11.5	-24.4	
07/16/95	-13570	755				-148			
	-20670								
	-20510								

Note: Three meter readings were taken on 7/16 for meter #1. For the first reading the final bag volume was below 150 ml. In the two subsequent replicates the final volume was greater than 200 ml.

07/17/95			22.3	6.7	-14.4		12.8	7.4	
07/19/95	-18290								
	-20918								
07/20/95		306	12.9	6.6	-7.8	-7.1	-7.4	-8.3	
07/24/95	728								
07/25/95	1673	195	-15.7	26.3	62.7	-49.5	-13.1	1.8	

Note: New location for meter # 6, meter #9 added prior to 8/14.

08/14/95	491	577							
08/15/95							-59	-55.9	
08/16/95			25.5	-11.9	10.2	2.1			-15.9
08/29/95	1087	700							
08/30/95			-69.6	5.9	63.2	-70.8	-91.3	86.4	73.1
	1	2	3	4	5	6	7	8	9

The implication of this statement is that the pond bottom cannot be modeled with a single permeability or bottom conductance value. In the absence of pumping tests or other field methods, ground-water numerical models rely on estimates of pond-bottom conductance to determine the influence of pumping on pond levels. This approach could be highly uncertain if the sampled distribution of conductance differs significantly from the true distribution. A large number of measurements (and meter locations) may be necessary to determine a statistically and spatially valid distribution of seepage and permeability for this purpose.

Conclusions

The results of the seepage meter measurements clearly demonstrate the influence of pumping on the level of Mary Dunn Pond. *Large* values of outseepage were seen in the vicinity of the pumping well. Some moderate increases in inseepage were seen in areas on the west side of the pond, away from the pumping well. After the conclusion of the test, seepage near the pumping well reverted to moderate values of inseepage, indicating that pumping at Mary Dunn #2 reversed the normal flow pattern in the adjacent section of pond shore.

The results also indicate that the hydraulic properties of the pond bottom are highly variable, necessitating a large number of measurements if numerical modelling is to be the sole method of determining the influence of pumping on the pond.

Overall Conclusions from the 1995 Pumping Test - Mary Dunn #2

Every form of data collected during the 1995 pumping test leads to the same conclusion; pumping Mary Dunn #2 at the volumes used in this test results in a rapid drawdown of Mary Dunn Pond. This is the first conclusive demonstration of this effect. The change in elevation of the pond surface also affected the relationship between the pond and the surrounding aquifer, producing a moderate enhancement of recharge as pond levels fell. Removal of water from the pond took place by two mechanisms, direct removal of pond water by reversal of pond-shore hydraulic gradients and interception of ground-water recharge to the pond.

The effect of pumping at lower rates should be lesser. It is not clear from the data gathered for this test whether the pumping-drawdown relationship is linear or whether there is a low threshold at which pumping has no effect. Two factors indicate that moderate levels of pumping will effect the pond. First, rapid establishment of downward vertical gradients along the pond shore near the pumping well (P17/18) was observed in this test. Downward vertical gradients associated with pumping were also observed in MDSM#1P, near P17/18 and in P19, about 350 feet south of P17/18. It appears that pumping results in an almost immediate establishment of downward vertical gradients, and therefore, outseepage in the area near the pumping well. Second, during the test, values of outseepage at MDSM#1(95), the seepage meter located nearest the pumping well, were much higher (> ten times) than inseepage values following the test. This indicates that, when the pumping schedule includes periods when the pump is idle, the overall balance of seepage in the area of the pumping well will be negative, unless daily run time for the pump is less than 10 % of 24 hours (2.4 hours). This tranlates to about 0.08 mgd at the pumping rates used during the 1995 test.

The elevation of the pond surface in Mary Dunn Pond went from 24.83 to 23.32 feet above mean sea level (MSL) during the pumping test. BWC has been recording pond elevations since May of 1992. The lowest levels of the pond observed in this period were 22.7 feet above MSL in late September and late October of 1995. The highest observed elevation (TNC data) was 29.97 feet above MSL in April 1997. The elevation of the pond bottom over most of the pond area is between 19.3 and 20.0 feet above MSL. This test was run in the lower 29 per cent of the observed range of pond level fluctuation over the last five years (7.3 feet). The lowest level the pond reached during the test was 0.6 feet above the lowest observed level in the last five years, or within 8 per cent of the bottom of the range of observed pond water elevations.

Horsley &Witten Inc. (H&W) has estimated pond levels prior to this date based on comparison to water levels in observation well A1W230 (H&W, 1997). They have developed a regression equation relating the two levels based on the BWC pond level data. This method provides an estimate of pond levels extending back to installation of A1W230 in 1958, but is subject to two caveats. First, A1W230 is between the Mary Dunn and Maher wellfields and may be subject to pumping influences from both fields (H&W, 1992). Since Mary Dunn Pond levels are also apparently influenced by pumping levels (this study) the two levels are not independent variables. Second, pumping at the Mary Dunn field has been considerably higher during some periods prior to 1992. The H&W regression method may only provide an accurate estimate of pond levels for periods during which pumping was similar to the period from 1992 onward. Periods during which significantly *higher or lower* pumping occurred will be subject to errors by this method. The lowest pond level estimated by H&W is 21.8 feet above MSL in the Fall of 1991. The 1995 pumping test was, therefore, run between 3.0 and 1.5 feet above the lowest estimated pond level for the last 39 years.

Summer 1996 and Discussion of Summer Pond Level Declines

Introduction

During the summer of 1996, pond levels remained relatively high due to a combination of factors. During the winter of 1995-'96, abundant snowfall had refilled the ponds from their low levels in the summer of 1995. In addition, temperatures were relatively mild during much of the summer and higher than normal precipitation fell in July and August. The Summer of 1996 provided an opportunity to examine behavior of the hydrologic system under climatic conditions significantly different from those encountered in 1995.

Method

For this section the method consisted of recording water levels in the pond and relating those level to pumping and climatic factors. Ground-water temperature measurements were taken in the summer of 1996 by the methods outlined previously.

Results

Pond level responses to these conditions are shown in Figure 16. All of the level changes in Figure 16 are calculated relative to the level measured on May 3rd, at which time Mary Dunn and

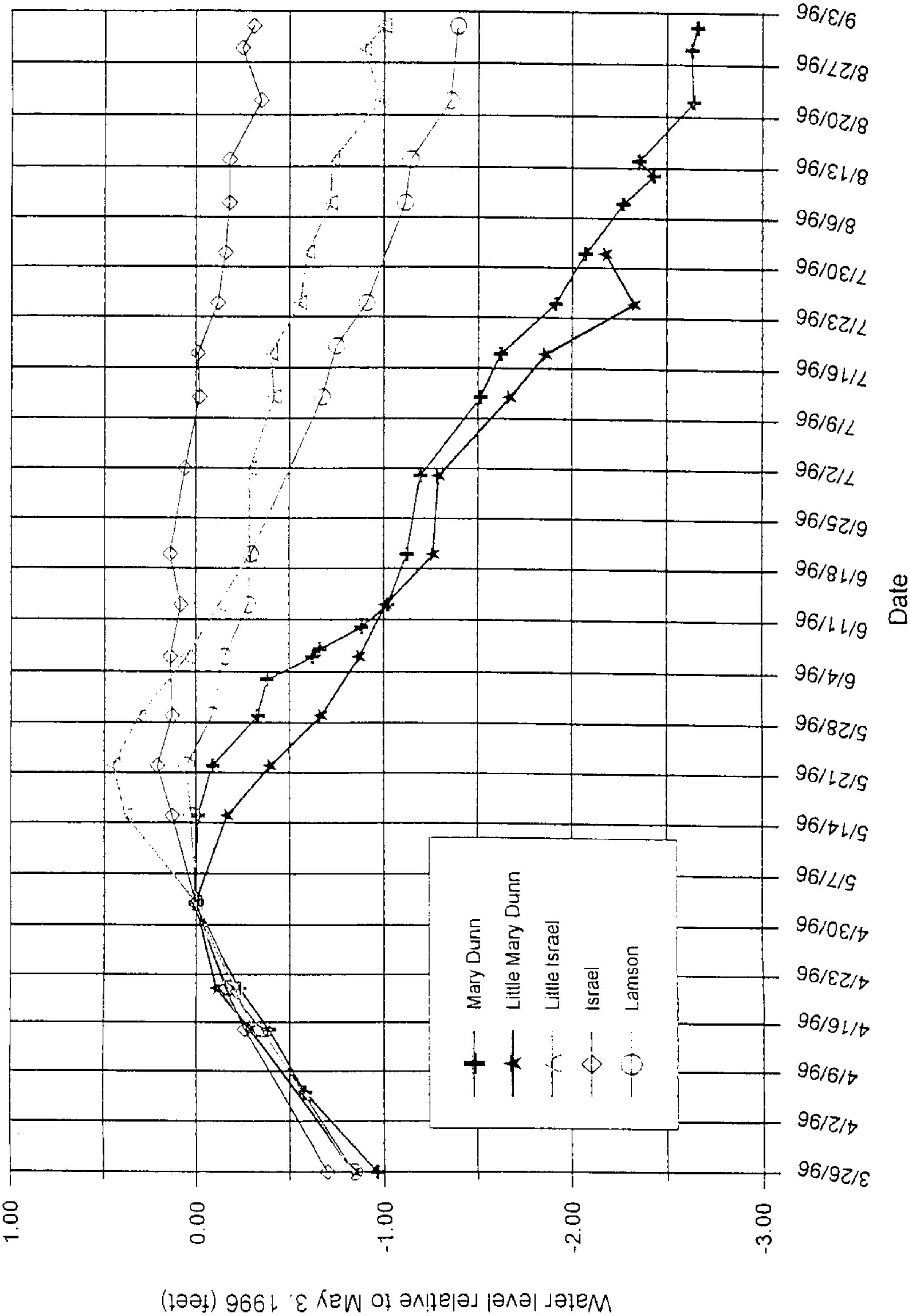


Figure 16. Pond level changes, summer 1996. Levels are relative to May 3rd. The greatest water level reduction is seen at Mary Dunn Pond.

Little Mary Dunn Ponds reached their highest levels of the year. The highest level of Mary Dunn Pond during this period was 25.11 feet above MSL, recorded on April 24th.

The highest ground-water temperatures recorded around the margin of Mary Dunn Pond were in P8, located on the section of shoreline between MD#1 and MD#2. During early June, the three piezometers showing the greatest increase in temperature were P6, P8, and P18, on the area of shoreline near supply wells MD#1 and MD#2.

Discussion

Lamson and Israel Ponds continued to rise for about two and one half weeks following May 3rd as did Little Israel Pond. The water level increases in Little Israel Pond during the period from May third to May 22nd are anomalously high with respect to the other ponds. Supply well Mary Dunn #4 is located directly adjacent * to Little Israel Pond. Mary Dunn #4 had been the base load well for the Mary Dunn Wellfield in 1995; monthly pumping varied from 5.5 to 19.1 mgal/month, averaging 12.0 mgal/ month (0.4 mgal/day). From Jan. 21, 1996 through March 13, 1996 the well was unpumped except for meter tests. From March 14th through May 1st, the well was pumped at a fairly steady rate averaging 0.381 mgal/day. Mary Dunn #4 was pumped very little for the remainder of May and most of the rest of the summer, the exception being two brief periods in early and mid-June. The cessation of pumping in early May corresponds to the period on Figure 16 during which Little Israel Pond rose at anomalous rates. The pond's behavior during this period may be attributed to recovery of the local water table around MD#4. The relatively rapid decrease in the level of Little Israel Pond in early June appears to be due to the brief resumptions of pumping during that period. For the remainder of the summer there is a close correspondence in pond level changes between Little Israel and Israel Ponds.

The level of Mary Dunn Pond fell 2.66 feet between May 3rd and September 1st, 1996. During the same period the total amplitude of pond level fluctuations of Israel and Lamson Ponds were 0.56 and 1.44 feet respectively, while reference wells OW6, A1W230, and MW7 fell 2.03, 2.1 and 2.13 feet respectively. Figure 17 shows the elevation of the water surface at Mary Dunn Pond from late March through August, 1996 with a bar chart of the combined pumping of supply wells MD#1 and MD #2. (Please note that the width of the bars corresponds to the time between pond-level monitoring rounds, while the height of the bars represents the average combined pumping during each interval.) Both of these wells are within 100 feet of the pond shore at high water levels. Mary Dunn Pond levelled out in early May, coincident with the first continuous pumping of the two nearby wells and two weeks before the other ponds in the area. A sharp decrease in the pond level is also apparent in early June coincident with an increase in pumping (dotted line). During July and August, pumping rates were less variable and the pond level also declined at a steadier rate, albeit at higher rates than at other ponds in the area.

The initial pumping in May came mostly from MD#1(>90% of the total of the two wells). This is apparent on Figure 16 since Little Mary Dunn Pond shows sharper declines in May than Mary Dunn Pond. This result is similar to pumping tests in 1997 (see section below), which showed clear evidence that pumping of MD#1 produced sharp declines in the level of Little Mary Dunn

* During the Spring of 1997, the shoreline of Little Israel Pond was within one foot horizontally of the wellhouse.

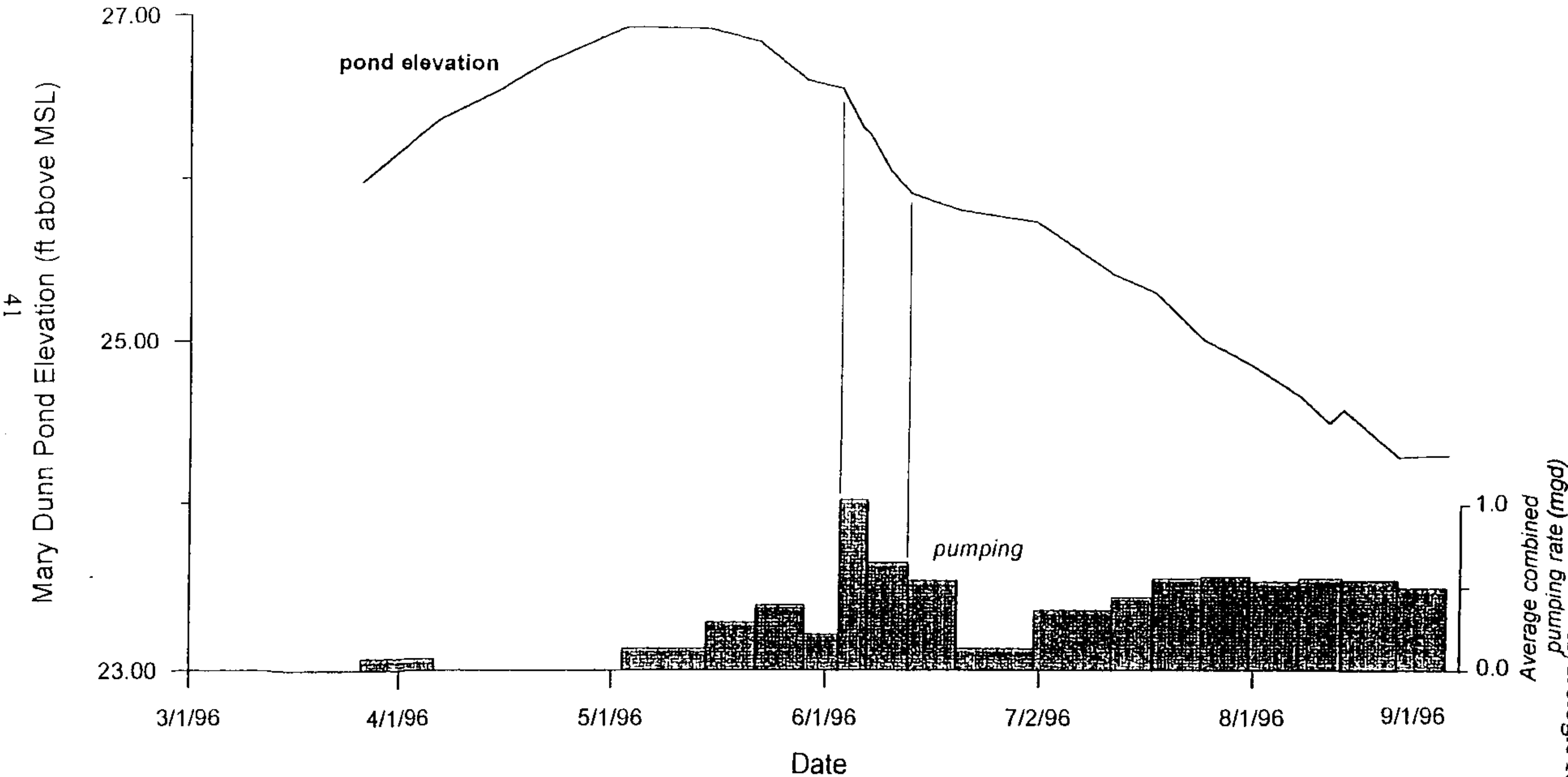


Figure 17. Mary Dunn Pond level compared to combined pumping on MD#1 and MD#2, summer 1996. Pumping rates are averaged over time period indicated by width of histogram bar. Greatest changes in pond level are coincident with highest pumping levels.

Pond. It is apparent from Figure 16 that MD#1 produced pond level declines in both ponds in the absence of significant pumping levels at MD#2. The distinct decline in Mary Dunn Pond in June occurred as overall pumping increased and Mary Dunn#2 became the dominant water withdrawal point.

While the abrupt downward change in pond level in June appears to be clearly related to an increase in ground-water withdrawal, this relationship is not as strongly indicated on Figure 17 for July and August. To evaluate the effect of pumping on Mary Dunn Pond for this period (and the summer as a whole), it is necessary to separate the effect of pumping from those of evaporation and precipitation.

Figure 18 shows the "residual" pond level change compared to pumping rate. The residual pond level change is an estimate of the amount of pond level change *not* due to direct precipitation onto, or evaporation from, the pond surface. It is calculated as:

$$\Delta_{Res} = E_{T2} - E_{T1} - PPTN + Evap,$$

where Δ_{Res} = residual pond level change,
E_{T2} = pond elevation at time T2,
E_{T1} = pond elevation at time T1,
PPTN = precipitation, and
Evap = evaporation.

Note that the equation is a simple water balance for the pond and that residual pond level change encompasses all of the influences on pond levels unaccounted for in the other terms. Evaporation was calculated by the method of Fennessey and Vogel (1996), an emulation of the Penman-Montieth method. This method provides a higher estimate of mid-summer evaporation than the Thornthwaite(1948) method by a factor of about 1.3. The calculation of Δ_{Res} was performed for each interval between pond level measurements using the evaporation rate calculated for the month in which most of the interval fell.

Precipitation measurements were taken at a rain gage adjacent to Mary Dunn Pond at the time of each pond level measurement. Some evaporation of the water in the gage took place since the rain gage was not read daily. Comparison with BWC rain gage measurements indicated that the Mary Dunn rain gage measurements are within 20%. It was intended to use the NOAA Hyannis measurements for this analysis but there are apparent inaccuracies in the July data. Since the Mary Dunn rainfall totals for each interval are likely to be low this produces a bias in the analysis toward lower residual pond level change, ie. less change not accounted for by precipitation and evaporation. Residuals should, therefore, be considered to be a conservative estimate of hydrologic influences other than evaporation and precipitation. As an example, for an interval in which the pond level fell from 25.5 to 25.0 feet, it rained 0.25 feet and evaporation is estimated at 0.30 feet, the residual change would be:

$$25.0 - 25.5 - .25 + 0.30 = -0.45 \text{ feet}$$

In other words, based on the rainfall and precipitation, the pond should have fallen 0.05 feet if there were no other influences on pond level. Since the pond level fell 0.50 feet (an additional

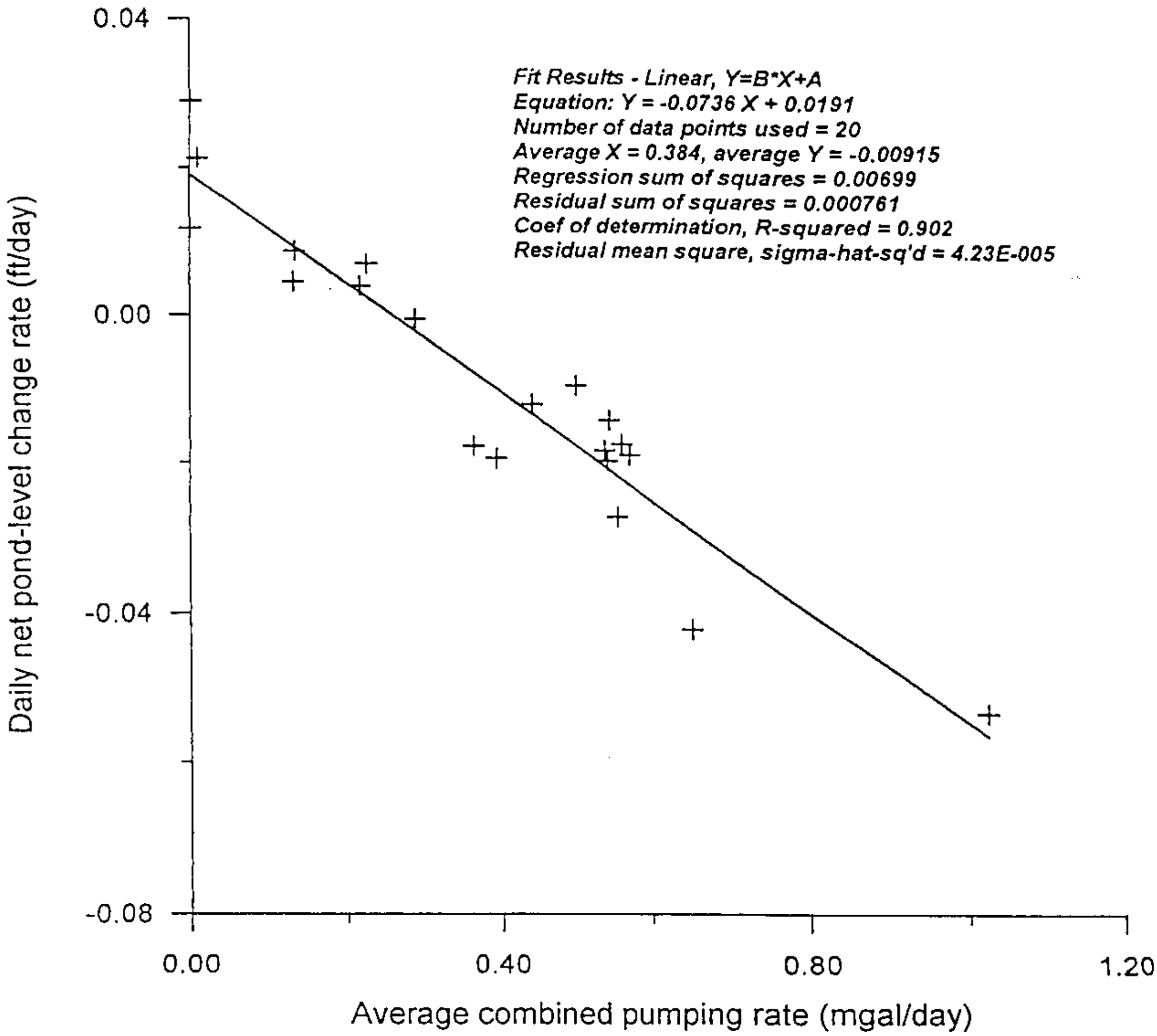


Figure 18. Net pond level change as a function of combined pumping of MD#1 and MD#2, summer 1996. Summary statistics of regression equation given as text. Note correlation coefficient of 0.90.

0.45 feet) there is a residual which must be accounted for by other hydrologic factors, such as ground-water loss. Note that if the precipitation measurement is low, for example if the true rainfall total had been 0.30 feet and 0.05 evaporated from the rain gage, the residual would be higher, in this case 0.50 feet.

Figure 18 indicates that the residual pond level changes are strongly correlated to ground-water withdrawal from MD#1 and MD#2. Note that R-squared for the regression is 0.90, indicating a robust relationship. It is therefore apparent that pumping of these two wells produced clear short term and seasonal effects on the level of Mary Dunn Pond during the late Spring and Summer of 1996.

Figure 19 displays a cumulative balance of precipitation and evaporation for 1995 and 1996. This chart was prepared by subtracting evaporation, as determined by the method of Fennessey and Vogel (1996) from precipitation. For this longer term analysis, precipitation totals from the Hyannis NOAA station were used, except for July 1996. Rainfall totals collected by the Barnstable Water Company were substituted, due to inaccuracies with the July rainfall totals from the NOAA station. This chart indicates that the cumulative difference between evaporation and precipitation for the period from the end of April to the beginning of September, 1996 is slightly greater than -1.5 feet. This matches the drawdown seen at Lamson and Little Israel Ponds during the summer of 1996, but Israel fell by about 0.5 feet and Mary Dunn Pond fell by about 2.6 feet.

The relatively small summer fluctuation of Israel Pond may have been due to the suspension of pumping of supply well MD#4, and recovery of the local water table. This well had been run at fairly steady levels for several years prior to February, 1996, as the base load well for the Mary Dunn wellfield. For example, monthly pumping averaged 12.0 million gallons per month (mgm) in 1995 with a low of 5.5 mgm and a high of 19.2 mgm. The average from May through September, 1995 was 15.2 mgm. In February, 1996, pumping of MD#4 was suspended. In March, 7.2 million gallons were pumped and in April, 11.4 million gallons were pumped from MD#4. For the remainder of the summer less than one million gallons were pumped in each month except June, when 2.2 million gallons were pumped. The average pumping from May through September, 1996 was 0.78 mgm, or five per cent of the pumping from the equivalent period in 1995. The pattern of pond level changes in Little Israel Pond, nearer to MD#4, (Figure 16) may be due to the episodic nature of pumping in the spring and early summer of 1996.

The pond level changes in 1996 took place during a period of relatively low on-season pumping. Total Mary Dunn wellfield pumping from June through August of 1996 was 71.4 million gallons, below the average pumping for the same months from 1992 through 1996 (94.1 million gallons). For the previous five-year period, 1987 through 1991, the average pumping was 187.4 million gallons (2.04 mgd for the field in total) during the summer months.

Similar patterns of summer drawdown at Mary Dunn Pond are evident in the data collected by BWC in 1993 and 1994. (Figures 20&21) From late-May/early June to the end of August in 1993 and 1994, Israel Pond fell 1.6 and 1.7 feet respectively. Mary Dunn fell 3.6 feet in 1993 (2.0 feet greater fall than Israel) and 3.1 feet in 1994 (1.7 feet greater fall than Israel). In 1993 total Mary Dunn Wellfield pumping was 124.3 million gallons from June through August; in 1994

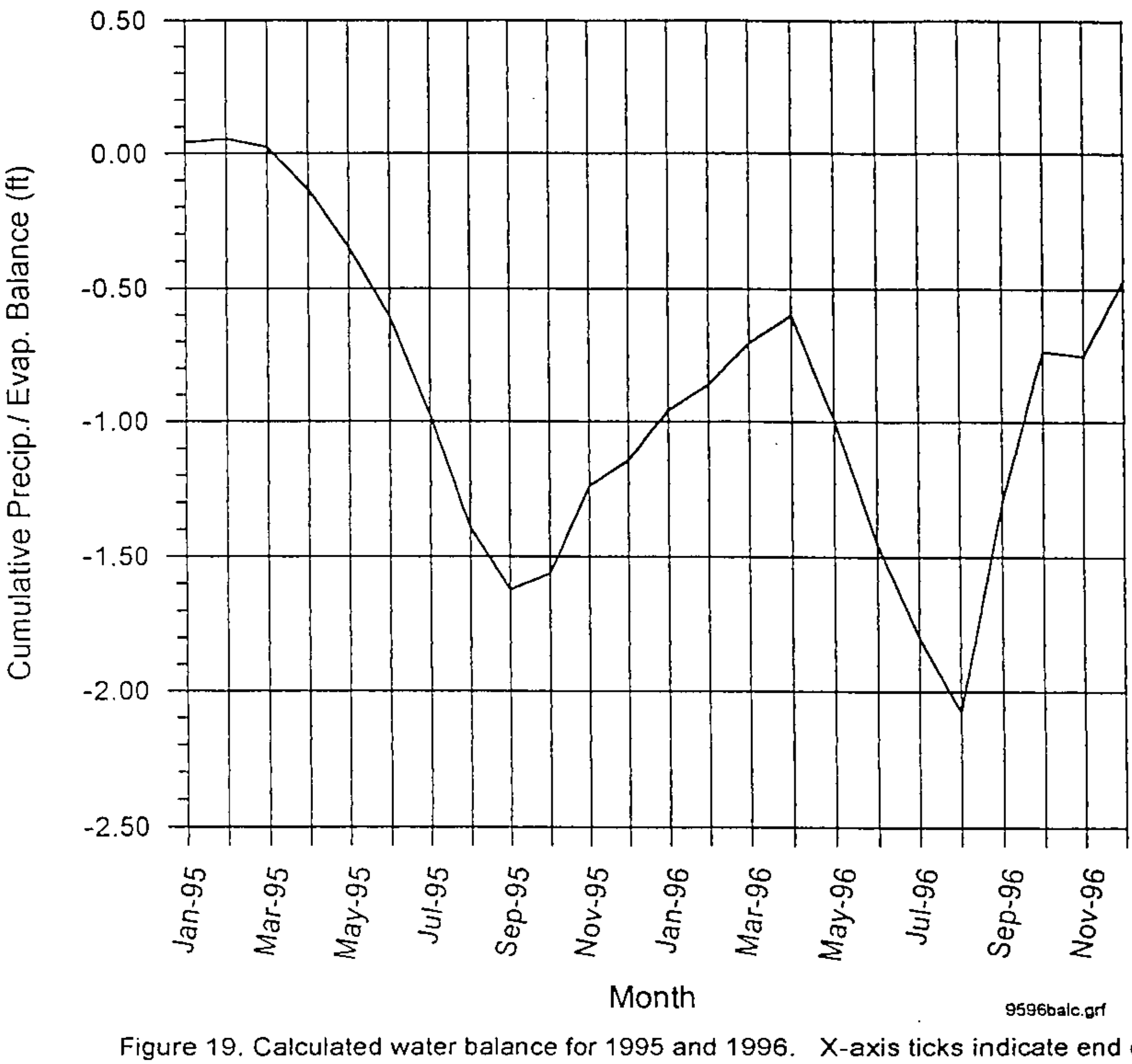
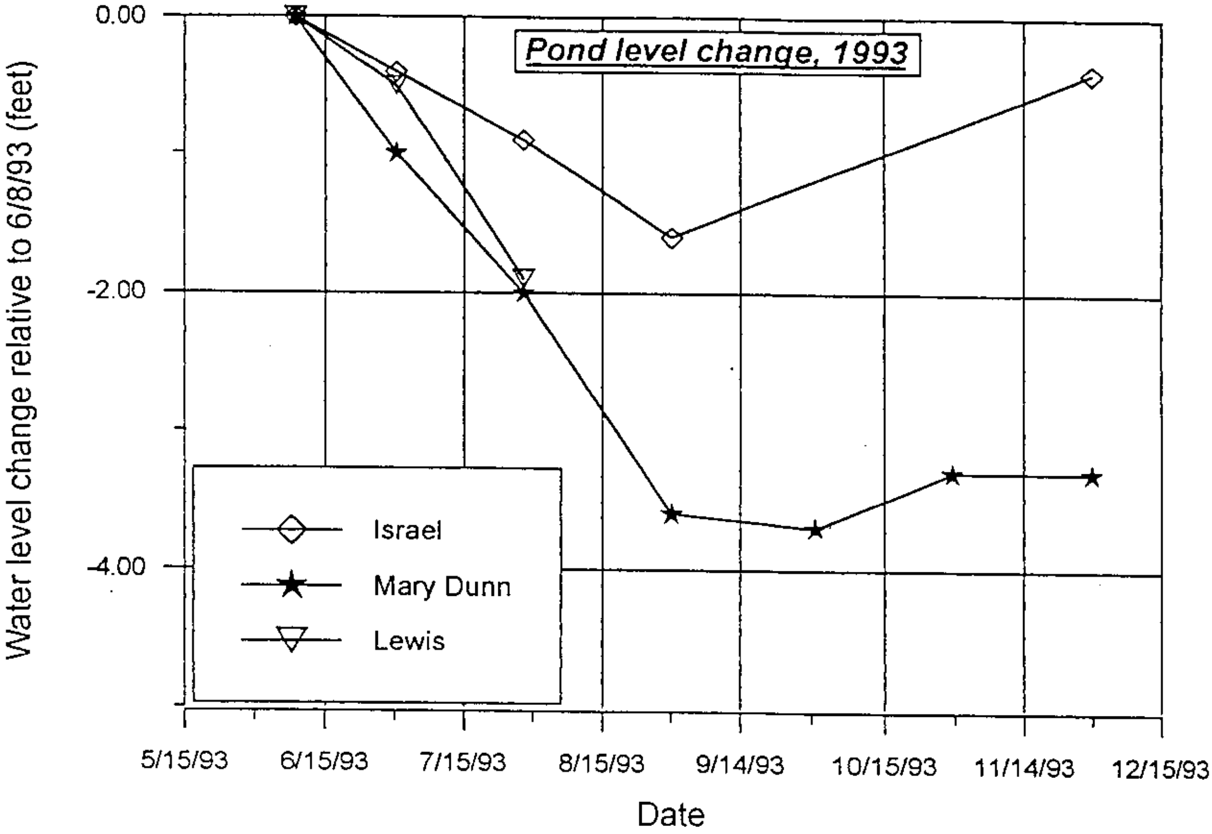
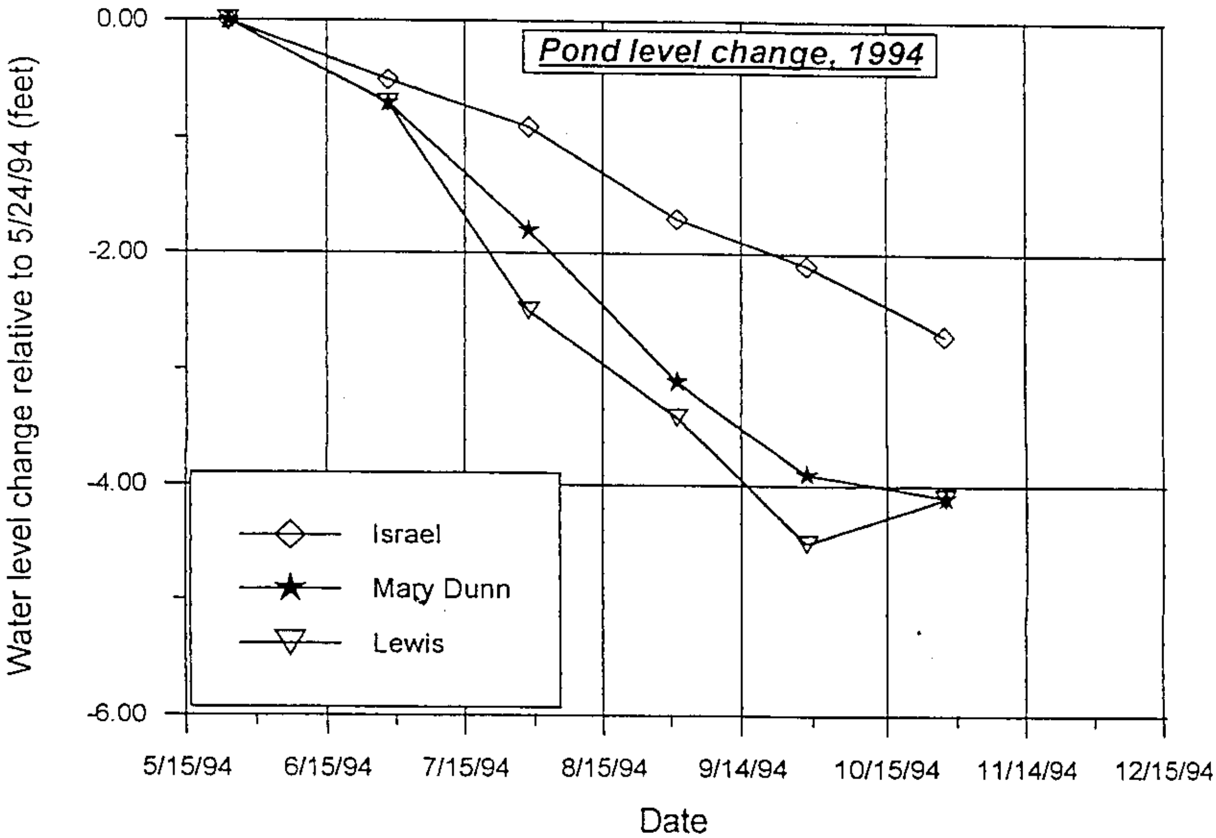


Figure 19. Calculated water balance for 1995 and 1996. X-axis ticks indicate end of month. Expected summer (late April-late August) water level changes are about one foot for both summers, based on this method.





Figures 20 (top) and 21 (bottom). Pond level changes, 1993 and 1994.

pumping totalled 115.9 million gallons in the same months. Lewis Pond fell in a pattern similar to Mary Dunn, due to pumping of Airport#1. Pumping-induced drawdowns of Lewis Pond were observed during the 1997 test of Airport #1. During the July and August of 1993 and 1994, pumping of Airport #1 averaged slightly over 2/3 of the rate used in the 1997 test.

In 1995 the nearby ponds lost most of their water by mid-August and a reasonable comparison of pond levels cannot be made for that year. Data for Israel and Lewis ponds do not exist for 1992, the first year of the BWC study of pond levels. Data do exist for Flintrock Pond, but must be examined with some caution as the area is being actively remediated by a pump-and-treat system. We do not have data on the configuration and extent of use of the remediation system in 1992.

During the summer of 1992, Mary Dunn Pond fluctuated only 0.2 feet, according to BWC data and Flintrock Pond fluctuated by 0.3 feet. Rainfall was abnormally high during June, July and August of 1992, totalling 17.32 inches (1.44 feet). Evaporation for the period is estimated at 21.84 inches (1.82 feet) by the method of Fennessey and Vogel (1996). Assuming no groundwater recharge to the pond, levels would be expected to fall slightly during the summer. Summer wellfield pumping was 60.6 million gallons, the lowest level in (our) records going back to 1971. Over half (57%) of the summer pumping in that year came from MD#4, the well farthest from Mary Dunn Pond, 27% came from Airport#1, the next most distant well.

Conclusions

Summer patterns of drawdown at Mary Dunn and surrounding ponds generally indicate a correlation between pumping and pond water loss, greater than that expected from climatic conditions alone. Residual drawdowns in Mary Dunn Pond in the summer of 1996 correlate closely to pumping on MD#1 and MD#2 and are greater than the drawdowns seen in other ponds in the study area. Temperature measurements indicate that the section of shoreline near these wells was influenced by an influx of pond water. The combination of these factors indicates that under *non-test* conditions, water supply pumping lowered the level of Mary Dunn Pond with respect to the surrounding ponds. The similar patterns seen in 1993 and 1994 also indicate the influence of pumping.

In 1992, however, pond levels fluctuated very little during the summer. The low level of pumping that summer was sustained almost entirely (84%) by the wells farthest from Mary Dunn Pond. High rainfall also kept nearby Flintrock Pond at nearly the same level all summer. The relative stability of the level of Mary Dunn Pond during the summer of 1992 and its similarity to Flintrock Pond are most likely due to the low level of pumping and the use of wells away from the pond shore. Although summer and yearly levels of pumping were similar in 1992 and 1996 (Figure 22), most of the pumping in 1996 (62%) came from the two wells adjacent to the Mary Dunn Pond. This factor accounts for the difference in the behavior of Mary Dunn Pond between the two years.

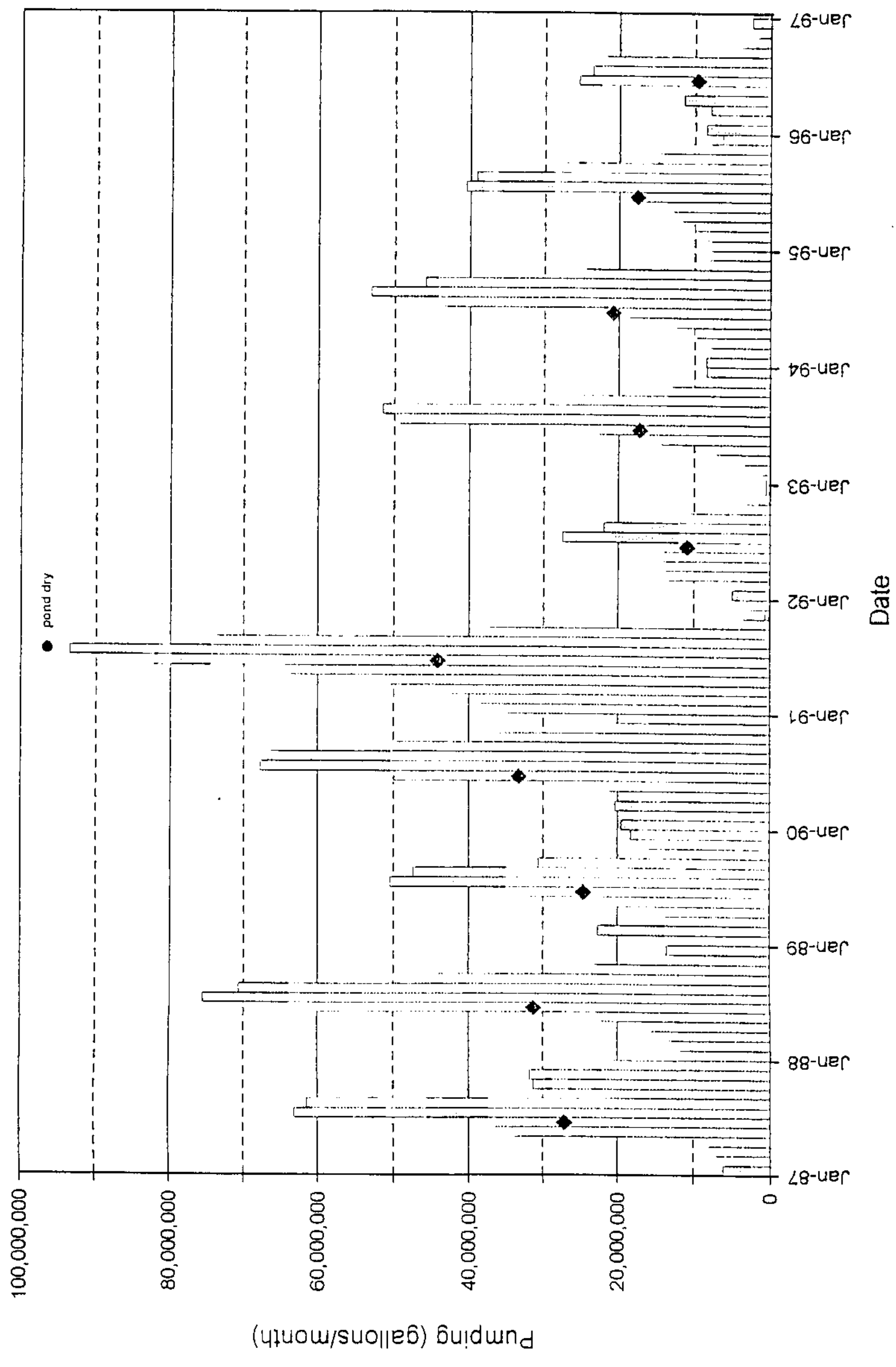


Figure 22. Pumping at the Mary Dunn Wellfield, by month from 1987 through 1996. Diamond symbols represent average monthly pumping for the year, ranging from 9.7 million gallons in 1996 to 44.2 million gallons in 1991. Diamonds are located on the month of June (for visual reference), date ticks are at the beginning of the indicated month.

Fall 1996 Recharge Events

Introduction

In the fall of 1996, Hurricane Edouard began a series of storms which raised the level of the water table in the study area and had a distinct effect on the ponds. A series of moderate to intense storms culminated in an event from October 19th through 23rd in which six inches of rain fell. During the months of September and October nearly two *feet* of rain fell on the area or about half of the average yearly rainfall.

Method

Monitoring of water levels during this period, including event monitoring for Edouard, and continued weekly monitoring until December.

Results

A hyetograph for this period is given as Figure 23. There are several significant results from this period.

First, water from individual storms reached the water table fairly quickly. Even in areas in which the depth to the water table is well below the ground surface, distinct pulses of water from individual rainfall events were observed. Figure 24 is a water level record for wells MW-3 and MW-5, which are in the moraine at the northern boundary of the Hyannis Pond Wildlife Management Area. Water levels in these wells vary between 50 and 60 feet below grade. The rapid response of both wells is indicative of the high permeability of the moraine sediments. MW 3 is in an area of uneven terrain indicative of thrusting during moraine development (Oldale, 1974). It is possible that the rapid response of the area of MW 3 to rainfall events is due in part to water movement along thrust planes within the moraine sediments.

Rapid ground water responses to rainfall events were also observed in other parts of the study area where the aquifer is composed primarily of outwash sediments. Figure 25 shows the response of selected wells in the area; all of these wells are at least 500 feet from any pond. The general response of the water table to the approximately two feet of precipitation was to rise between 3.75 and 4.75 feet before cresting in late October to early November. The changes in the rates of water table rise clearly indicate that the water table responded quickly to single events or series of closely spaced events.

Second, the rise in the all of the ponds studied exceeded the amount of rainfall. In the four primary ponds studied, the increase in water level varied from about 1.4 to 2.4 times the total depth of rainfall (about 1.9 feet, depending on the measurement station) for the period from September 1 to November 21, 1996. Figure 26 shows the record of increase in depth for Lamson, Israel and Mary Dunn Ponds as well as the cumulative depth of precipitation, as measured at the Hyannis NOAA station, for the fall of 1996. The greatest increase in water level occurred in Mary Dunn Pond which increased in depth by 4.61 feet. From 9/1 to 10/25, the period during which most of the rain fell, Mary Dunn Pond rose 2.02 times the amount of rain, 1.39 times the rise of Lamson Pond and 2.08 times the rise of Israel Pond. From 9/1 to 12/10, 1996, Mary Dunn

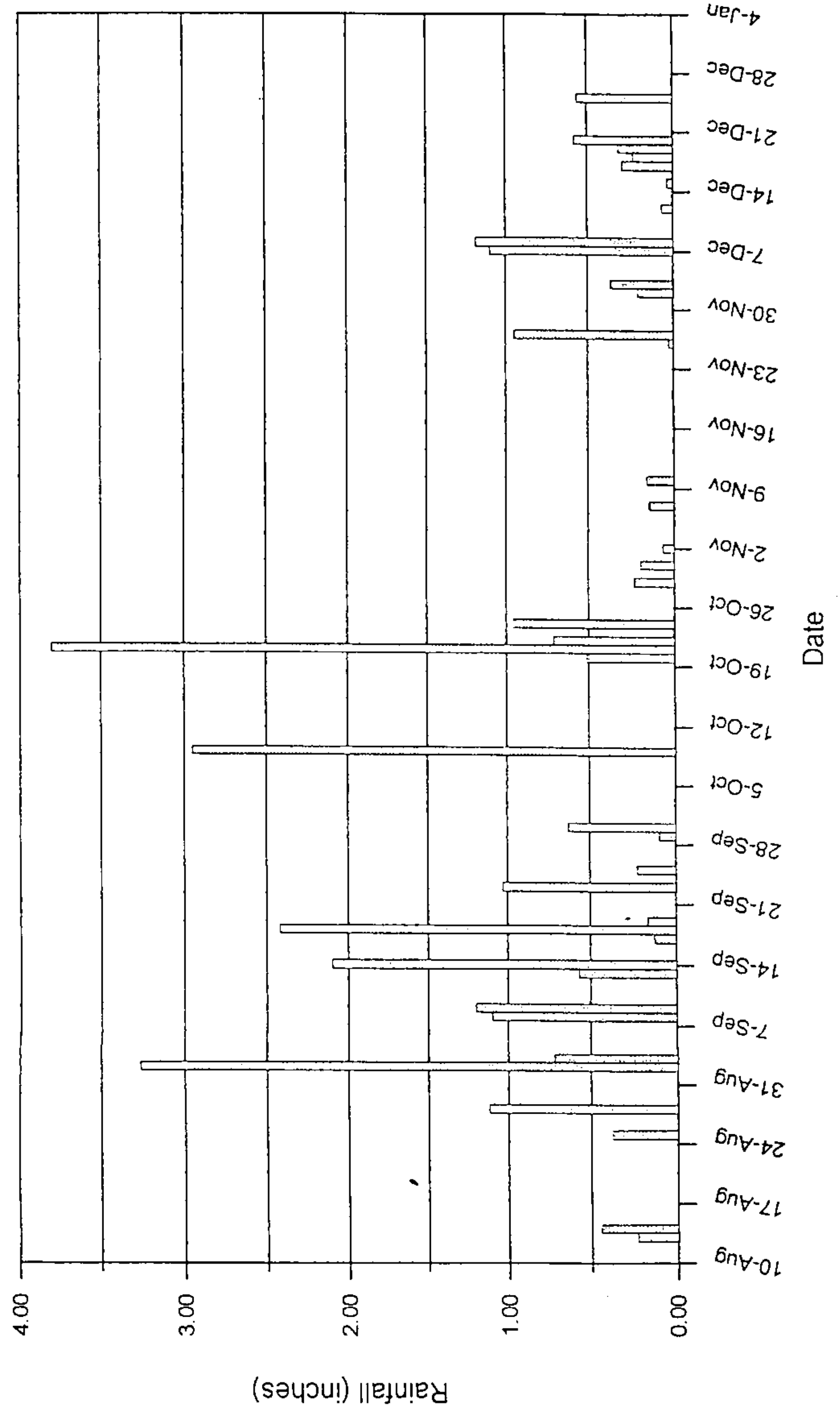


Figure 23. Daily rainfall depths, August through December, 1996. Recorded at Hyannis NOAA weather station.

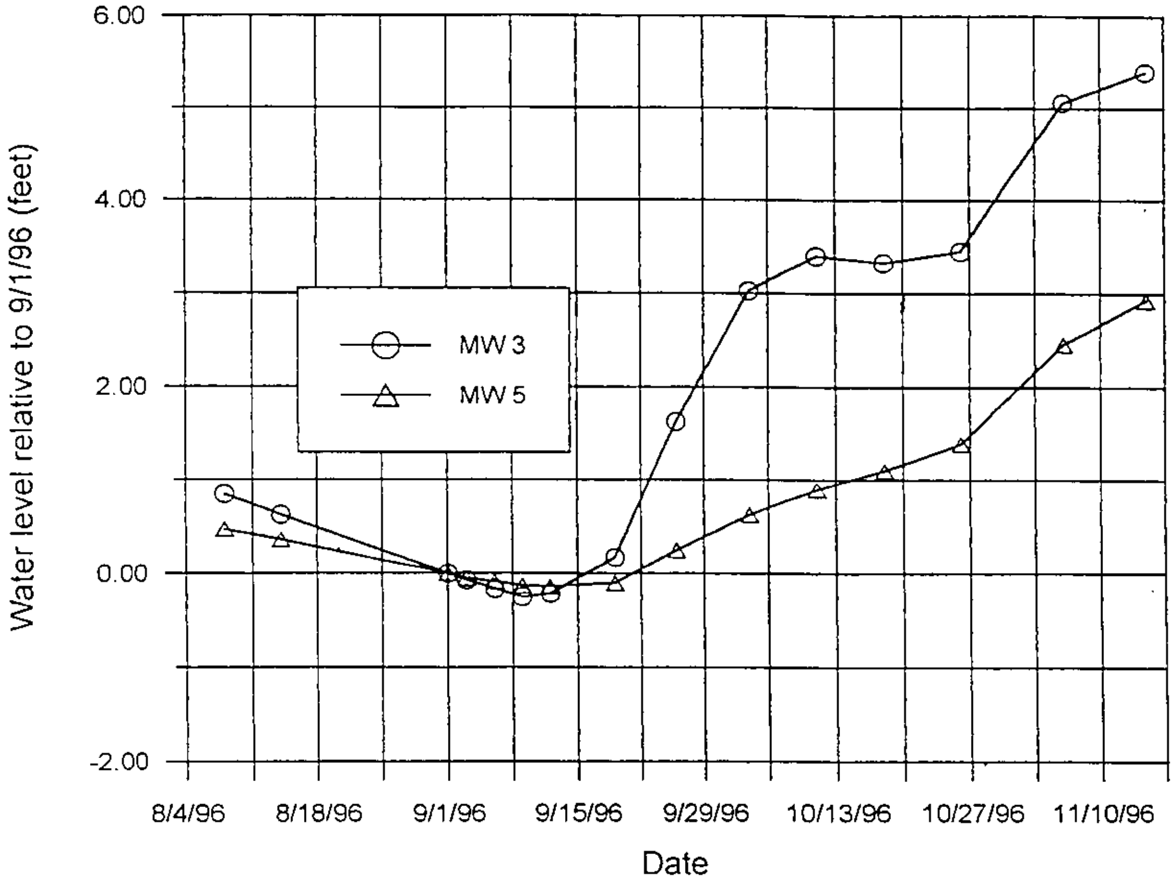


Figure 24. Water level changes in moraine wells, relative to September 1, 1996.

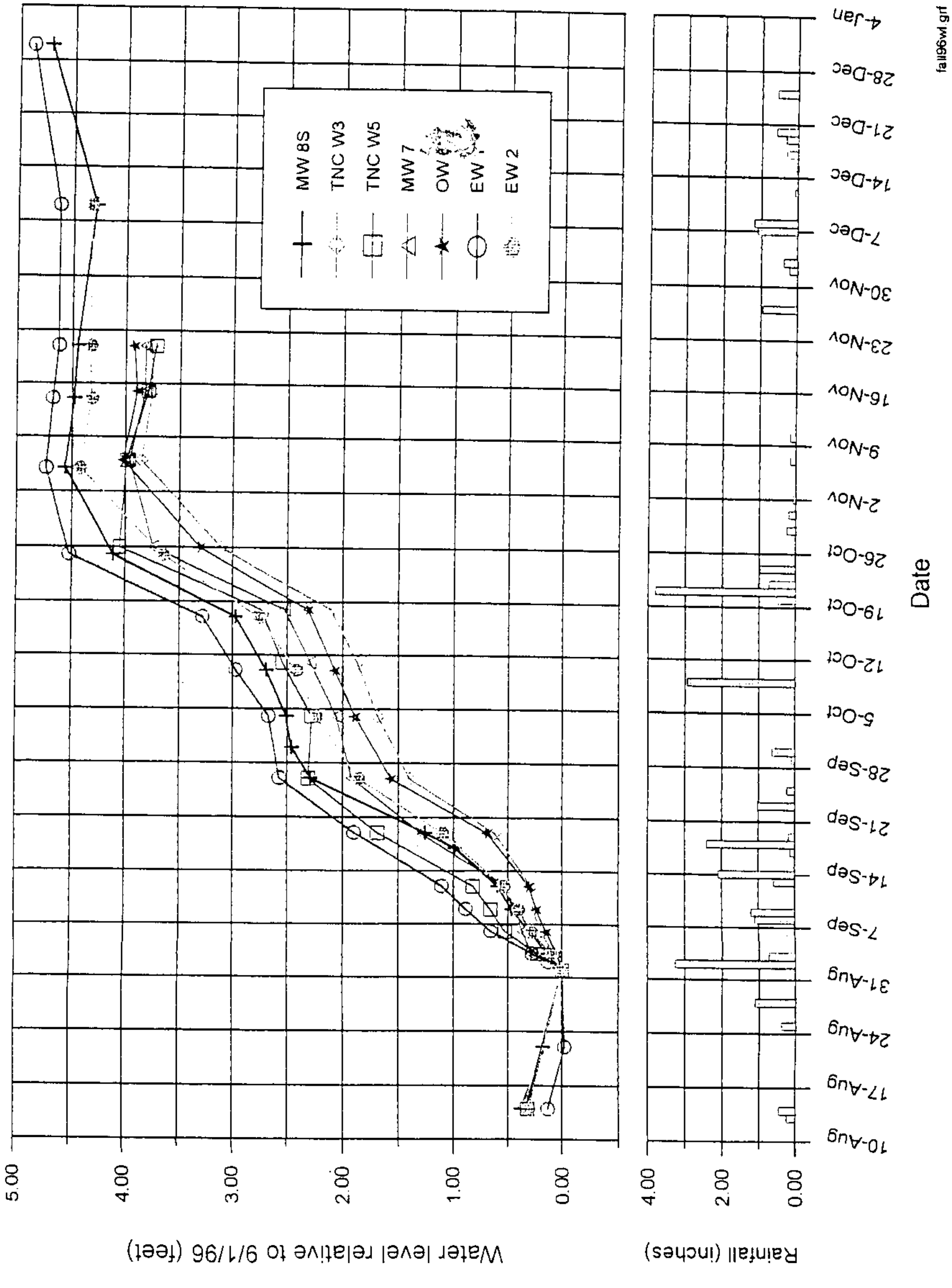


Figure 25. Water level changes in study area wells compared with rainfall events. Water level changes are calculated relative to September 1, 1996.

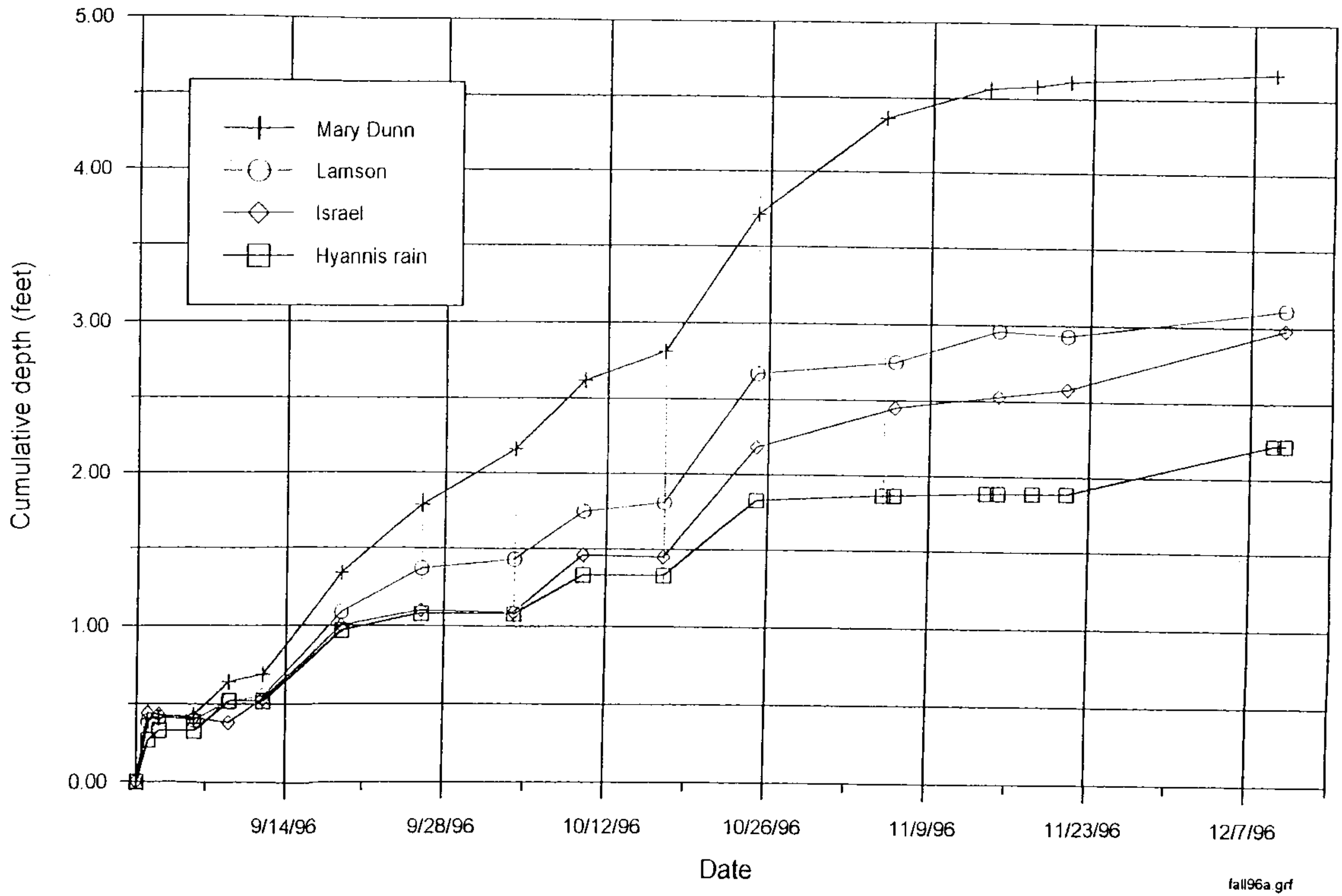


Figure 26. Pond level changes compared with cumulative rainfall depth. Note periods of little or no rainfall coincident with significant water level increases at Mary Dunn Pond (indicated by shading).

Pond rose 2.1 times the amount of rain, 1.50 times the rise of Lamson Pond and 1.57 times the rise of Israel Pond.

The increase in water level in Mary Dunn Pond is *very* similar to the rise in the water table as indicated by numerous wells in the area. Figure 27 shows water level changes in Mary Dunn Pond compared with area wells.

Third, the ponds studied experienced periods during which little or no rain fell, but the ponds continued to rise. This characteristic was most pronounced at Mary Dunn Pond, as indicated in Figure 26. There is one period during which Mary Dunn rose in the absence of rain. From 10/10 to 10/17 the pond rose 0.20 feet in seven days (an average of 0.028 ft/day). There were two periods of significant rise in pond levels in excess of rainfall. From 9/26 to 10/4 Mary Dunn rose 0.37 feet in eight days while 0.05 feet of rain fell (an average of 0.040 ft/day after subtraction of rainfall). In the period from 10/25 to 11/5 the Mary Dunn rose 0.65 feet over eleven days while 0.04 feet of rain fell (an average rise rate of 0.055 ft/day after subtraction of the rainfall). No adjustment for evaporation has been made to these data, therefore the rise rates should be considered minimum estimates of net ground-water inflow to the pond.

Similar periods of ground-water inflow in the absence of rain (or in excess of rainfall) have been observed during the recovery phases of the pumping tests performed at Mary Dunn Pond.

Discussion

Continued increase of pond levels in the absence of rainfall, or well in excess of rainfall, is indicative of ground-water input. As mentioned previously, surface runoff does not appear to contribute significant amounts of water to the ponds. Some sections of Mary Dunn road probably do contribute runoff to Mary Dunn and Israel Ponds. During low-water conditions, road runoff does not enter the ponds directly but discharges from the road surface to soils near the ponds. During very high-water conditions, such as have occurred from late fall 1996 to late spring 1997, the pond margins are almost directly adjacent to the road and road runoff enters the ponds directly. There are no culverts or any engineering works to divert or transport road runoff. Any road runoff entering the ponds has been transported a short distance (less than 400 feet) and is water that, in the absence of the road, would have entered the ground-water flow system close to its discharge point from the road surface. The area of road surface adjacent to Mary Dunn Pond, which I have observed to contribute runoff to the pond, is approximately 10,000 square feet, less than two per cent of the high water areal extent of the pond. A similar area of road surface adjacent to Israel Pond contributes runoff, however, as Israel Pond is roughly half the size of Mary Dunn Pond, as much as three per cent of the water contributed to Israel Pond by rain events may come from road runoff.

The results of water level monitoring clearly indicate that all of the ponds monitored respond to direct precipitation and ground-water inflow during recharge-dominated periods. The difference in the increase in pond levels at Mary Dunn, Lamson and Israel Ponds may be due to differences in the degree to which each pond is connected to the ground-water flow system. As mentioned earlier, Israel and Lamson Ponds are shallower and lack a broad sandy margin. The 1990 study by IEP Inc. found much lower seepage rates at Lamson and Israel Ponds than at Mary Dunn. In

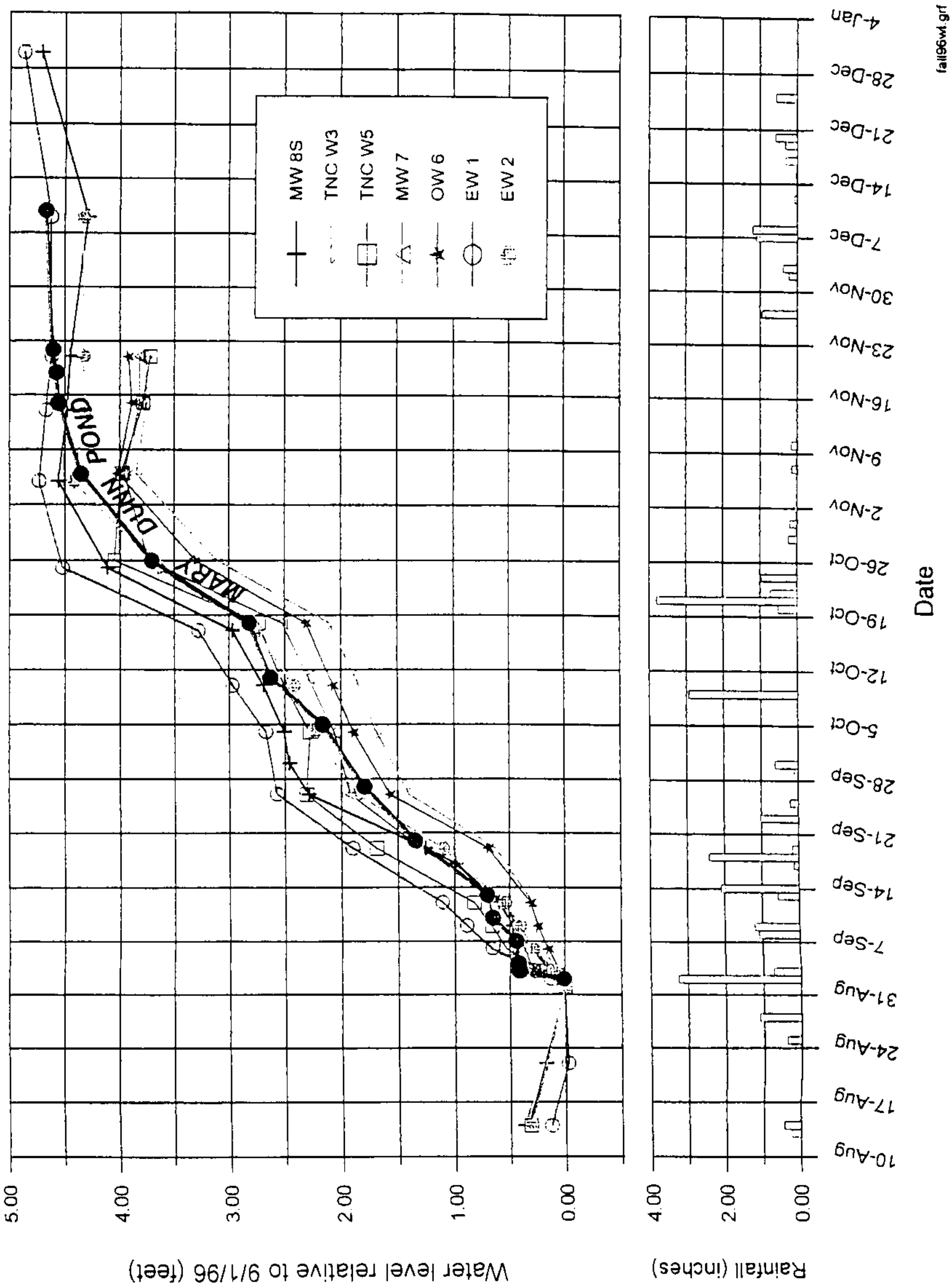


Figure 27. Water level changes in study area wells and Mary Dunn Pond compared with rainfall events. Mary Dunn Pond indicated by thick blue line.

this study I have found large downward vertical gradients in mid-pond piezometers at Lamson and Israel during low water conditions and the pond shores support fairly large downward vertical gradients without the influence of pumping. It is likely that these ponds are less well connected to ground water than Mary Dunn Pond.

The agreement between the pattern and magnitude of water level rise in Mary Dunn Pond and the surrounding aquifer also suggest that ground-water levels are the primary control on pond levels. During recharge periods, ground-water levels will rise as the pore space in the aquifer materials fills. (For example one inch of rainfall will fill a sand with 33% porosity to a depth of three inches.) This accounts for the fact that water levels rise in the aquifer by amounts greater than the rainfall depth despite continued drainage to local or regional discharge zones. Ponds which receive ground-water discharge(recharge from the perspective of the pond) will also rise inexcess of the balance between precipitation and evaporation (+/- transpiration). For a pond in which the water level increase during a recharge period closely matches the ground-water-level increase, it is apparent that ground-water flow into the pond is a dominant hydrologic process.

Discharge of ground-water into the pond (pond recharge) will take place when there is an elevation of the aquifer level with respect to the pond or a depression of the pond level with respect to the aquifer. In the recovery phases of *all* of the pumping tests performed during this study, pond recharge has been clearly demonstrated at high and low pond levels. The lowest post-test elevation of Mary Dunn Pond was 23.5 feet above msl, following the 1995 test of MD#2.

Recharge under non-test conditions can also be demonstrated at somewhat lower levels. The lowest levels of the pond observed during this study occurred in late October 1995 when the pond reached about 22.7 feet above msl. In the period from October 27th to December 12th, the pond rose 0.76 feet in response to 0.58 feet of rain. If evaporation is factored in (0.17 feet by F&V method) this represents a rise of 0.35 feet in excess of the sum of precipitation and evaporation. It appears that ground-water movement into Mary Dunn Pond occurs over a wide range of pond levels, and it is therefore likely that movement of water out of the pond occurs over a similar range.

Conclusions

During periods of ground-water recharge, water movement from the aquifer into the ponds can be demonstrated. This water movement occurs over a wide range of pond levels and is a significant aspect of the hydrology of the ponds. Monitoring ponds in periods between rainfall events provides the most direct evidence of ground-water inflow to the ponds.

1997 Spring Pumping Tests

Introduction

In the Spring of 1997, BWC conducted three pumping tests in cooperation with The Nature Conservancy. The purpose of these tests was to evaluate the effects of pumping wells not previously tested, to test the effect of intermittent (non 24-hour) pumping, to test the effect of pumping multiple wells, to test the effects of pumping during conditions of low evapotranspiration, and to evaluate the influence of higher water table conditions on the pond-aquifer relationship. The pumping tests and recovery periods spanned 14 weeks.

Methods

The average daily pumping rate for each test varied with the capacity of the well and are given in the results section for each test. The data collected for these tests included well and pond water levels and precipitation. I will also be receiving air temperature data from the Hyannis NOAA station for estimation of evaporation and calculation of a water balance, for a later report. High water levels and the timing of the test precluded collecting water temperature and seepage meter data. A summary graph of the pumping and pond level changes is given as Figure 28. A summary of the tests is presented below. More detailed analysis of the extensive data collected during these tests will be presented in the final project report. Well data from the tests are being used to refine hydraulic parameters for the ground-water numerical model being developed as part of this study.

Results

Test - Airport #1

The initial test, of Airport#1(Airport well), began on March 19th and ran for three weeks. The average daily pumping rate for the Airport well during the test was about 1.2 mgal/day. The pumping schedule was set to meet the demands of the BWC system and, therefore, slowed overnight with the decrease in demand. Well-level data indicate that the effect of this diurnal variation in pumping did not produce significant diurnal fluctuations in the water table at distances greater than 500 feet from the pumping well. There also did not appear to be any significant drawdown induced in the areas of the deeper aquifer (below the basal clay layer) sampled by wells in the vicinity of the pumping well.

During the Airport Well test several rainfall events raised water levels in the surficial and deep aquifers and in all of the ponds in the area. On March 31st - April 1st, a combined snow and rainfall event deposited about 3.7 inches of rainfall equivalent precipitation on the area (TNC data). Precipitation totalled 6.46 inches (0.54 feet) during the test (TNC data). Mary Dunn Pond rose by 0.32 feet during the test while Israel (0.68 ft), Lamson (0.81 ft) and Little Israel (0.85 ft) all rose by greater amounts. Evaporation from the pond surfaces was probably not a significant factor, especially during the first phase of the test when most of the margins of the ponds were frozen.

For all of the ponds, increases in pond levels took place during periods with and without rainfall, indicating recharge by ground water as well as direct atmospheric input. During the Fall of 1996, similar precipitation events resulted in a reversed pattern of pond level increase, with Mary Dunn Pond rising more than the other ponds in response to rainfall and ground-water input. The recharge behavior of Mary Dunn Pond during the Fall of 1996 was similar to water table wells, including reference well A1W230. During the test of the Airport well, A1W230 rose by 1.29 feet. A1W230 continued to rise, peaking mid-way through the subsequent two-week recovery period at about 1.4 feet above it's level at the beginning of the test. Other wells outside of the area of influence of the test were also measured during this period. Figure 29 shows the water levels in A1W230 and two wells within the Hyannis Ponds WMA, MW 7 and OW 6 during the entire testing period and into July. All of these wells responded in a similar manner to the rainfall events during the test of Airport #1.

During the test most of the southern shore of the pond developed a moderate to strong downward gradient, the largest downward hydraulic gradient (-0.09ft/ft) was found in the piezometer P Beach S, closest to the pumping well. Prior to, and after the test, an upward gradient (+0.03ft/ft) was present in P Beach S.

First Recovery Period

During the recovery period between the first and second test, the behavior of Mary Dunn Pond appears similar to the Lamson, Israel and Little Israel Ponds, except that it exhibited greater water level increases during rain-free periods. Just prior to the start of the second test, the increase in pond level at Mary Dunn had nearly ceased and vertical gradients in those areas of the pond closest to the Airport well had returned to values and directions measured prior to the test. The other ponds in the study area began to exhibit discharge-dominated behavior in the interval between the first and second tests, ie. rainfall events no longer produced subsequent periods of ground-water recharge to the ponds.

Test 2 - Mary Dunn #2

The second test began on April 23rd to evaluate the influence of high water table and pond levels on the interaction between supply well Mary Dunn #2 and Mary Dunn Pond. This interaction had been examined during the summer of 1995 when pond and aquifer water levels were lower. It had been intended to match the average daily pumping rate from the 1995 test using higher instantaneous rates and fewer hours of daily run-time. The average rate during this test was 0.82 mgd while the 1995 test averaged 0.77 mgd. During the two weeks of the second test, Mary Dunn Pond fell 0.69 feet. The reference ponds either fell or rose slightly, reflecting a balance between precipitation, evaporation and ground-water inflow and outflow. During the second test 1.32 inches (0.110 ft) of rain fell.

In the initial days of the test of MD#2, pond levels fell at a rate of 0.07 feet per day after correction for a small amount of rainfall. Prior to the start of the test the level of Mary Dunn Pond had been rising slightly and it appears that the pond would have levelled out over the first several days of the test without the influence of pumping. (As was seen in the final recovery phase, see below.) The area of the pond surface at this time was approximately 20 acres (870,000 sq.feet). The loss of 0.07 feet per day is equivalent to about 450,000 gallons per day or 55% of the water pumped from MD#2. During the equivalent pumping test in 1995, similar calculations indicated that about 28% of the water being pumped came from the pond. Water levels during the 1995 test were much lower and water being supplied to the well travelled through finer-grained and presumably less permeable pond-shore sediments. Drawdowns in observation well

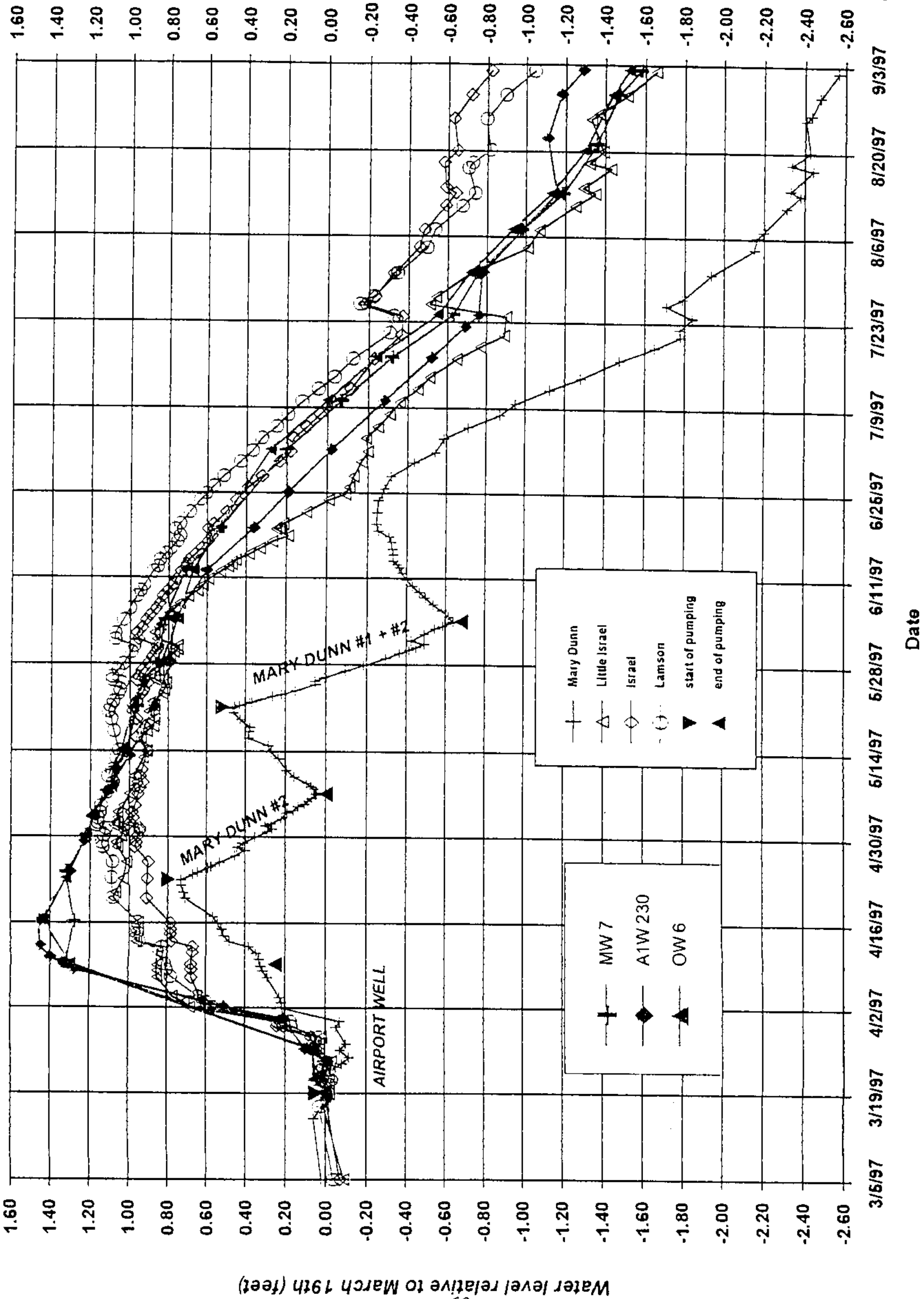


Figure 29. Changes in pond levels and reference wells, Spring and Summer, 1997.

TNC W9 (≈270 feet WNW of MD#2) were lower during the 1997 test of MD#2, as would be expected if the water were flowing through highly permeable sediments high on the shoreline.

The levels of all of the ponds reached their seasonal highs during the second pumping test, except Mary Dunn. The rate of pond level decline at Mary Dunn slowed during the test somewhat. Pond level measurements were also taken twice daily at the end of the test to determine whether there was any diurnal variation in pond level changes. The data do indicate some diurnal variation, although the amplitude of variation is near the measurement error for the water level instrument. The slowed rate of pond level decline probably indicates increased recharge of ground-water to the pond as pond levels fell below the water level in the surrounding aquifer.

Second Recovery Period

During the recovery period between the second and third tests, the level of Mary Dunn Pond rose by 0.42 feet recovering 61% of the water level loss experienced during the test. Lamson and Israel Ponds also rose slightly in response to three moderate rainfall events totalling 1.43 inches (0.119 feet). Little Israel Pond fell by 0.12 feet during the second recovery phase, concurrent with renewed pumping of supply well Mary Dunn #4, adjacent to that pond. During the course of the second recovery phase the rate of rise of Mary Dunn Pond slowed during rain-free periods and pond margin vertical gradients returned to their pre-test values and directions.

Test 3 - Combined pumping of Mary Dunn #1 and #2

During the third pumping test supply wells Mary Dunn #1 and #2 were tested in combination, with MD#1 running as the lead well. As with the previous tests, the wells were pumped during the day on a demand basis and pumping slowed or ceased during the night. Combined pumping on these wells averaged about 1.35 mgd. During the first four days of the test Mary Dunn Pond fell at a rate of 0.109 ft per day, equivalent to 3.27 feet per month. As in the second test, the rate of water loss slowed through the course of the test; in the final two days of the test the pond fell at an average rate of 0.075 feet per day. Over all, Mary Dunn Pond fell 1.11 feet while Lamson, Israel and Little Israel Ponds all fell less than 0.1 feet during the two-week test. Rainfall during the combined test totalled 1.97 inches (0.164 feet). The average daily water loss after adjustment for rainfall (but no evaporation adjustment) is 0.09 feet per day. This slowing of water loss is even more apparent for Little Mary Dunn, located adjacent to MD#1 (Figure 30). By the end of the combined pumping test Mary Dunn Pond was 1.5 feet lower than the average of the three reference ponds with respect to their levels on March 19th, the beginning of the cycle of tests. The initial rate of water level decline in Little Mary Dunn had been equivalent to over eight feet per month, but slowed dramatically as the test proceded.

Final Recovery Period/Overall Test Recovery

The final recovery phase for the pumping tests produced an overall rise in Mary Dunn Pond of 0.40 feet over sixteen days. The rate of pond level increase moderated during the final recovery period, but was also punctuated by more rapid increases due to moderate rainfall events. Water supply pumping in the Mary Dunn Field during the last recovery phase was provided by Airport#1 and MD#4. Little Israel Pond fell during this period with respect to the Lamson and Israel Ponds by about 0.4 feet. On June 25 pumping was halted on MD#4 due to an "odor" problem (G.

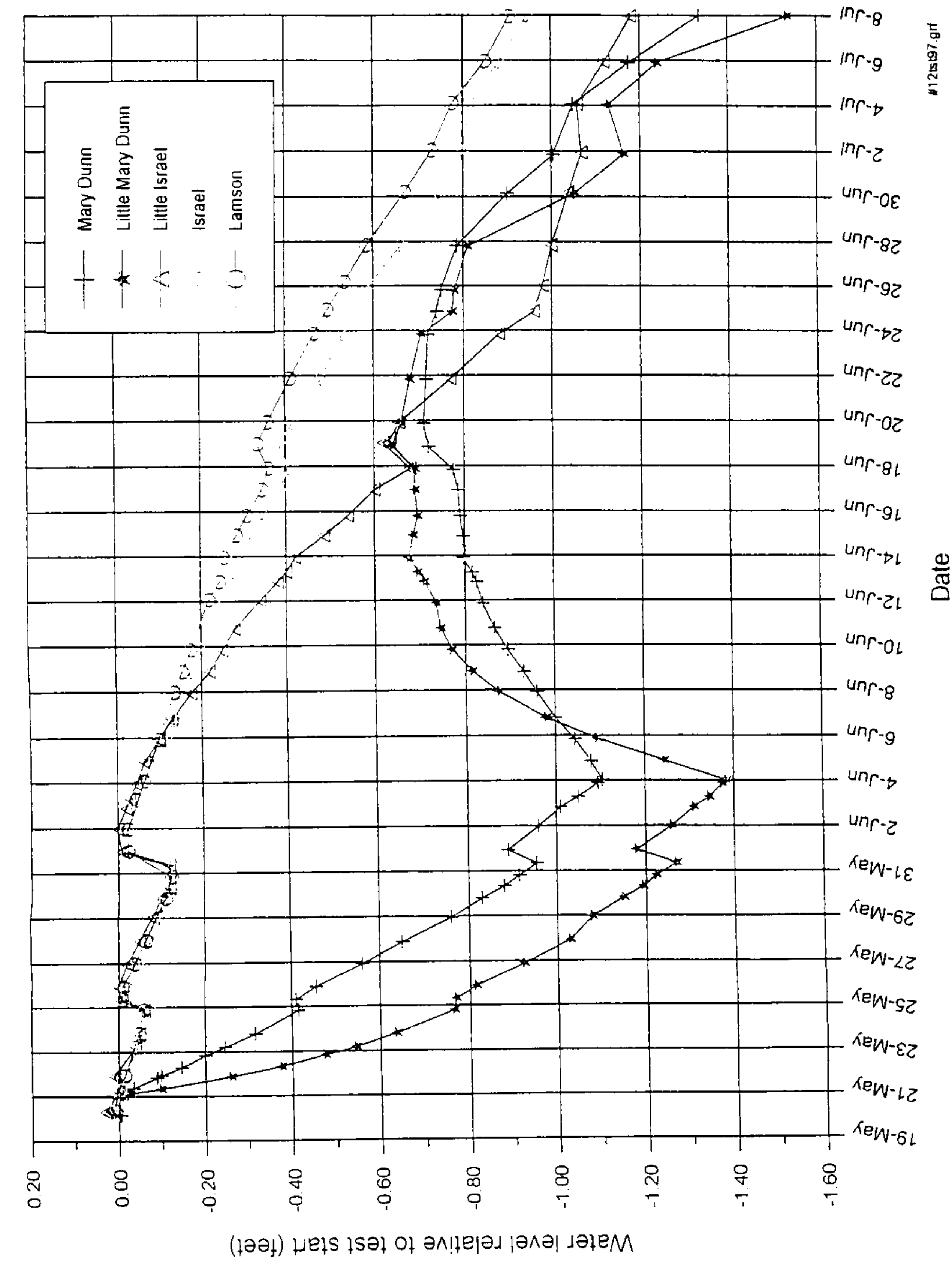


Figure 30. Pond level changes during and following combined test of Mary Dunn #1 & #2. Water levels changes are relative to the beginning of the test. X-axis ticks at 12:00 of indicated date.

Wadsworth, pers. comm. 7/2/97) and supply pumping switched to a combination of Airport#1, MD#1 and MD#2.

The effect of the resumption of normal water supply operation is evident on Figure 28 in the period from June 25th onward. The level of Mary Dunn Pond fell abruptly during this period, effectively halting the final recovery phase and ending the testing period. From June 25th to July 30th, Mary Dunn Pond fell by 1.64 feet, while Lamson Pond fell by 0.94 feet, Israel fell by 0.84 feet and Little Israel fell by 0.63 feet.

Discussion

This series of well tests clearly established the relationship between water supply pumping and pond level decline in Mary Dunn, Little Mary Dunn and Little Israel Ponds for all four wells pumped.

The test of Airport #1 clearly indicated a loss of water from Mary Dunn Pond and an even greater rate of water loss was seen at Lewis Pond, about 400 feet from the pumping well. Mary Dunn pond actually rose during the test, but this result must be examined in context of the likely behavior of the pond in the absence of pumping. Two points are relevant to interpretation of the test results. First, Mary Dunn Pond rose less than the total of precipitation during a period of cold weather and ground-water recharge to the ponds. Under similar conditions, but warmer, conditions in the Fall of 1996, Mary Dunn Pond rose more than the total of precipitation and in amounts similar to the surrounding aquifer. Second, Mary Dunn Pond rose less than other ponds in the area. Under similar water table and precipitation conditions in the the Fall of 1996, and without the influence of pumping, Mary Dunn Pond had demonstrably risen more than these other ponds. It is likely that without the influence of the pumping at Airport #1, Mary Dunn Pond would have risen in excess of one foot during the period of the initial test. This result for the Airport well is also significant because of the distance from the Airport to Mary Dunn Pond. The previous test of MD#2 in the summer of 1995 had clearly shown the influence of pumping a well within 100 feet of the pond, however, Airport #1 is about 1000 feet from the pond shore.

For the test of MD#2, the drawdown of Mary Dunn Pond was as distinct as was seen in the 1995 test. The 1995 test of MD#2 was run two months later than the 1997 test, and therefore less evaporation from the pond is expected during the 1997 test. Overall pumping rates were similar, with the 1997 test pumping at a six per cent higher rate than was used in 1995. Drawdown rates were similar to the 1995 test, despite the lower expected evaporation rate (in an average year about 35% lower for the late April vs. late June). Since the pond area at higher water levels is larger, the same rate of vertical (linear) water loss translates to a higher volumetric rate of water loss from the pond. For the 1997 test of Mary Dunn #2, the majority of the water flowing from the well was derived from the pond. The large amount of water loss from the pond is consistent with the conclusion that water flows easily from the pond through the permeable sediments found high on the shoreline, and that late spring pumping produces strong pond drawdowns despite abundantly available water in the adjacent aquifer.

The combined test of Mary Dunn #1 and #2 demonstrated the dramatic rate of water loss resulting from both of these wells being pumped. Linear and volumetric water loss rates at Mary Dunn Pond during this test are the highest seen during the course of this study. During the first four days of the test Mary Dunn Pond fell at a rate of 0.109 ft per day, equivalent to 3.27 feet per month. Previously, the highest rate of water loss seen during this study had been 0.08 feet per day (73% of the initial rate for this test) from June 3 to June 6, 1996. During June 3rd, 4th and 5th, 1996 MD#1 and MD#2 had been pumping at a combined average daily rate of 0.97 mgd, or 72% of the 1997 pumping test rate.

After the last recovery period, pumping resumed under non-test conditions, although the combined pumping of MD#1, MD#2 and the Airport Well exceeded test levels. During this period, the resumption of pond-level decline at Mary Dunn clearly demonstrates the effect of pumping on the level of the pond.

The tests also demonstrated a clear recovery phase during which the ponds begins to equilibrate with the surrounding water table. Based on seepage results from the 1995 test, this period is one in which seepage into the pond (pond recharge) is enhanced by the lowered elevation of the pond water levels with respect to the surrounding aquifer. During the pumping period, a large portion of the water supplied to the well comes from the pond. The pond then acts in effect as a large well drawing water from other areas of the pond margin. If drawdown is rapid enough, portions of the pond margin normally characterized by downward gradients will experience a reversal of gradient as pond levels are lowered below those in the surrounding aquifer. Reversals of this type have been noted in the 1995 test and in the latter two tests in 1997. This reversal of gradient may produce inseepage in some areas of the pond normally characterized by outseepage and drawdowns will also enhance inseepage in other areas. The increased inseepage will slow the rate of water loss from the pond in the latter stages of the test and produce a distinct recovery response after the well is shut off. The overall effect is to remove water from a larger area of the aquifer than would take place without the pond to act as a "shunt". As water levels in the surrounding aquifer equilibrate with the pond, the rate of pond level rise slows and eventually the pond reverts to its normal balance of inseepage (recharge), outseepage (discharge) and atmospheric input/output. Renewed pumping will upset that balance and inhibit recovery of the pond, particularly if the well pumps from an area which normally supplies recharge to the pond.

Additional analysis of the results of these pumping test will be included in the final project report. The analyses will include: water table maps from the start of the test series and at several times during the test; drawdown curves for several wells with hydraulic calculations and water balance for each test and the testing period as a whole.

Overall Conclusions

The work performed for the hydrologic portion of this study has clearly established a strong relationship between the hydrology of the ponds in the study area, particularly Mary Dunn Pond , and the surrounding aquifer. We have demonstrated that water levels in Mary Dunn Pond are affected by ground-water recharge, pumping under test conditions, and pumping under normal water supply conditions in addition to direct precipitation, evaporation and ground-water flow in the absence of pumping. Within the study area, Mary Dunn , Little Mary Dunn and Little Israel Pond are clearly affected by ground-water pumping, although it less clear whether Lamson and Israel Ponds are strongly affected. The behavior of Lamson and Israel Ponds during ground-water recharge periods indicates that they are less strongly connected to the aquifer flow system than Mary Dunn Pond.

The remaining hydrologic work will focus on refinement of the results presented herein and their incorporation into a numerical ground-water flow model. This model will be used to determine patterns of withdrawal that will mimic ecologically vital natural pond-level fluctuations, while providing adequate water supply.

Bibliography

Barlow, P. M. (1987) The use of temperature as a ground-water tracer in glacial outwash. unpublished Master's thesis. Univ. of Arizona.

Domenico, P.A. and Schwartz, F. W. (1990) Physical and chemical hydrogeology. John Wiley and Sons, New York, NY., 824 pp.

Fennessey, N. M. and Vogel, R. M. (1996) Regional models of potential evaporation and reference evapotranspiration for the northeast USA. Jour. Hydr., v. 184, p. 337-354.

Fletcher (1993) Soil survey of Barnstable County, Massachusetts. USDA - Soil Cons. Service., 221 pp.

Freeze, R. A. and Cherry, J. A. (1979) Groundwater. Prentice-Hall, Englewood Cliffs, NJ., 604pp.

Horsley, Witten and Hegemann, Inc. (1992) Application for Amendment to Water Management Act Permit no. 9P-4P22P0.20.05. June 1992.

Horsley and Witten Inc. (1994) 1994 Annual Report: Hydrologic Monitoring. Water Management Program, Dept. of Environmental Protection for Barnstable Water Company Water Management Act Permit no. 9P-4-22-020.04. January, 1995.

Horsley and Witten Inc. (1996) 1996 Annual Report: Hydrologic Monitoring. etc., as above, February, 1996.

Horsley and Witten Inc. (1996) 1996 Annual Report: Hydrologic Monitoring. etc., as above, March, 1997.

IEP Inc. (1990) Independence Park Hyannis, Massachusetts - Second supplemental draft environmental impact report (EOEA #7193). Chapter 3, Hydrology, p.41-76.

Le Blanc, D. R. et. al. (1986) Groundwater resources of Cape Cod, Massachusetts. U.S.G.S. Hydrologic Atlas HA-692.

Lee, D. R. (1977) A device for measuring seepage flux in lakes and estuaries. Limnology and Oceanography. vol. 22, p. 140-147.

Oldale, R.N. (1974) Geologic Map of the Hyannis Quadrangle. USGS Map GQ-1158.

Oldale, R. N. and O'Hara, C. J. (1994) Glaciotectonic origin of the Massachusetts coastal end moraines and a late Wisconsinan ice margin. GSA Bull. v. 95, p. 61-74.

Bibliography, cont.

Thornthwaite, C. W. (1948) Toward a rational classification of climate. The Geographical Rev., v. 38, no. 1, p. 55-94.

Weast, R.C. (1976) Handbook of Chemistry and Physics. CRC Press, Cleveland, OH.