Lake Wequaquet Water Level Study

FINAL REPORT

(December, 1998)

prepared for

Town of Barnstable Conservation Commission
Town of Barnstable Department of Public Works

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Executive Summary

Lake Wequaquet is one of the largest great ponds on Cape Cod covering over 570 acres and is connected by herring run to Long Pond, which covers over 50 acres. Due to extremely high rainfall amounts associated with Hurricanes Edouard and Josephine during the Fall of 1996, lake levels and groundwater levels across Cape Cod were among the highest ever recorded. In the vicinity of Lake Wequaquet, in particular, the resultant high water levels resulted in flooded basements, losses of shoreline, and stormwater and wastewater disposal problems for homeowners. In order to address these concerns, the Town of Barnstable Conservation Commission and the Department of Public Works formed a cooperative partnership with the Cape Cod Commission to initiate a project to better understand the lake level of Lake Wequaquet, its flow into Long Pond, and their connection to the groundwater. Under the scope of this project, the following tasks have been completed and are documented in this report: 1) collection of water level data in and around Lake Wequaquet and Long Pond, 2) collection of flow information into and out of the lakes, and 3) analysis of the collected data. In Lake Wequaquet and Long Pond, it was initially expected that groundwater factors would be the dominant factors for determining their water levels.

Water levels in these lakes, as with most of the large lakes on Cape Cod, fluctuate due to a number of factors, including annual changes in groundwater levels, seasonal changes in precipitation, and hourly changes in stream outflows. The relationships between these factors are complicated and characterization of these relationships often depends on how frequently measurements are collected.

During this project the following data were collected: 1) water level data at a permanent stilling well at the Lake Wequaquet Town of Barnstable beach, 2) streamflow measurements coming out of Lake Wequaquet and into and out of Long Pond, 3) multiple measurements of groundwater levels at more than 20 locations, and 4) daily precipitation data and bi-monthly water level data collected by Town of Barnstable staff at the Hyannis Wastewater Treatment Facility.

Analysis of the data has found that water levels of Lake Wequaquet and Long Pond generally fluctuate together with the level of Lake Wequaquet exceeding the level of Long Pond by an average of 8 ft. This contrasts to the 6 ft difference indicated on the USGS Topographic map for this area (Long Pond elevation, 28 ft; Lake Wequaquet elevation, 34 ft).

The level of Lake Wequaquet fluctuates within a relatively narrow range (~2 ft) compared to the large (~6 ft) range observed in the groundwater surrounding the lake. The relative stability of the water level of Lake Wequaquet means that water inflows (groundwater and precipitation) into the lake are generally balanced by water outflows (streamflow, groundwater, and evaporation) out of the lake.

Groundwater inflows into Lake Wequaquet occur from the north and west sides of the

lake with seasonal (March to September), transient inflows from the eastern side, that is influenced by the groundwater mound associated with discharges at the Town of Barnstable WWTF. The majority of flow (~80%) comes from the western portion of its watershed.

Groundwater surrounding Lake Wequaquet was in equilibrium with the level of the lake until Fall 1996 when precipitation exceeded seasonal averages by 12 inches. Groundwater levels have remained higher than lake levels, largely supported by higher than average seasonal precipitation, creating a relatively constant upward pressure on the level of the lake. Even with this higher pressure, however, the level of the lake has remained fairly stable (range of ~1 ft). The greater groundwater discharge into the lake has been nearly balanced by higher streamflow, and presumably higher groundwater discharge, out of the lake.

Streamflows out of Lake Wequaquet (at Phinneys Lane), into Long Pond (at Route 28), and out of Long Pond (at Pine Street) generally move together (within ~0.5 cfs of each other). Streamflows out of Long Pond are generally greater than flows out of Lake Wequaquet indicating that any upward pressure on water levels in Long Pond are not due to streamflows out of Lake Wequaquet and that increases in Long Pond water levels are likely due to the same regional increases in groundwater levels that are causing the level of Lake Wequaquet to rise.

Board heights at the outflow of Lake Wequaquet (at Phinneys Lane) do not appear to have any long term impact on lake levels. However, the board heights can impact streamflows on a weekly basis. This short-term impact indicates that active management of the boards should continue to ensure that adequate flow is available for alewife movement up and down the herring run.

Overall, it appears that Lake Wequaquet's groundwater inflow and outflow fluctuate within a fairly small range, with any rises in water level creating an equivalent increase in groundwater discharge. Streamflow out of Lake Wequaquet appears to function in a similar fashion.

Analysis of the data has led to the recommendation that collection of water level, board height, and streamflow information should continue in order to complete long-term evaluation of board management, especially during low water conditions. It is also recommended that the elevations on the gauge at Phinneys Lane be remeasured, marks on the gauge be numbered in tenths of feet, and daily notes on board heights be recorded.

Given the importance of streamflow for alewife movement and the negligible relationship measured between streamflow out of Lake Wequaquet and board height or lake level, it is recommended that streamflow be measured on a weekly basis at the Phinneys Lane culvert, especially during periods of declining streamflows. It is also noted that further evaluation of existing data be enhanced through the use of a groundwater model with an ability to accommodate transient inputs.

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INTRODUCTION

During the Fall of 1996, extremely high rainfall amounts caused lake levels and groundwater levels across Cape Cod to be among the highest ever recorded. In the vicinity of Lake Wequaquet, in particular, the resultant high water levels resulted in flooded basements, losses of shoreline, and stormwater and wastewater disposal problems for homeowners.

The Town of Barnstable Conservation Commission and the Department of Public Works formed a cooperative partnership with the Cape Cod Commission to initiate a project to better understand the lake level of Lake Wequaquet, its flow into Long Pond, and their connection to the groundwater. Water levels in lakes on Cape Cod fluctuate due to annual changes in groundwater levels, seasonal changes in precipitation, daily changes in temperature and wind strength, and hourly changes in stream outflows. The relationships between these factors are complicated and often change depending on how frequently measurements are collected. The overall goal of this project is to provide quantitative measures to evaluate best management options for lake water levels.

Under the scope of this project, the following tasks have been completed and are documented in this report: 1) collection of water level data in and around Lake Wequaquet and Long Pond, 2) collection of flow information into and out of the lakes, and 3) analysis of the collected data, including a discussion of potential water level management options for Lake Wequaquet, Long Pond, and their surrounding neighborhoods.

LAKE DESCRIPTIONS

Lake Wequaquet is one of the largest great ponds on Cape Cod covering over 570 acres and is connected by herring run to Long Pond, which covers over 50 acres (Figure 1). Lake Wequaquet and Long Pond are located within the Barnstable Outwash deposits within the Sagamore groundwater lens (see Figure 1). The deeper depressions in the bathymetry of Lake Wequaquet (Figure 2) were formed by one or more large ice blocks left by retreating glaciers 12,000 to 17,000 years ago during the Wisconsin Stage of the Pleistocene Epoch (Strahler, 1966; Winkler, 1985). Other ice blocks in the area created the depressions that have become Bearses Pond, Shallow Pond, and the two basins of Long Pond. Based on pollen collected in pond sediments in outer Cape Cod (Winkler, 1985), it is likely that these Barnstable ponds are at least 12,000 years old. The herring run connecting the ponds and the Centerville River estuary system is 131 years old; it was dug in 1867 by unemployed veterans of the Civil War (Hays and Ranta, 1976).

Lake Wequaquet, which includes Bearses Pond, has an average depth of 12 ft, a maximum depth of 30 ft, and holds an average of 364 million cubic feet (2.7 billion gallons) (Figure 3). Long Pond has an average depth of 9 ft, a maximum depth of 20 ft, and holds an average of almost 23.3 million cubic ft (170 million gallons) (Figure 4). The herring run/surface water outlet from Lake Wequaquet discharges into the

Figure 1. - Locus Map of Lake Wequaquet and Long Pond
Barnstable, MA

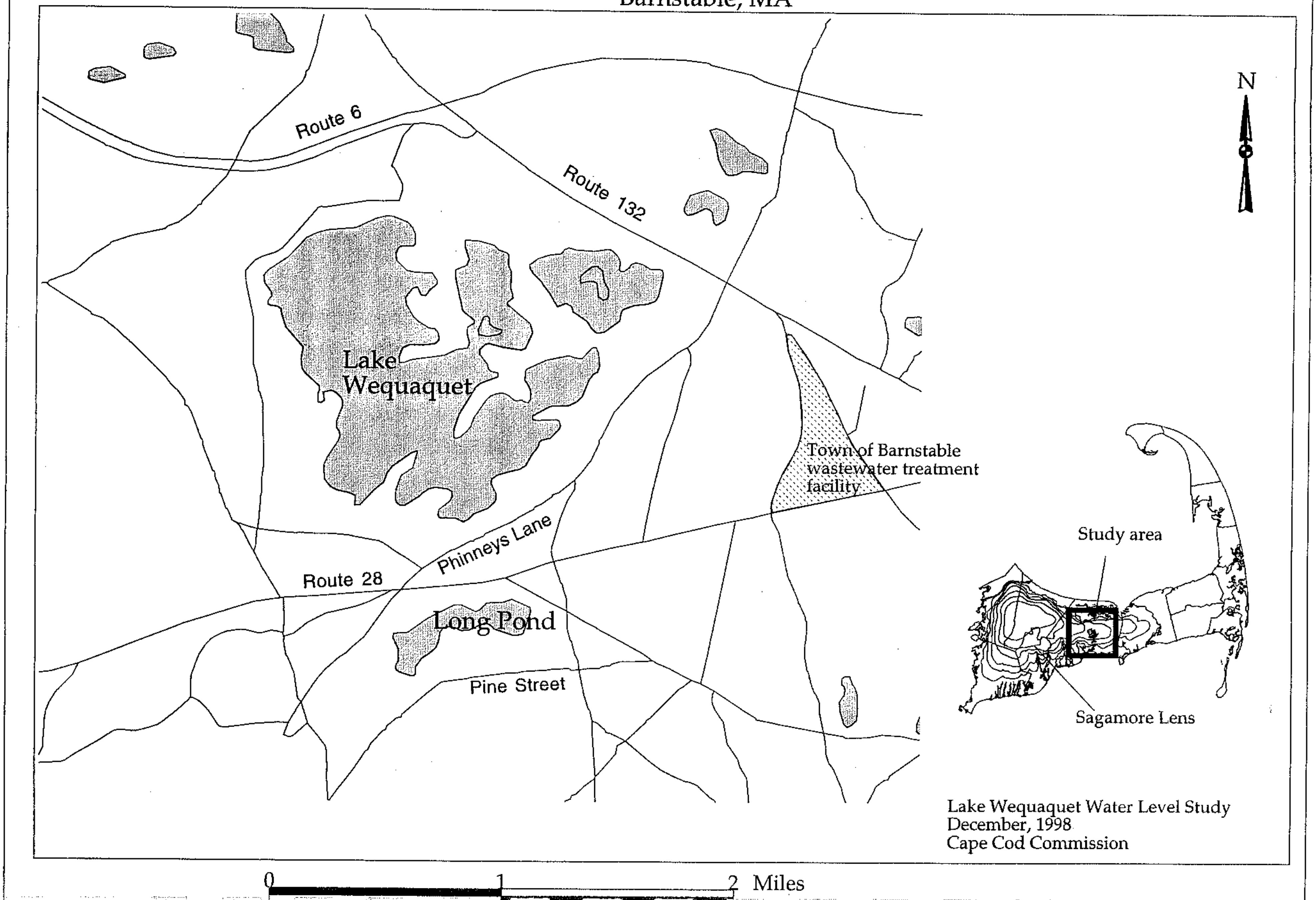
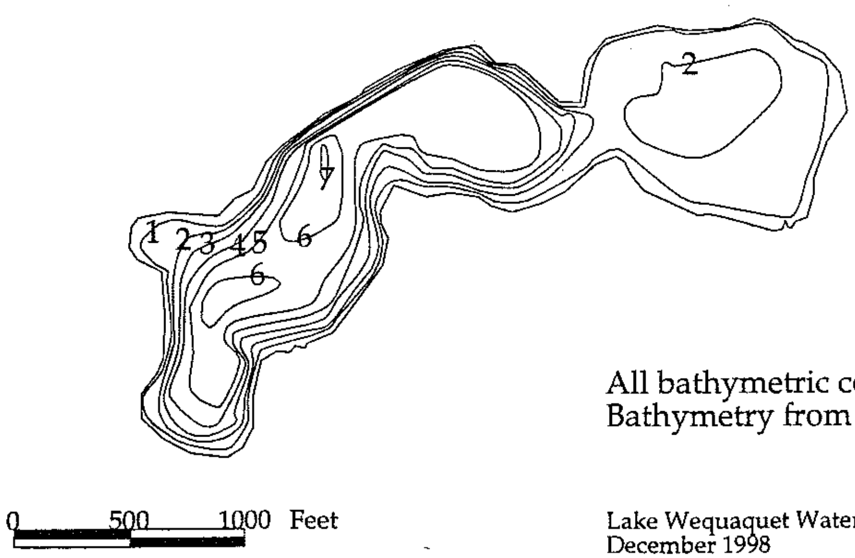


Figure 2. - Bathymetry of Lake Wequaquet and Long Pond

Barnstable, MA



All bathymetric contours in meters
Bathymetry from IEP (1988)

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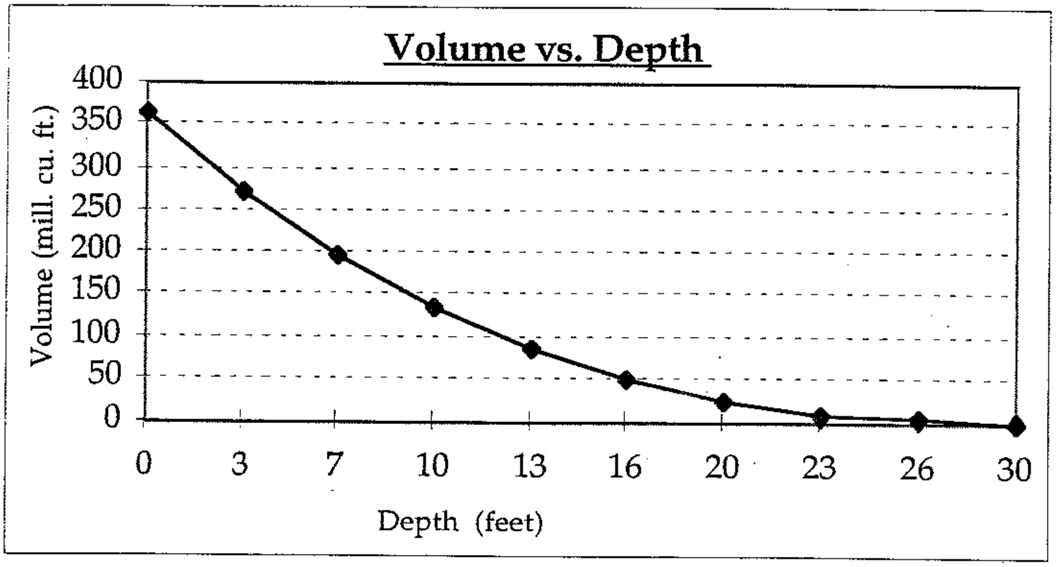
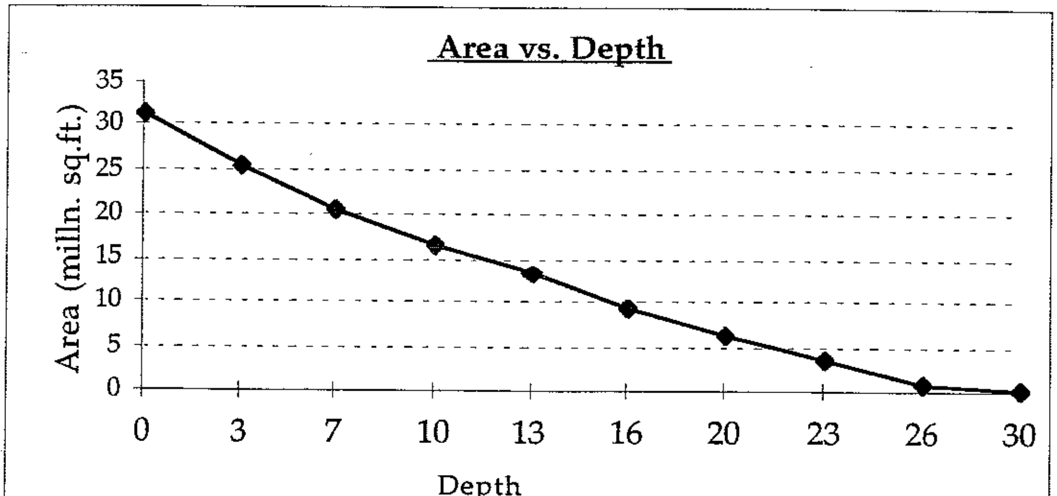
Figure 3. Lake Wequaquet Volume, Area, and Perimeter Data

(Depth)	Volume, in million c.ft.
0	364.00
3.28	272.00
6.56	196.00
9.84	135.00
13.12	86.20
16.40	49.40
19.69	23.60
22.97	7.60
26.25	1.80
29.53	0.12



Depth	Area, in million sq.ft.
0.00	31.50
3.28	25.50
6.56	20.60
9.84	16.60
13.12	13.30
16.40	9.53
19.69	6.26
22.97	3.66
26.25	0.90
29.53	0.23



Depth (ft.)	Perimeter Length
0.00	62,138
3.28	58,025
6.56	48,092
9.84	40,621
13.12	37,894
16.40	27,455
19.69	20,845
22.97	12,750
26.25	4,282
29.53	2,141

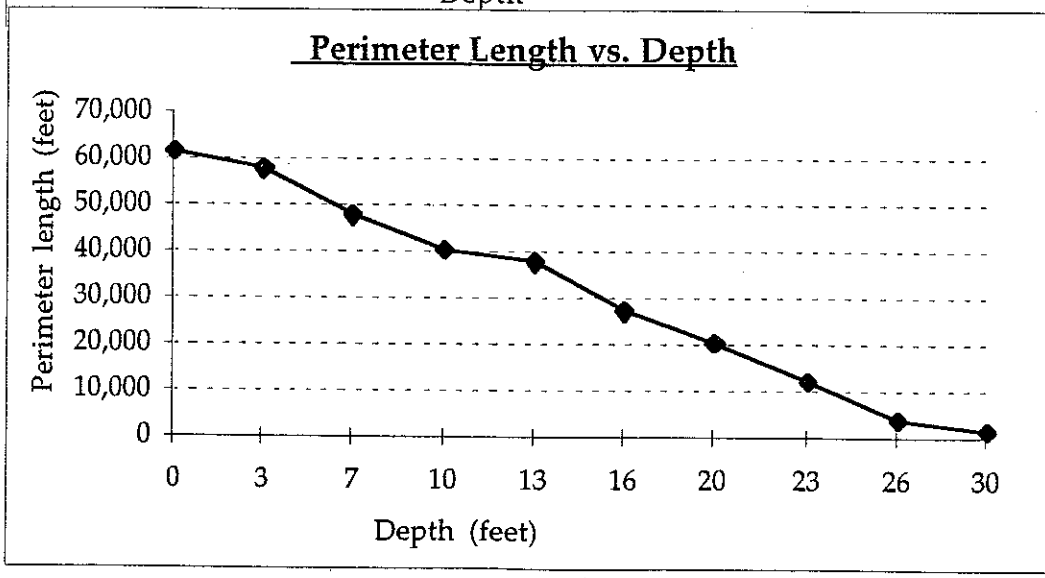
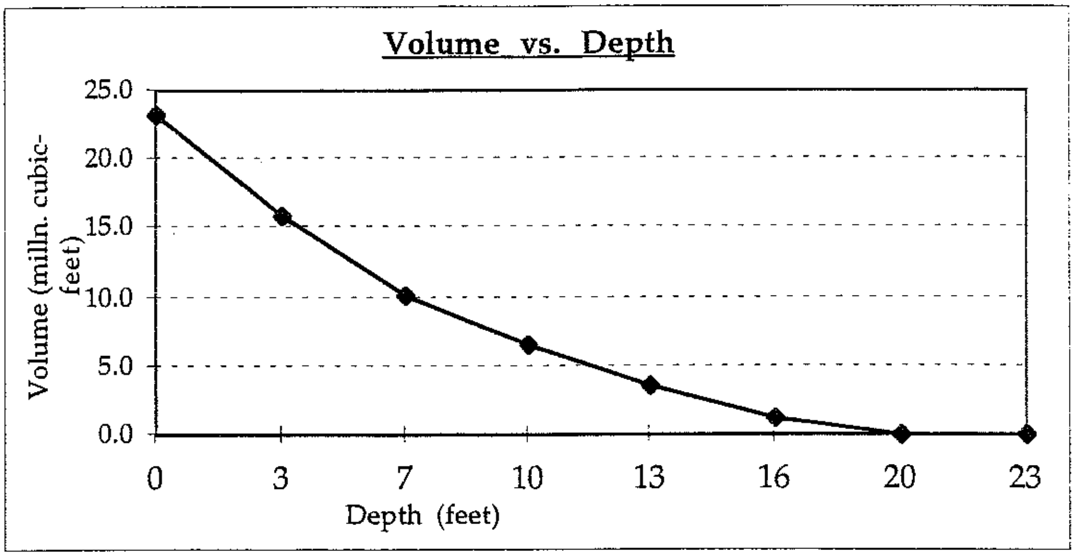
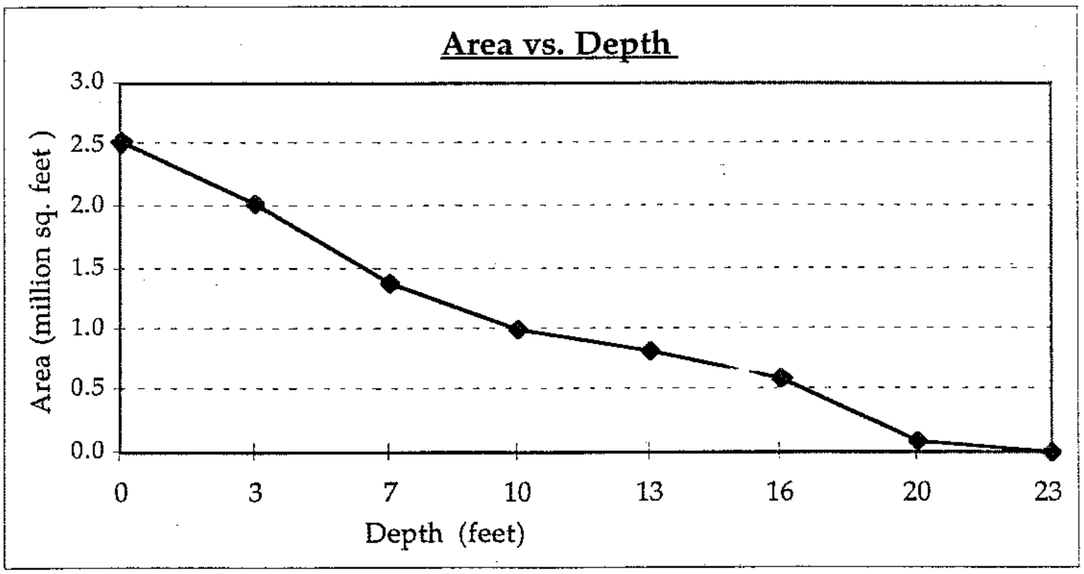


Figure 4. Long Pond (Centerville) Volume, Area, and Perimeter Data

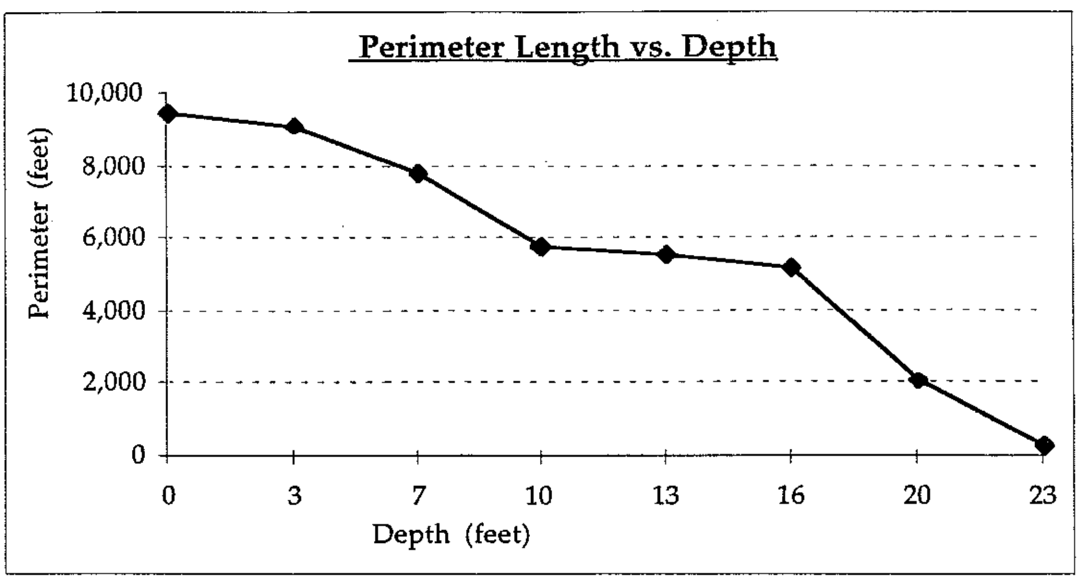
(Depth)	Volume, in million c.ft.
0	23.30
3.28	15.90
6.56	10.20
9.84	6.57
13.12	3.56
16.40	1.23
19.69	0.08
22.97	0.00



(Depth)	Area, in million sq.ft.
0	2.53
3.28	2.02
6.56	1.38
9.84	1.00
13.12	0.82
16.40	0.58
19.69	0.10
22.97	0.00



(Depth)	Perimeter Lengths (ft.)
0.00	9,503
3.28	9,123
6.56	7,847
9.84	5,831
13.12	5,575
16.40	5,219
19.69	2,098
22.97	334



northern portion of Long Pond after passing under Route 28, while the herring run/surface water outlet from Long Pond discharges into the Centerville River estuary system after passing under Pine Street (see Figure 1).

Lake Wequaquet is located within a portion of the Sagamore Lens (see Figure 1). The lake is located near the central spine or groundwater divide of the lens. Groundwater to the north of the divide flows toward Barnstable Harbor, while groundwater to the south of the divide flows toward Nantucket Sound. The location of the lake within the lens and its relatively large size suggests that the lake should have a fairly unique relationship with the surrounding groundwater as compared with other lakes on Cape Cod. Since it is located near the top of the lens, it should maintain the groundwater elevation of the top of the lens across its whole surface, which extends over a mile to the south. Also since it is near the top of the divide, flow from a significant distance to the west should flow through the lake and water levels in the lake should be fairly stable with small elevation changes as compared to groundwater levels further to the south.

DATA COLLECTION/METHODS

During this project the following data were collected: 1) water level data at a permanent stilling well at the Lake Wequaquet Town of Barnstable beach, 2) streamflow measurements coming out of Lake Wequaquet and into and out of Long Pond, 3) multiple measurements of groundwater levels at more than 20 locations, and 4) daily precipitation data and bi-monthly water level data collected by Town of Barnstable Department of Public Works (DPW) staff at the Hyannis Wastewater Treatment Facility.

Pond Water Levels

In order to expand the existing groundwater monitoring network, the Cape Cod Commission and the US Geological Survey cooperatively installed a number of stilling wells (Figure 5) at Cape Cod lakes, including one at the Town of Barnstable beach on the north side of Lake Wequaquet. A Solinst Model 3001 Levelogger™, a self-contained programmable data logger and pressure transducer, was installed inside the stilling well at the beginning of January 1998. The Levelogger™ was programmed to measure the water level of Lake Wequaquet every 15 minutes. Data was downloaded from the Levelogger™ at the beginning of each month and the system was reprogrammed. Water level data was collected from January 1998 to December 1998; a programming error prevented data collection during May 1998. Figure 6 presents the Levelogger™ data, including average daily water levels on Lake Wequaquet and the daily range of water level fluctuations.

The Town of Barnstable Department of Natural Resources (DNR) also records water levels on Lake Wequaquet and Long Pond (Figure 7). These readings are based on visual observation of water levels at the gauges near the outlets and have generally been collected on a daily basis since September 1996. Prior to September 1996, DNR staff collected 1 to 20 daily readings per month; available data begins in July 1994.

Figure 5. - Pond Well Schematic

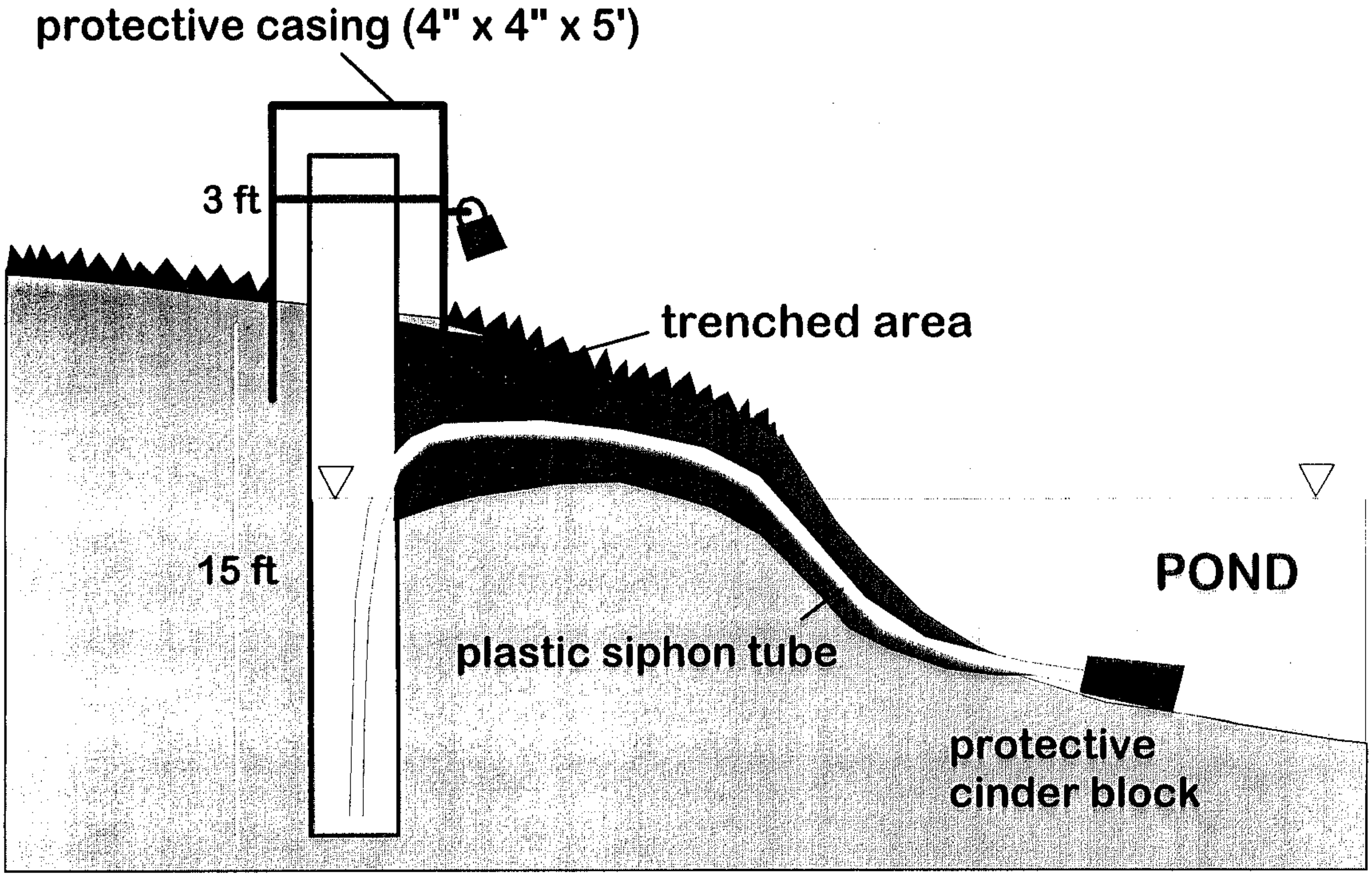
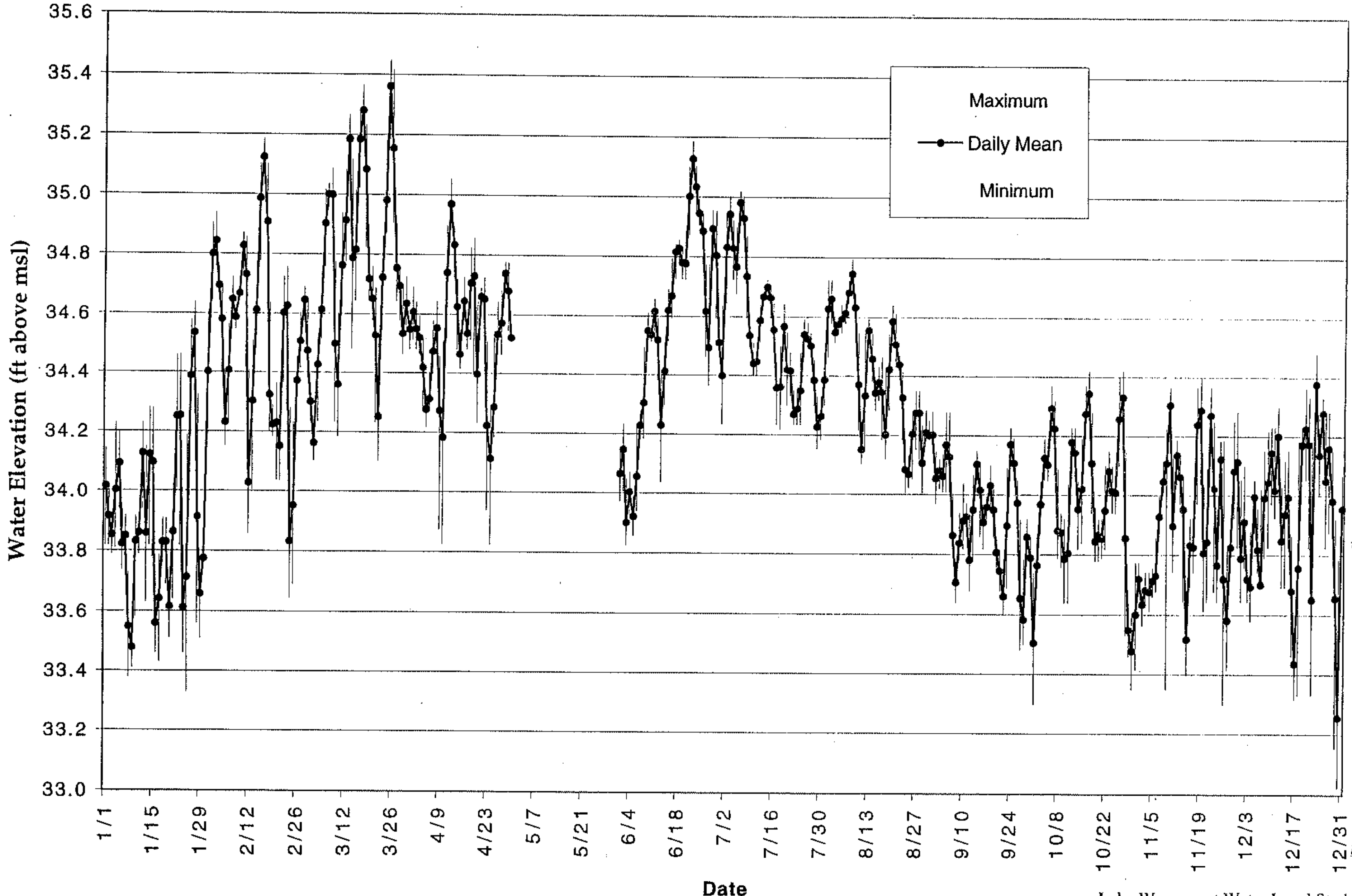
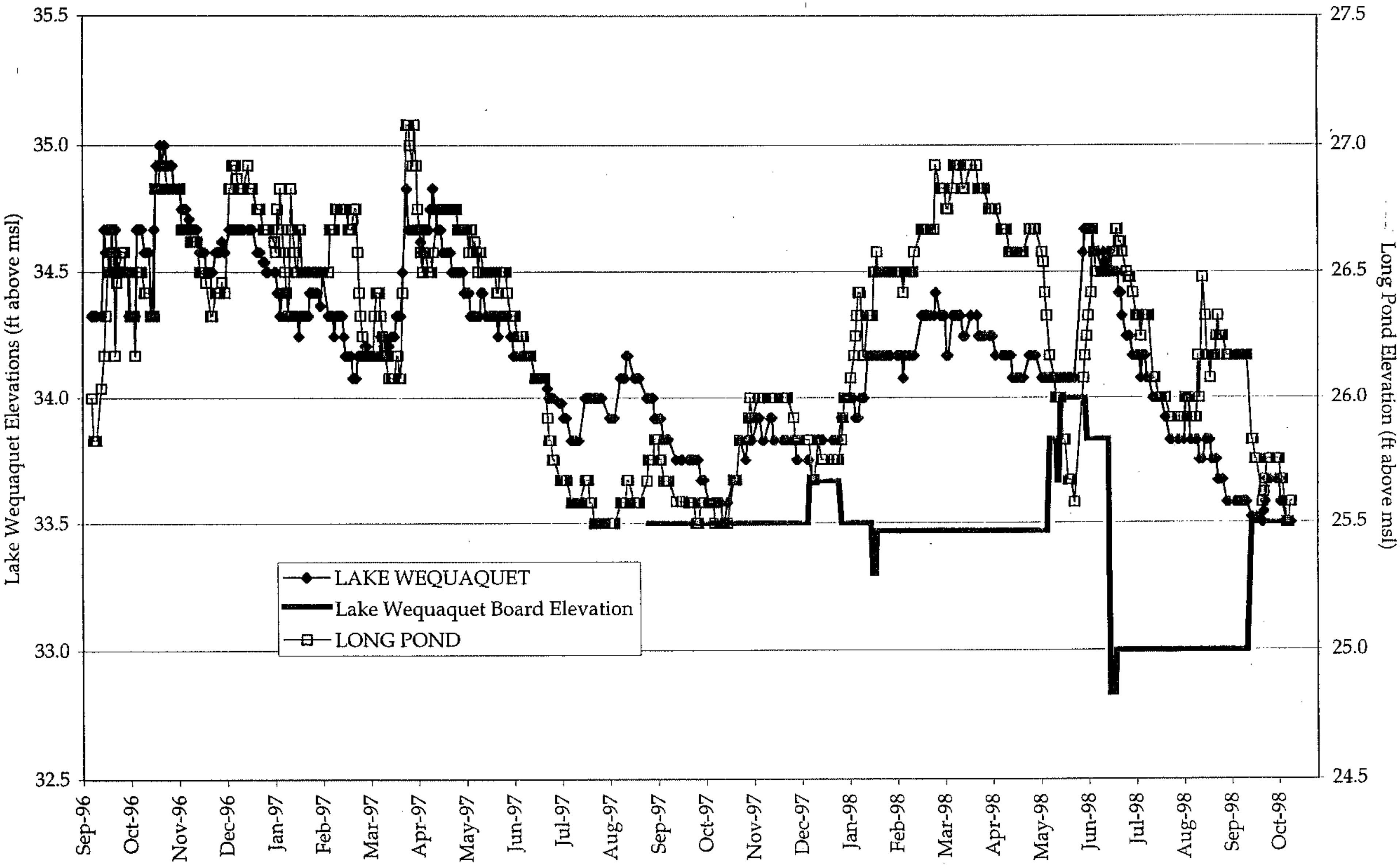


Figure 6. - Lake Wequaquet Daily Water Levels
(January to December, 1998)
Barnstable, MA



Source: Cape Cod Commission

Figure 7. - Lake Wequaquet and Long Pond Water Levels
(September, 1996 - October, 1998)
Barnstable, MA



Source: Town of Barnstable Department of Natural Resources

Streamflow Measurements

Project staff recorded streamflow measurements at three locations along the herring run connecting Lake Wequaquet and the Centerville River estuary: 1) at culvert on the south side of Phinneys Lane, 2) at culvert on the north side of Route 28, and 3) at the culvert on the north side of Pine St (see Figure 1). The cross-sectional area of each culvert opening (height times width) was determined for each flow measurement. Three readings were taken at each location, equally spaced across the width of the opening at mid-depth; a site flow reading is the sum of flows across the opening. Readings were taken with a Rickly Hydrological Company pygmy meter. Streamflow readings were collected approximately weekly between January and August 1998 (Figure 8).

Groundwater Levels

Eight small diameter (3/4 inch) drive point steel wells were installed at the locations noted on Figure 9 (designated as "CCC" wells). Each well is composed of one or two 5 ft sections with four 3/64 inch holes drilled in the lower 1 to 2 ft. Wells were installed using a 60 pound slide hammer. A number of additional pre-existing wells were also identified (see Figure 9 for locations). Water level readings were collected at all wells on July 16, 1998 and at selected wells on fourteen other dates. Water levels were obtained in the wells using a Slope Indicator electric tape (Model# 51453). Data were also obtained from Town of Barnstable staff for the wells located around the Hyannis Wastewater Treatment Facility (WWTF). Elevations of measuring points on all wells were determined by Town of Barnstable, Department of Public Works staff. All wells were developed and checked for their connection to the underlying aquifer.

Additional historic water level data from Cape Cod Commission files was also considered. The Commission collects monthly water levels at a over 60 sites across Cape Cod, in support of the high groundwater methodology recommended in Title 5 (310 CMR 15) for determining minimum separation distances for septic system leachfields (Frimpter and Belfit, 1992) and for use in hydrologic studies. Some wells in the network have over 30 years worth of water level information, which provide valuable insights into the variations in water levels. Water level information from three of these wells were considered during this project.

Precipitation

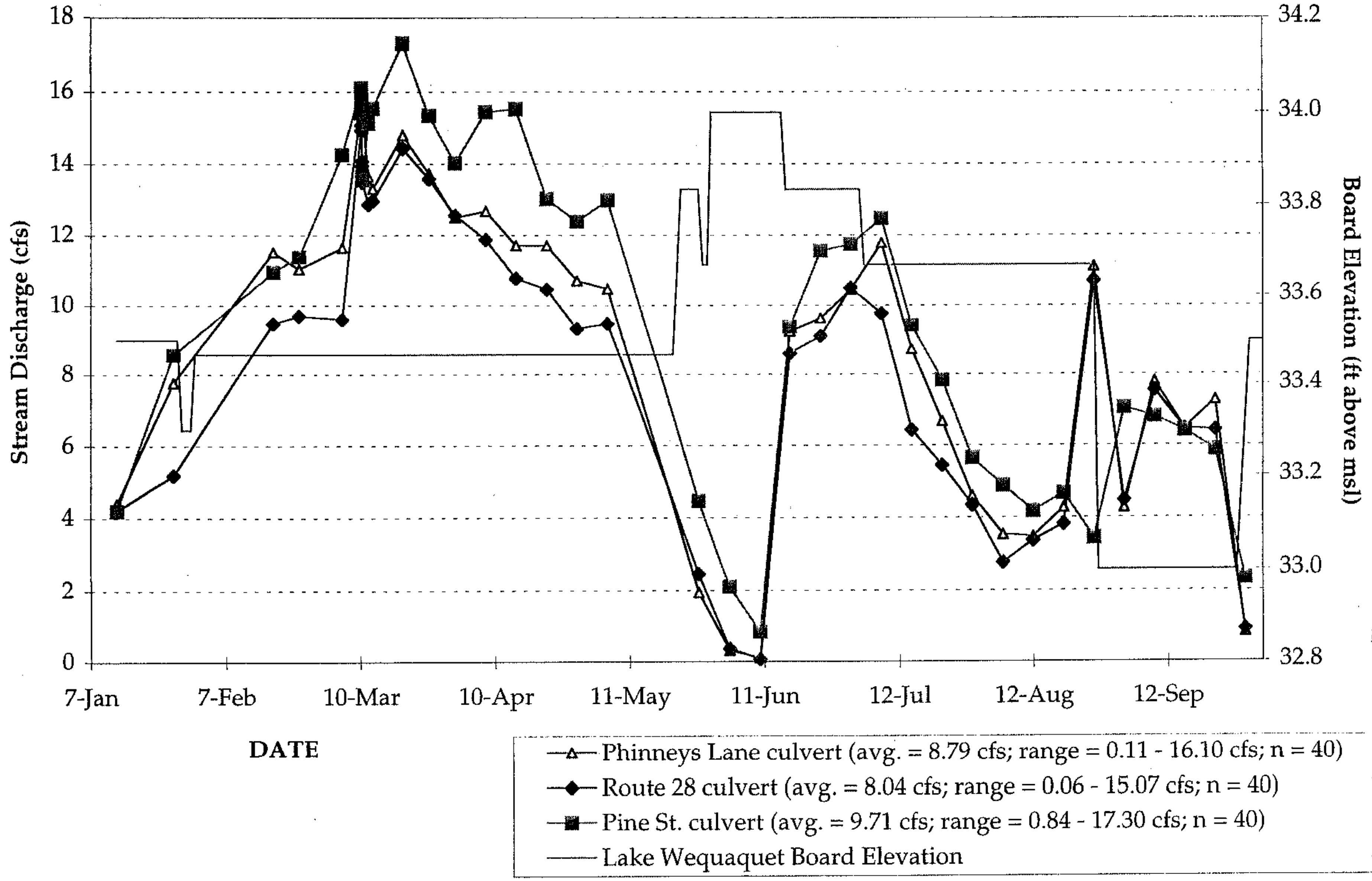
Town of Barnstable staff at the Hyannis WWTF collect daily precipitation data. The quantity of precipitation is measured at 8 AM every morning. This data is utilized by the National Oceanic and Atmospheric Administration (NOAA) and the WWTF has been listed as a secondary weather reporting site on the NOAA web site (www.noaa.gov/). Figure 10 displays Hyannis WWTF precipitation data from December 1994 to November 1998 aggregated by season and compared to long term average seasonal amounts.

Figure 8. - Streamflows and Board Elevations

Lake Wequaquet and Long Pond Area

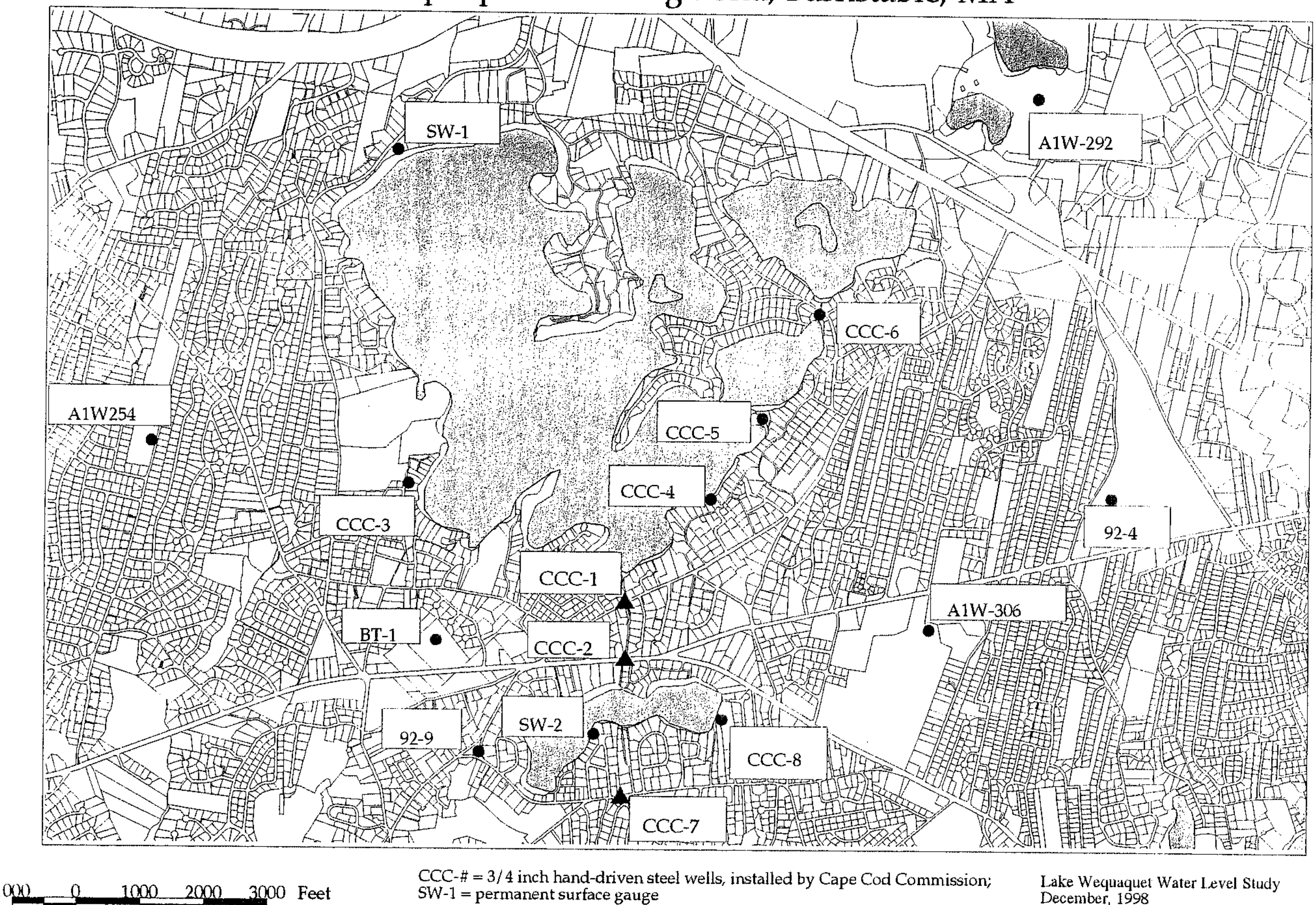
Barnstable, MA

January - September 1998



sources: Board Elevations, Town of Barnstable Department of Natural Resources; Streamflows, Cape Cod Commission

Figure 9 - Water Level Measuring Points
Lake Wequaquet and Long Pond, Barnstable, MA



CCC-# = 3/4 inch hand-driven steel wells, installed by Cape Cod Commission;
SW-1 = permanent surface gauge
▲ = well and streamflow measuring points ● = well measuring point only

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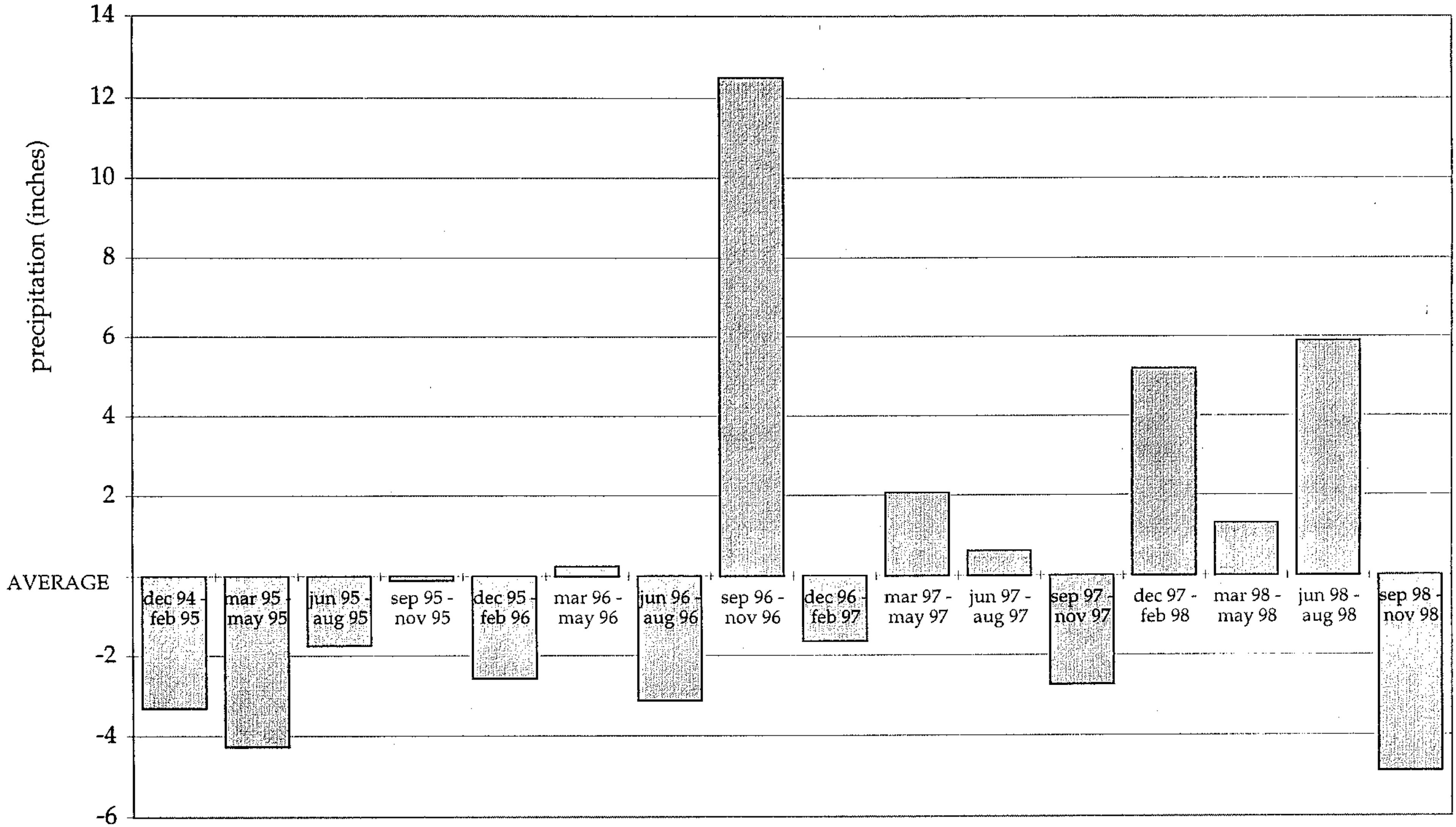
Figure 10.

Seasonal Precipitation (December 1994 - November 1998)

Hyannis, MA



Source data: aggregated from daily precipitation data from Hyannis Wastewater Treatment Facility

FINDINGS AND DISCUSSION

If the water level in a lake does not change, the flows of water coming into the lake must equal the flows of water leaving the lake. Of course, lake levels are rarely constant; if more water is coming in, the water level will go up and if more water is leaving, the water level will go down (*i.e.*, input = output ± Δ storage). The balance of input and output can be broken down into their component parts and be expressed in the following formula:

$$P + S_{in} + G_{in} = E + S_{out} + G_{out}$$

where:

- P = precipitation
- S_{in}/S_{out} = surface flow into/out of the lake
- G_{in}/G_{out} = groundwater flow into/out of the lake
- E = Evapotranspiration (both transpiration and evaporation)

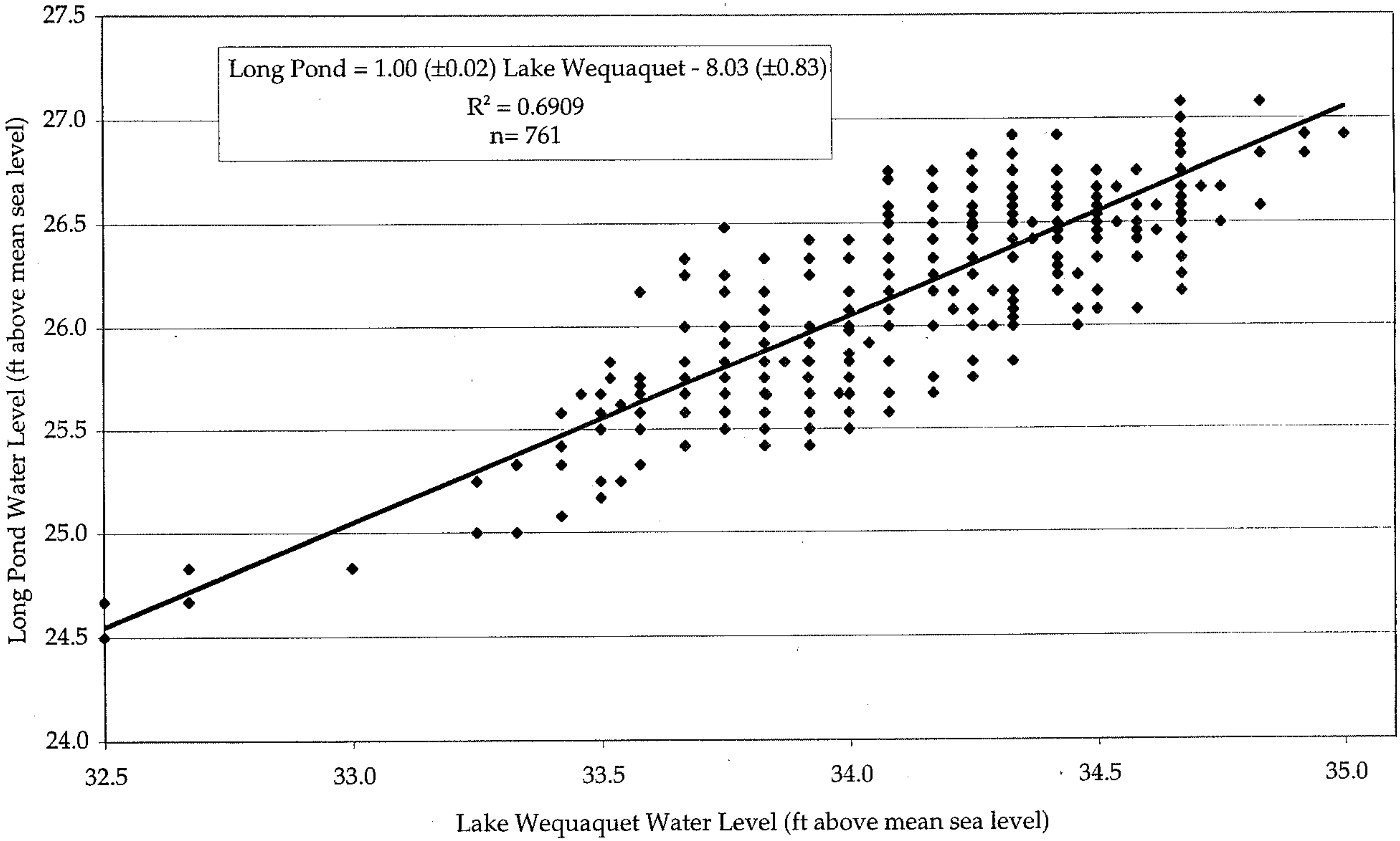
In most studies of lakes which are significantly impacted by mostly groundwater levels (*i.e.*, seepage lakes), the groundwater inflow and outflow terms are often derived by determining the other factors and then determining a net groundwater flux. In Lake Wequaquet and Long Pond, the initial theory is that groundwater factors are the dominant factors in determining the water levels of the lakes.

Lake Water Levels

The town DNR data is the longest term dataset available for water levels on both Lake Wequaquet and Long Pond (see Figure 7). The water levels in Figure 7 generally move together, although differences of up to 0.5 ft occurred. Linear statistical comparison of the water levels of the two ponds indicates that the levels generally fluctuate together (slope ≈ 1) with the Lake Wequaquet water level generally 8 ft above (intercept) the level of Long Pond (Figure 11). The R^2 of this dataset (0.69) also indicates that the water levels generally move together, and thus it can be hypothesized that the water levels in both ponds are largely influenced by the same factors. As indicated on Figure 11, the linear relationship between the water levels (in ft above msl) in the two ponds is: Long Pond = Lake Wequaquet - 8.03. This contrasts to the 6 ft difference indicated on the USGS Topographic map for this area (Long Pond elevation, 28 ft; Lake Wequaquet elevation, 34 ft).

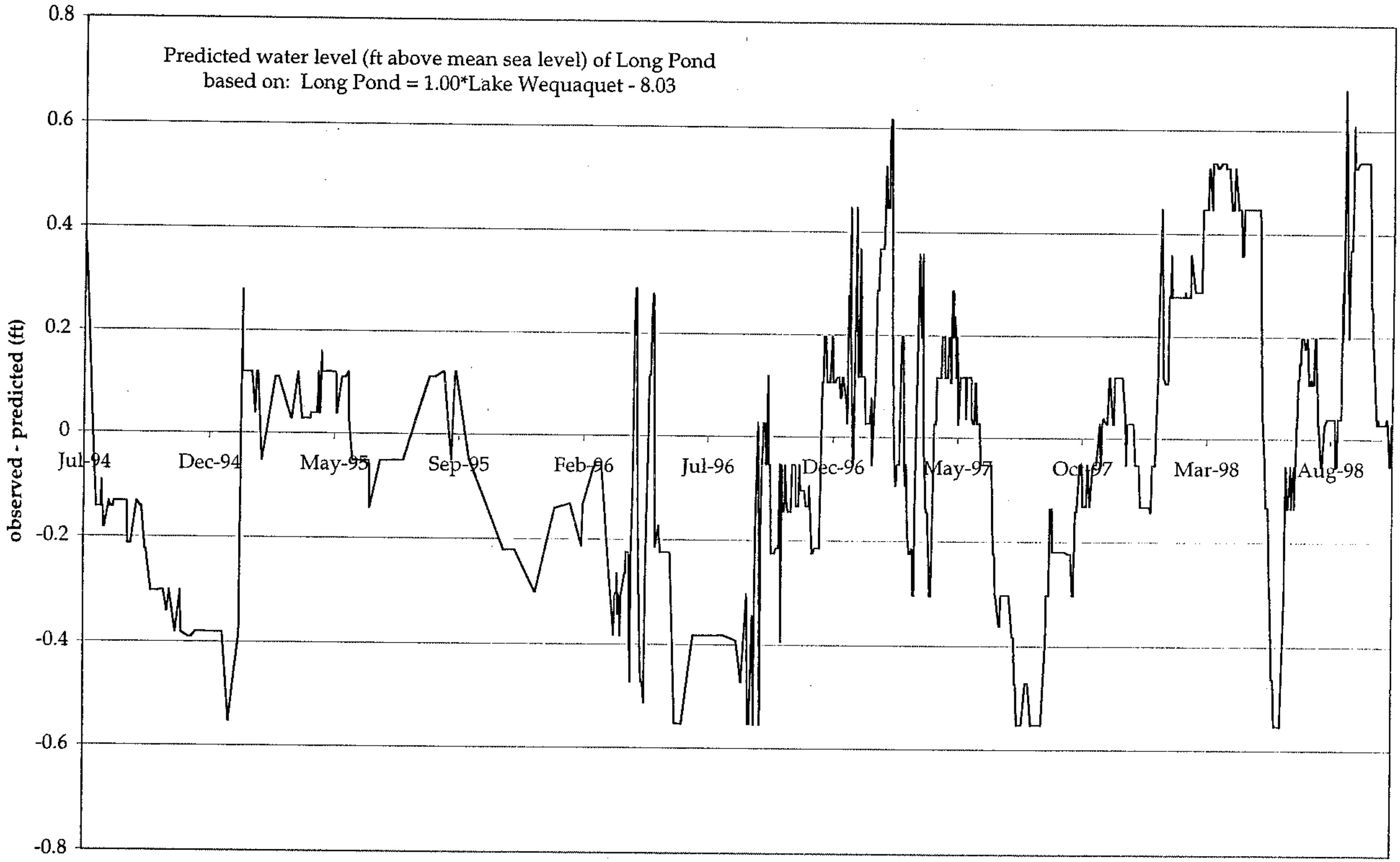
When this linear relationship is compared to the actual data, the variability of the water levels on a daily, monthly, and yearly basis is presented. In Figure 12, the predicted water levels of Long Pond based on the linear relationship are subtracted from the observed water levels; any values greater than zero, the water level of Long Pond was greater than predicted by the linear relationship, while any values less than zero, the water level was less than predicted. The results in Figure 12 show that the linear relationship between water levels in the two lakes has good ability to predict the water level of one lake if one has the water level of the other; approximately 15% of the readings are outside of the 0.83 ft error range associated

Figure 11.
Relationship between Lake Wequaquet and Long Pond Water Levels
(July 1994 - October 1998)



Source Data: Town of Barnstable Department of Natural Resources

Figure 12.
Predicted Long Pond Water Levels
(residuals analysis)



Source: Observed Long Pond Elevations from Barnstable Department of Natural Resources with the linear relationship. Generally the results show average conditions in 1995, below average conditions in most of 1996, and a period characterized by generally above average conditions during 1997 and 1998.

When the Levelogger™ data shown in Figure 6 is evaluated, the variability in Lake Wequaquet water levels during the course of a day is shown. During the January through September data collection by the Levelogger™, 22,953 water level readings were collected (96 readings each day). The average water level during this period was 34.39 ft above mean sea level (msl) with a maximum of 35.45 ft above msl (3/25/98 @10:15 AM) and a minimum of 33.33 ft above msl (multiple times on 1/25/98) (see Figure 6).

During the same time period, 184 water level readings were collected by DNR staff; staff observed one reading almost every day. The average water level during this period was 34.11 ft above msl with a maximum of 34.67 ft above msl (measured 6/15 - 6/17, 6/19, 6/20) and a minimum of 33.58 ft above msl (measured 9/15, 9/16, 9/20 - 9/28) (see Figure 7). Data was not collected by the DNR on the days that are not listed (*e.g.*, 6/18 for the maximum calculations).

Although the average water levels are very similar in the two datasets (regression slope of 0.99), the range of data is over a foot higher for the Levelogger™ dataset. The majority of the range difference is due to higher water levels collected by the Levelogger™. If the elevations of the two measuring points are comparable, the difference due to the greater accuracy and recording frequency of the Levelogger™ as compared to the once a day readings by the DNR staff. However, it is unclear whether the elevations are comparable.

According to the Levelogger™ data, water levels on the lake exceeded an elevation of 35 ft above msl, which the DNR data never exceeded, thirty times during the January to September period. Ten of these occurrences occurred for the majority of a day or for longer than one day (one day = 96 readings). Since these readings were collected by the Levelogger™ during a time period when DNR staff recorded a water level measurement, there is an elevation difference that needs to be resolved between the DNR measuring point and the Levelogger™ data. Comparison of observed water levels, DPW spot elevations, and elevations of project wells installed close to the shore of the lake suggest that 35 ft readings did occur on the lake during the study period and also suggest that the elevation of the Levelogger is correct. Project staff recommend that the elevation of the Phinneys Lane gauge be checked by the Barnstable DPW.

Since Lake Wequaquet and Long Pond water levels are measured using the same technique by the DNR, the dataset comparing the two water levels is still valid for comparing the relative fluctuations between the two ponds (see Figure 11). Since the water levels of the two ponds generally move in concert, at least on an annual basis, we can then examine the factors (listed in the above equation) that would determine the water levels.

The similar movements of two lake water levels suggest that the boards at the control structure do not have a significant long-term impact on the water levels of Lake Wequaquet. Comparison of Lake Wequaquet water levels to the elevations of the control boards show ranges of approximately 0.3 and 0.7 ft in lake levels at a given board height (Figure 13). These ranges are within the error range (0.83 ft) in the linear relationship between the two ponds. These findings support the idea that the boards in the control structure may impact flow out of the lake on a daily time scale, but they have little impact during longer time frames.

Groundwater

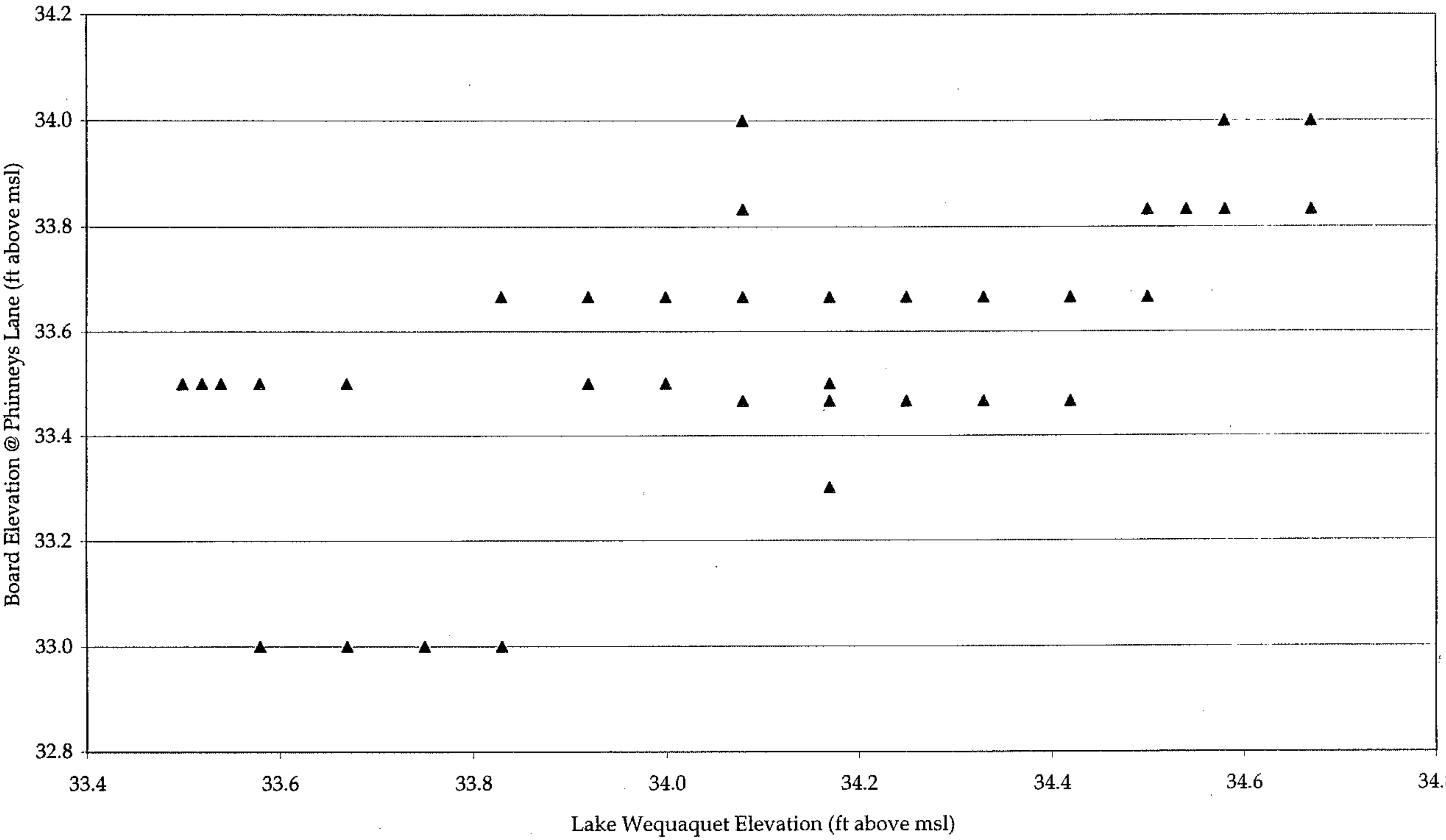
Since most lakes and ponds on Cape Cod are completely connected to the surrounding aquifer, groundwater levels are usually considered to be the primary determinant of lake levels. Cape Cod lakes generally function as "flow-through" areas with groundwater discharging into the lake on the upgradient (higher elevation groundwater) side and discharging out of the lake the downgradient (lower elevation groundwater) side. As groundwater moves toward the lake, flows from deeper in the aquifer move toward the lake. A lake functions as a "relief valve" for the hydrologic pressures in the aquifer; water moves toward the area where it does not need to "fight" its way through the pathways between sand particles. In groundwater models, lakes are often treated as zones of high hydraulic conductivity (*e.g.*, Masterson, *et al.*, 1996) to reproduce this effect. The high conductivity in large lakes or coastal embayments has also been shown to focus groundwater flow not only from deeper portions of the aquifer, but also from areas outside of their horizontal cross-section (Cherkauer and McKereghan, 1991).

Historical measurement of water levels in areas around Lake Wequaquet have generally focussed on the area just to the east of the lake (LeBlanc and Guswa, 1977; SEA, 1985; Cambareri, 1986; Heath and Mascoop, 1987; Geraghty and Miller, 1993; Barlow, 1994) Most of these studies focussed on the impacts of the town WWTF and few measurements were taken near the western or northern sides of Lake Wequaquet.

Town-wide groundwater studies (LeBlanc and Guswa, 1977; SEA, 1985; Geraghty and Miller, 1993; Barlow, 1994) generally indicate that Lake Wequaquet is either at the top of the groundwater lens or just south of the regional groundwater divide. If the divide is located just to the north of Lake Wequaquet, water on one side of the divide would flow to Barnstable Harbor/Cape Cod Bay and water on the other side would flow to Nantucket/Vineyard Sound through the lake. It is likely that the location of this divide moves north or south depending on pumping from nearby public water supplies, long-term precipitation differences, and the amount of discharge at the town WWTF.

Evaluation of historic water level records of well A1W292 (see Figure 9 for location)

Figure 13.
Comparison of Board Elevation at Phinneys Lane Culvert and Elevation of Lake Wequaquet
(January to October, 1998)



Source data: Town of Barnstable DNR

shows that DNR water levels of Lake Wequaquet matched groundwater levels until October, 1996 (Figure 14). After October, 1996, the surrounding groundwater rose higher than the lake and has remained higher than the lake through October, 1998. The October, 1996 rise in the groundwater corresponds to the higher than normal precipitation (12 inches higher) received during September to November, 1996 (see Figure 10). These higher precipitation amounts generally correspond to Hurricanes/Tropical Storms Edouard and Josephine, which passed near or over Cape Cod in September and October, respectively. This increase in groundwater levels was sustained by continuing higher than normal precipitation during the 5 of the 7 seasonal periods which followed. It should also be noted that although the surrounding groundwater rose over 2 ft higher, the level of the lake rose only about 0.5 ft (see Figure 14). This relative stability of the lake level suggests that although more groundwater would be discharging into the lake due to greater surrounding hydraulic pressure, it is being nearly balanced by groundwater and surface water flow out of the lake.

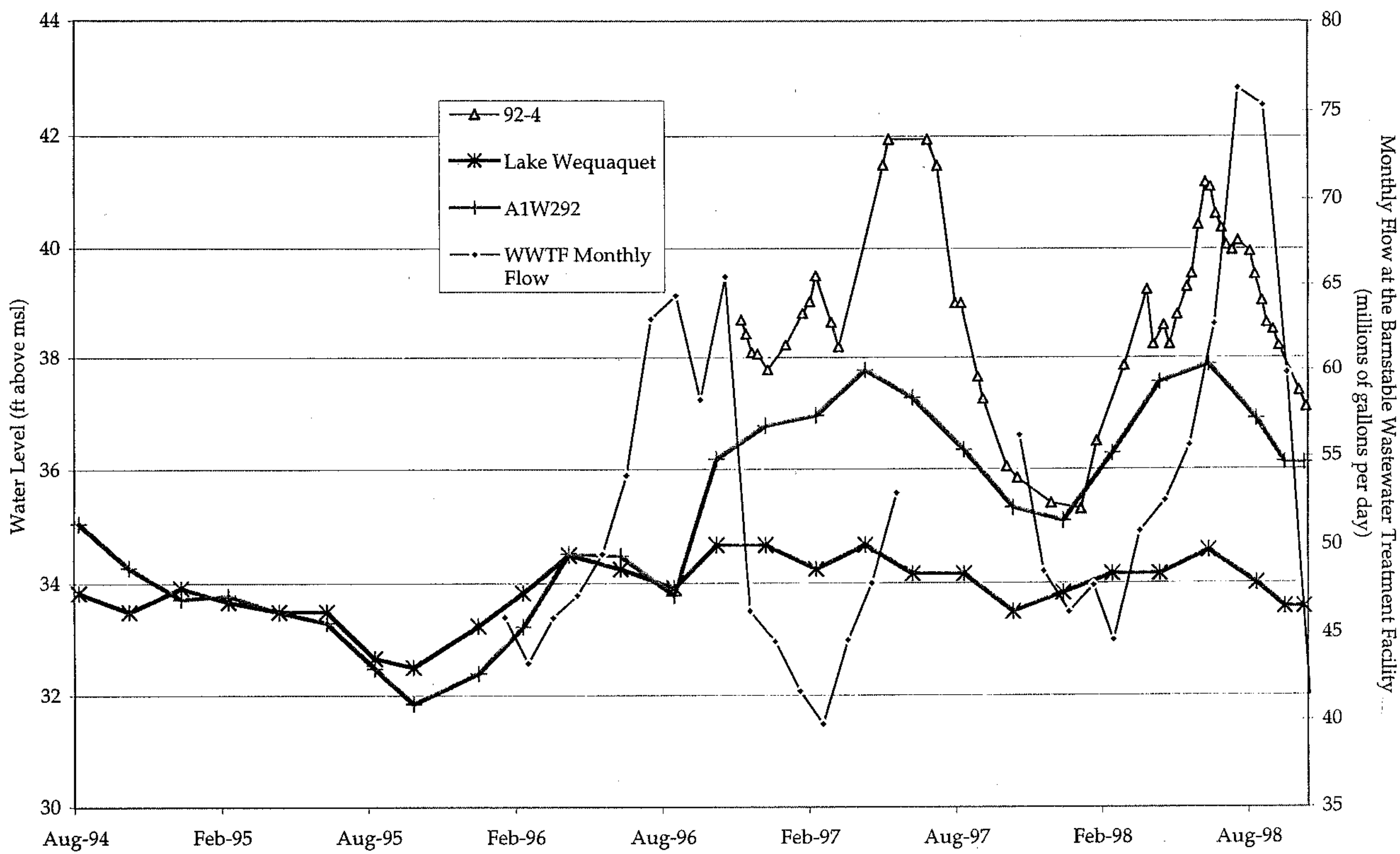
A key to understanding how much groundwater is flowing into and out of the lake is determining the size of its watershed. IEP, Inc. and K-V Associates (1988) determined a watershed to Lake Wequaquet after installing three wells near the western side of the lake and measuring groundwater flow direction and magnitude at 10 locations along the shore of the lake. This watershed has been included in the Commission's Regional Policy Plan Cape Cod Water Resources Classification Map I (CCC, 1996).

Water table measurements were obtained on July 16, 1998 from available wells (Figure 15). These measurements indicate a groundwater mound with a peak of approximately 40 ft above mean sea level (msl) near the town WWTF (see Figure 15). This mound causes groundwater flow from the east toward Lake Wequaquet and Long Pond. The elevations of the water table indicate that Lake Wequaquet is groundwater is discharging into the lake along its western, northern and eastern shores, while only discharging along its southern shoreline. The watersheds to Lake Wequaquet and Long Pond based on the July 1998 water table readings are shown in Figure 16.

It should be noted that the water table measurements on July 16 are representative of a higher than average water table conditions (see A1W292 in Figure 14) and during the larger summer-time wastewater flows from the WWTF. Most of the previous groundwater studies in this area of the town have included a delineated mound near the WWTF, although most of the measurements have been collected during May, June or July when flows at the WWTF would be higher. Cambareri (1986) collected additional water table measurements in September and December of 1983 and documented that the mound decreased in height relative to surrounding groundwater as WWTF flows decreased following higher summer flows (Figure 17).

The drop in water levels observed at well 92-4, which is located on the west side of

Figure 14.
Factors Affecting Water Levels in the Lake Wequaquet Area
(August, 1994 - October, 1998)



Sources: Lake Wequaquet, Barnstable DNR; A1W292, Cape Cod Commission; 92-4 and WWTF flows, Barnstable Department of Public Works

Figure 15.

Water Table Map: July 16, 1998
Lake Wequaquet/Long Pond Area

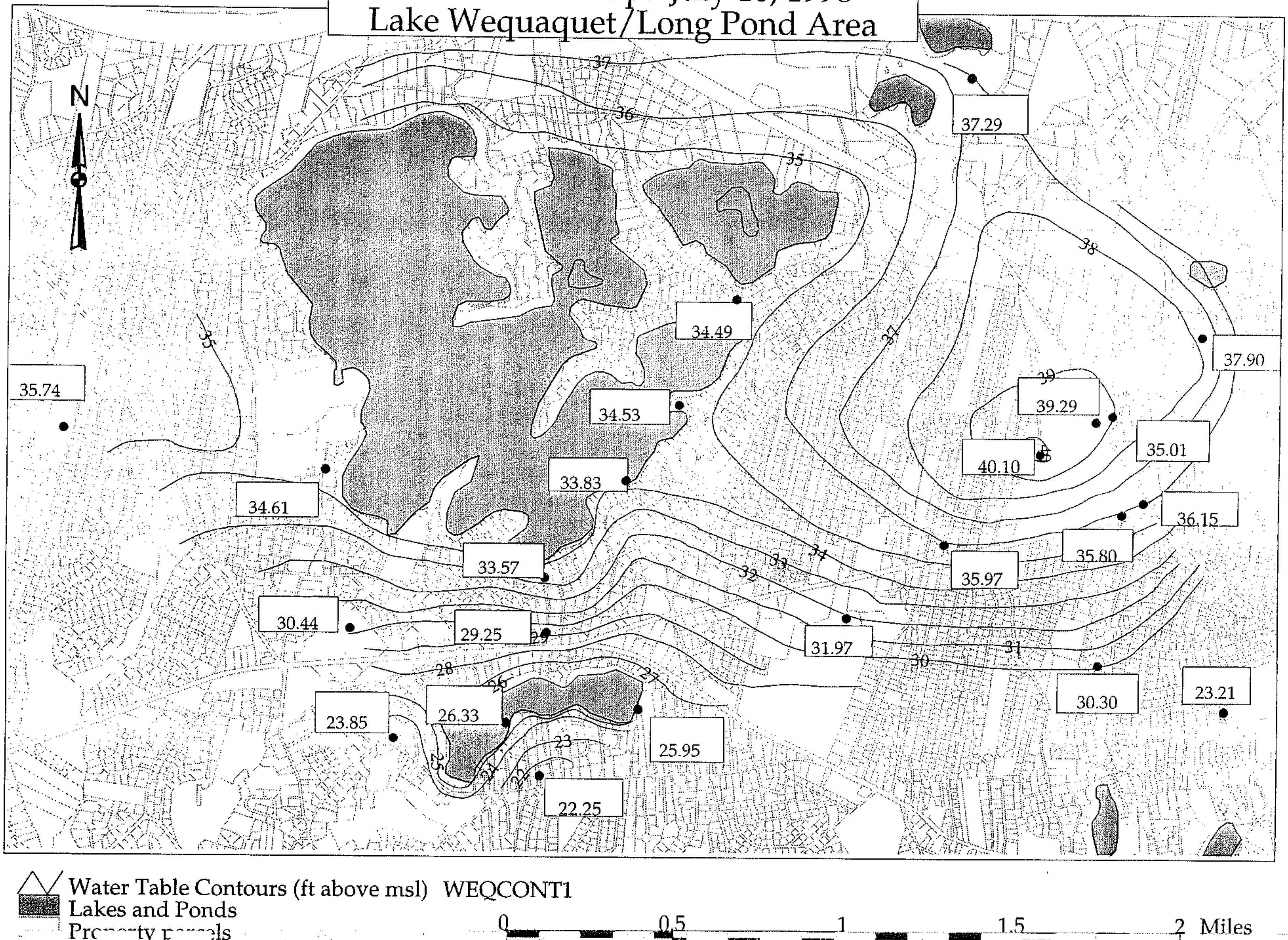


Figure 16.

Watersheds and Water Table

Lake Wequaquet and Long Pond Area
Barnstable, MA

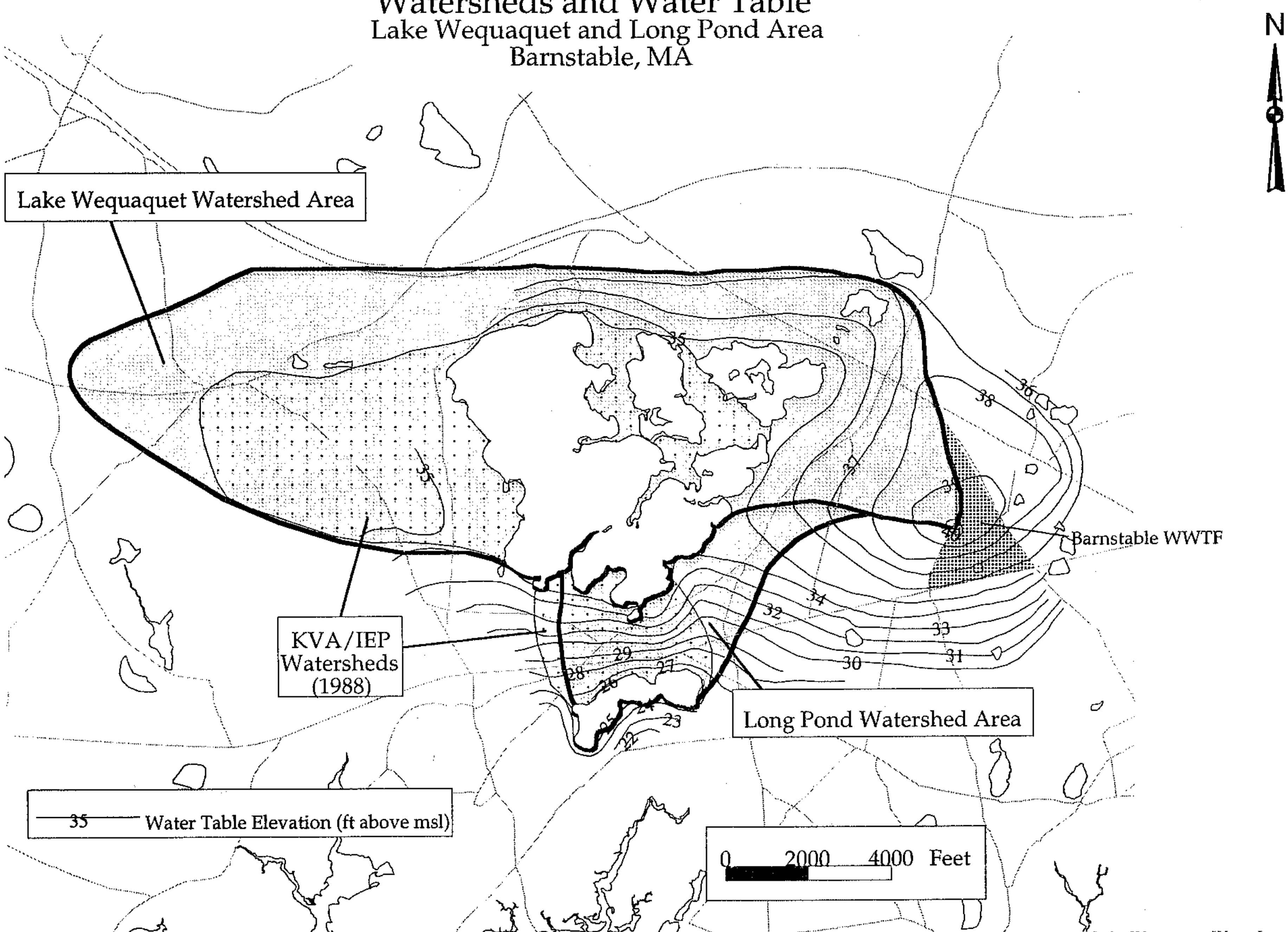


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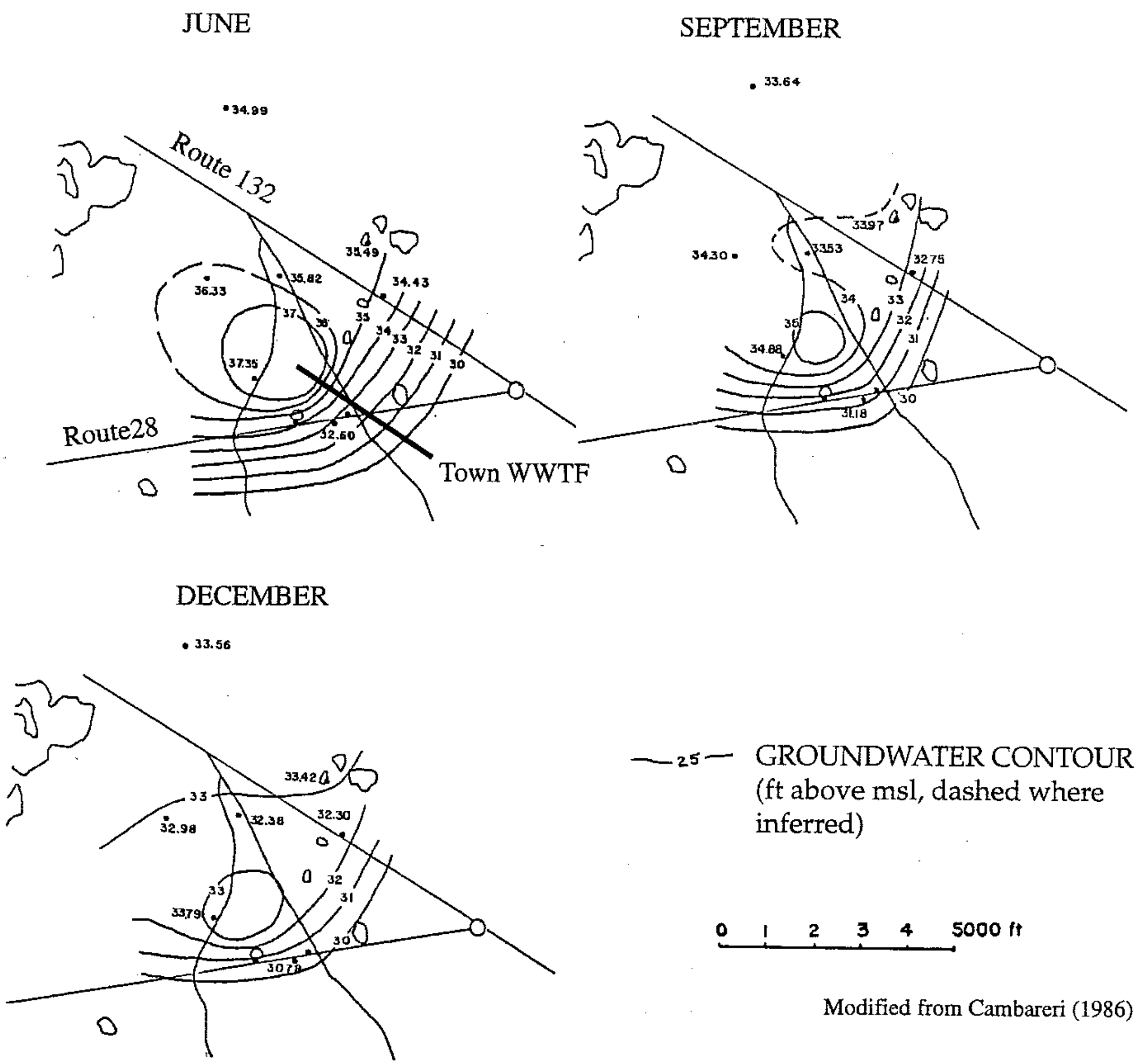
Figure 17.

Water Table Fluctuations near the Town of Barnstable WWTF during 1983



Modified from Cambareri (1986)

the WWTF parcel (see Figure 9 for location), show how this fluctuation is still occurring, although at what appears to have a greater amplitude. Well readings at well 92-4 indicate that water levels varied nearly 6 ft between July 1997 and January 1998 (see Figure 14), while 1983 readings have an amplitude of approximately 4 ft (see Figure 17). The water levels in the wells around the WWTF also indicate that these elevations generally followed the regional fluctuations in the groundwater levels, but with a larger amplitude (see Figure 14).

Since the level of the WWTF mound fluctuates over a greater range than the surrounding groundwater, so does the effect of the mound on the Lake Wequaquet watershed delineation and levels of the lakes. As the mound decreases in height after the summer season, the portion of groundwater flow into Lake Wequaquet from the east probably decreases and more of the eastern shoreline of the lake discharges out of the lake. If this occurs, the watershed to Long Pond would also likely lose the eastern arm from the WWTF mound and some groundwater discharging from Lake Wequaquet on its eastern side would discharge to the south, bypassing Long Pond. Additional water table readings would be required to measure the seasonal changes in groundwater elevation and the resulting watershed delineation and analysis of data within a groundwater model could help to better understand the factors influencing the watershed delineations, including the influence of the higher than average water table conditions during the study period. The July 1998 watershed on the eastern side of Lake Wequaquet (see Figure 16) is probably the largest area that would be expected.

During the KVA/IEP study, a well was installed in a small depression south of Haviland Drive. Project staff did not locate this well and could not get access in order to install a replacement well. The groundwater elevation at this well in January 1986 was 36.5 ft above msl. The July 1998 water level at A1W-306, which is located near the Hyannis Middle School (see Figure 9 for location), is 3.83 ft higher than the level measured in January 1986; a somewhat smaller increase than observed at A1W-292. If the January 1986 reading on the Haviland Drive well is increased by 3.83 ft, the resulting elevation (40.33 ft above msl) would cause a change in the water table contours in this area, an order of magnitude increase in the groundwater gradient, and, correspondingly, a significant increase in the size of the watershed to Lake Wequaquet delineated by KVA/IEP and the watershed based on the available water table information in this study. Figure 16 displays this larger watershed area based on this estimated water level; an addition of 1,001 acres compared to the watershed based on available water table readings. If the high groundwater level method (Frimpter and Belfit, 1992) is used to estimate the highest groundwater level at Haviland Drive, the water table elevation would increase by approximately 2 ft more. Based on the information above, the size of the watershed fluctuates with fluctuations in the water table. Overall, the whole CCC Lake Wequaquet watershed based on the 1998 readings is 1,369 acres larger than the KVA/IEP watershed.

Additional water level measurements are necessary in the northwestern area to refine delineation of the lake watershed. Obtaining these measurements would require the installation of a three to four wells and quarterly or monthly water level measurements from the wells over one to two years.

In summary, the impact of groundwater levels on water levels in Lake Wequaquet has changed as groundwater levels have risen during the last three years. Average conditions, pre-October 1996 indicate that water levels of both Lake Wequaquet and Long Pond generally matched the levels in the surrounding groundwater. After the extremely high precipitation in fall 1996 and generally higher than average precipitation in subsequent seasons, groundwater levels around the lake are higher than the level of the lake and act as a constant source and upward pressure on the water levels of the lakes on both an annual and seasonal cycle. Additional seasonal variability in groundwater levels also occurs due to a seasonally occurring mound from higher summer discharges at the Hyannis WWTF. This condition causes an expansion in the watershed area and increased upward pressure on the water level of the lakes during a period when groundwater levels in the area are generally falling. However, even with all these increased flows toward the lake, lake water levels have remained relatively level, increasing only ~0.5 ft (approximately 25% of the increase experienced in the surrounding groundwater). The relatively small increase with higher inflows suggests that outflows should be only slightly less than inflows.

Streamflow

The most obvious "relief valve" for releasing the increased groundwater flows into Lake Wequaquet is streamflow discharge through the herring run at Phinneys Lane. Forty streamflow measurements taken between January 13 and September 23, 1998 at the three locations identified in Figure 9. Average flows during the measurement period are: Phinneys Lane, 8.79 cubic feet per second (cfs); Route 28, 8.04 cfs; and Pine Street, 9.71 cfs. Flows ranged from 0.11 to 16.10 cfs at Phinneys Lane, 0.06 to 15.07 cfs at Route 28, and 0.84 to 17.3 cfs at Pine Street (see Figure 8). Flow at Pine Street generally was higher than flow at either Phinneys Lane (30 of 40 readings) or Route 28 (36 of 40 readings) and flow at Route 28 was generally lower than flow at Phinneys Lane (35 of 40 readings).

Since flows at Route 28 are generally lower than flows at Phinneys Lane, the herring run would be categorized as a "losing stream." This means that water within the herring run is generally discharging into the aquifer between Phinneys Lane and Route 28 rather than "gaining" discharge from the underlying groundwater. Groundwater levels measured in the wells at the two measuring points have an average 3.48 ft difference. Comparison of the groundwater elevations at the two wells and available spot elevations from the Barnstable DPW suggest that the majority of the stream loss to the aquifer occurs closest to Lake Wequaquet. This finding generally supports the concept that Lake Wequaquet water levels are generally coincident with groundwater levels on the southern discharge side. The lack of a relationship between board height and lake levels also tends to discount the long-term impact of the boards as a controlling factor (see Figures 8 and 13).

On a daily or weekly basis, however, the boards can impact streamflows. For example, Figure 8 shows a dramatic (~6 cfs) increase in streamflows measured at Phinneys Lane and Route 28 on 8/27/98 following the removal of a number of boards at the Phinneys Lane control structure. This increase in flow did not immediately impact streamflows out of Long Pond, although flows at Pine Street one week later were ~2 cfs higher than the other two measuring points. The next following week, all readings were within 0.5 cfs of each other, which is generally observed in other weekly readings.

Figure 8 also includes data collected to assess the variability of flows over the course of one day. On March 10, 1998 between 9:45 AM and 3:00 PM, seven sets of readings were taken at the three measuring locations (Figure 18). No precipitation occurred during the test and the boards on the herring run were not moved. Pine Street and Phinneys Lane readings generally fluctuated within the same range (0.82 and 0.62 cfs, respectively) except for the final reading at Pine Street, which decreased from the prior reading by almost 2 cfs. The range of fluctuations were 5% of the average flow at Phinneys Lane, 11% at Route 28, and 16% at Pine Street (4% if the final reading is ignored). All readings decreased during the duration of the test; the last measured flows at Route 28 and Pine Street were the lowest measured at those locations, while the lowest at Phinneys Lane was recorded on the second to last reading. If the percentage of fluctuations recorded during this one day test continued over one week, the potential fluctuations at Phinneys Lane would be 5.7 cfs or 37% of average; Route 28, 11.0 cfs or 78% of average; and Pine Street, 4.8 cfs or 30% of average (based on the record without the final reading). The magnitude of these fluctuations suggest that the weekly measurement of streamflows accomplished during this study reflect only a small portion of the actual variability of these flows.

Comparison of the flows at the three locations generally indicate that flows are greater out of Long Pond than flows out of Lake Wequaquet. This suggests that the land area determining the flow (*i.e.*, the watershed) is comparatively larger for Long Pond than for Lake Wequaquet. Analyses in other parts of Cape Cod has shown that recharge within watershed areas determined by groundwater contours correspond with measured annual streamflows (Cambareri and Eichner, 1998). Based on the average streamflows collected during the 9 months of this study and assuming 18 inches of recharge, 4,244 acres of watershed would be needed to create the 8.79 cfs flow at Phinneys Lane and 4,688 acres of watershed would be needed to create the 9.71 cfs flow at Pine Street. In Figure 16, the Lake Wequaquet watershed, including the lake is 2,850 acres (or 5.9 cfs at 1.5 ft/yr of recharge). The combined Long Pond and large Lake Wequaquet watershed is 3,249 acres (or 6.7 cfs).

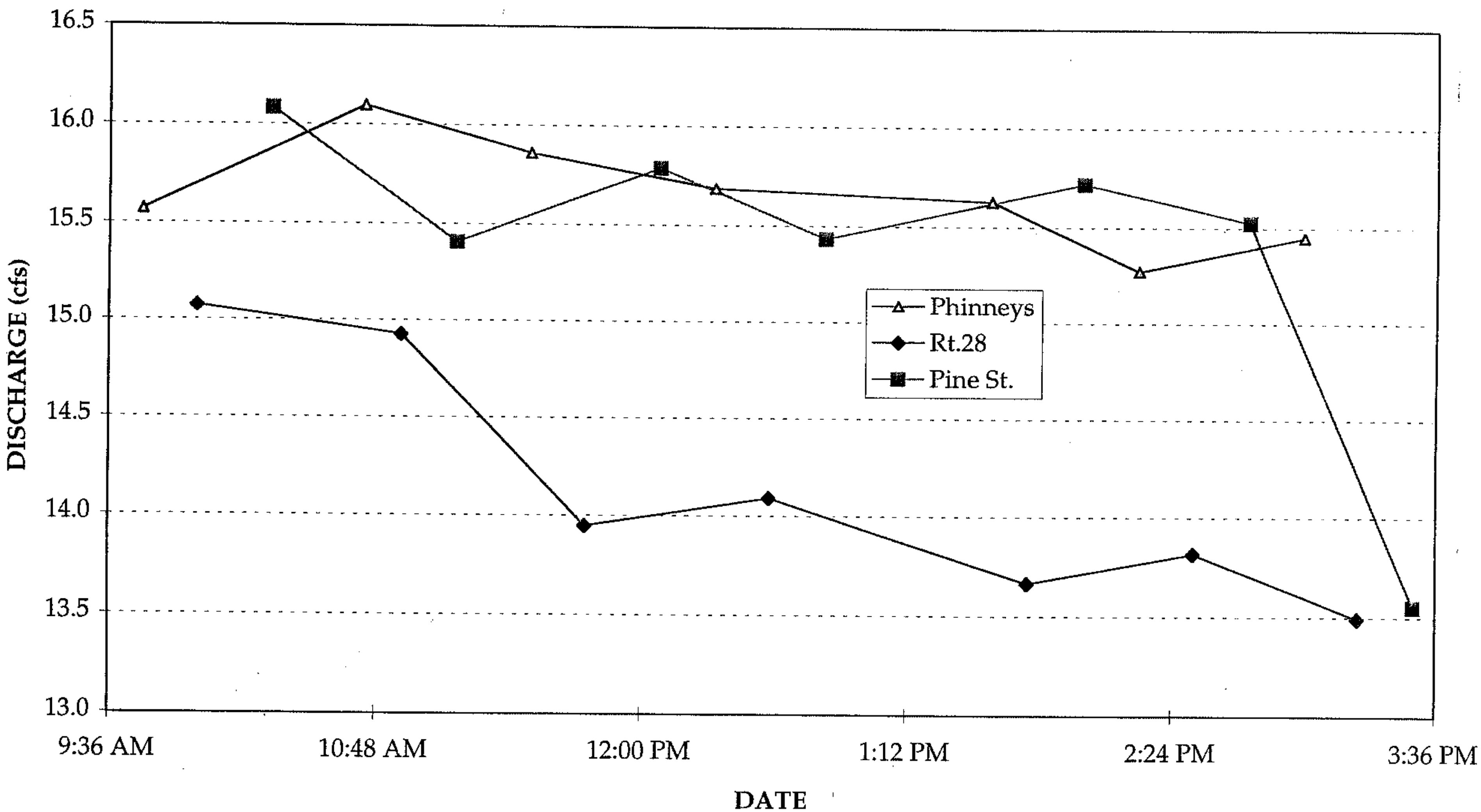
These comparisons again raise issues about the time-scales of various data. An examination of average flows based on a watershed delineation generally use

Figure 18.

March 10, 1998 Streamflow Measurements

Lake Wequaquet and Long Pond Area

Barnstable, MA



Data Source: Cape Cod Commission

annual information (*e.g.*, 1.5 ft/yr of recharge), while the measured flows represent a period of particularly high precipitation (a cumulative 12.39 inches above normal between January and August) (see Figure 10), recharge, and groundwater levels. If the excess precipitation during January to May (6.5 inches), when most of the recharge to the aquifer would likely occur, is added to the CCC Lake Wequaquet watershed (see Figure 16), the average flow rises to 8.04 cfs; nearly the average 8.79 cfs measured at Phinney Lane and matching the average measured at Route 28.

The general agreement between the ratio of the flows and watershed areas also supports the idea that the watershed areas are approximately correct and the higher streamflows are due to increased recharge to the aquifer within these areas. The average flow at Phinney Lane is 90.5% of the Pine Street flow, while the Phinneys Lane watershed is 87.7% of the combined Lake Wequaquet/Long Pond watershed.

Comparing the streamflows at all the measuring points to the water level of Lake Wequaquet produces poor correlations ($0.19 \le R^2 \le 0.32$) (Figure 19), while the comparison of streamflows to water levels of Long Pond produces strong correlations ($0.81 \le R^2 \le 0.96$) (Figure 20). The flows at Pine Street produce the best fit for Long Pond elevations, which suggests that elevations of Long Pond can be used to determine the magnitude of flow at Pine Street. The poor correlation between the streamflows and Lake Wequaquet water levels suggest that the lake's water level explains only a small portion of the variability in flows. This follows the observation that water levels in Lake Wequaquet are relatively stable and the hypothesis that precipitation and recharge play more important roles in determining the streamflows.

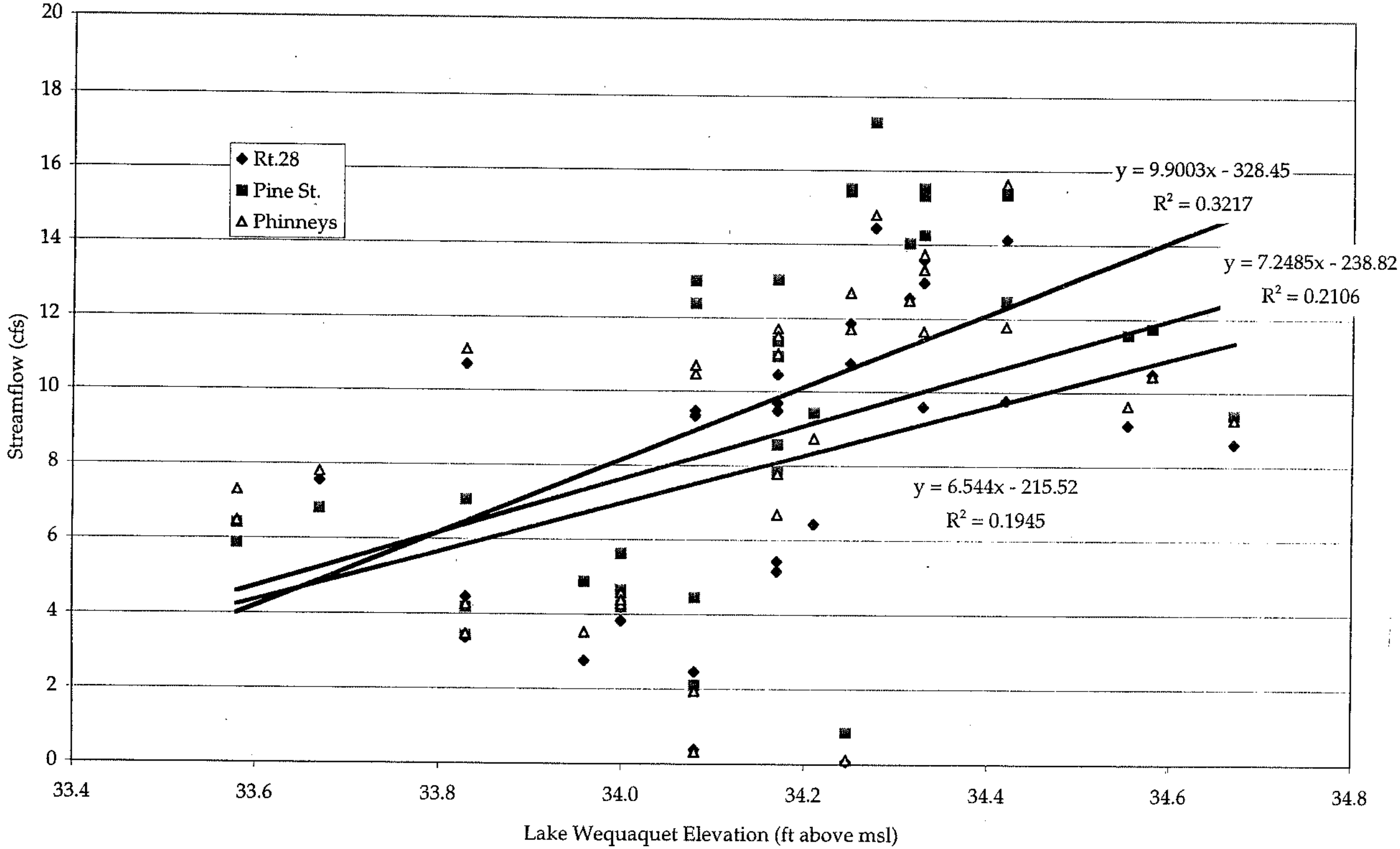
Combined analysis of precipitation and streamflow impacts on lake levels shows that if one starts with a selected water level and adds precipitation and subtracts streamflow, the lake level can be fairly well predicted. Figure 21 shows the observed daily average water levels (as measured by the Levelogger™) and predicted water levels based on measured streamflow and precipitation. Streamflow is assumed to be linear between measurements and precipitation is cumulative between streamflow measurements. Statistical analysis (t-test) shows that these two data sets are not significantly different at the $\rho<0.05$ level. This simple type of analysis suggests that net groundwater flow through the lake is relatively stable during the time period examined.

Use of a groundwater model which includes the capability to model transient conditions, such as differences in monthly precipitation and the fluctuations in the eastern mound associated with WWTF flows, would help to explore the factors influencing the fluctuations of the pond water and groundwater levels. Groundwater models have been developed for this area by Geraghty and Miller (1993) and the US Geological Survey (Barlow, 1994). One of these models could be used as the basis for an enhanced transient groundwater flow model which uses the data gathered in this study for the development of input parameters and calibration. It should be noted that transient modeling is a relatively new activity and caution should be exercised defining the study if the town chooses to examine this further.

Figure 19.

Comparison of Streamflows to Lake Wequaquet Water Levels

January to September, 1998

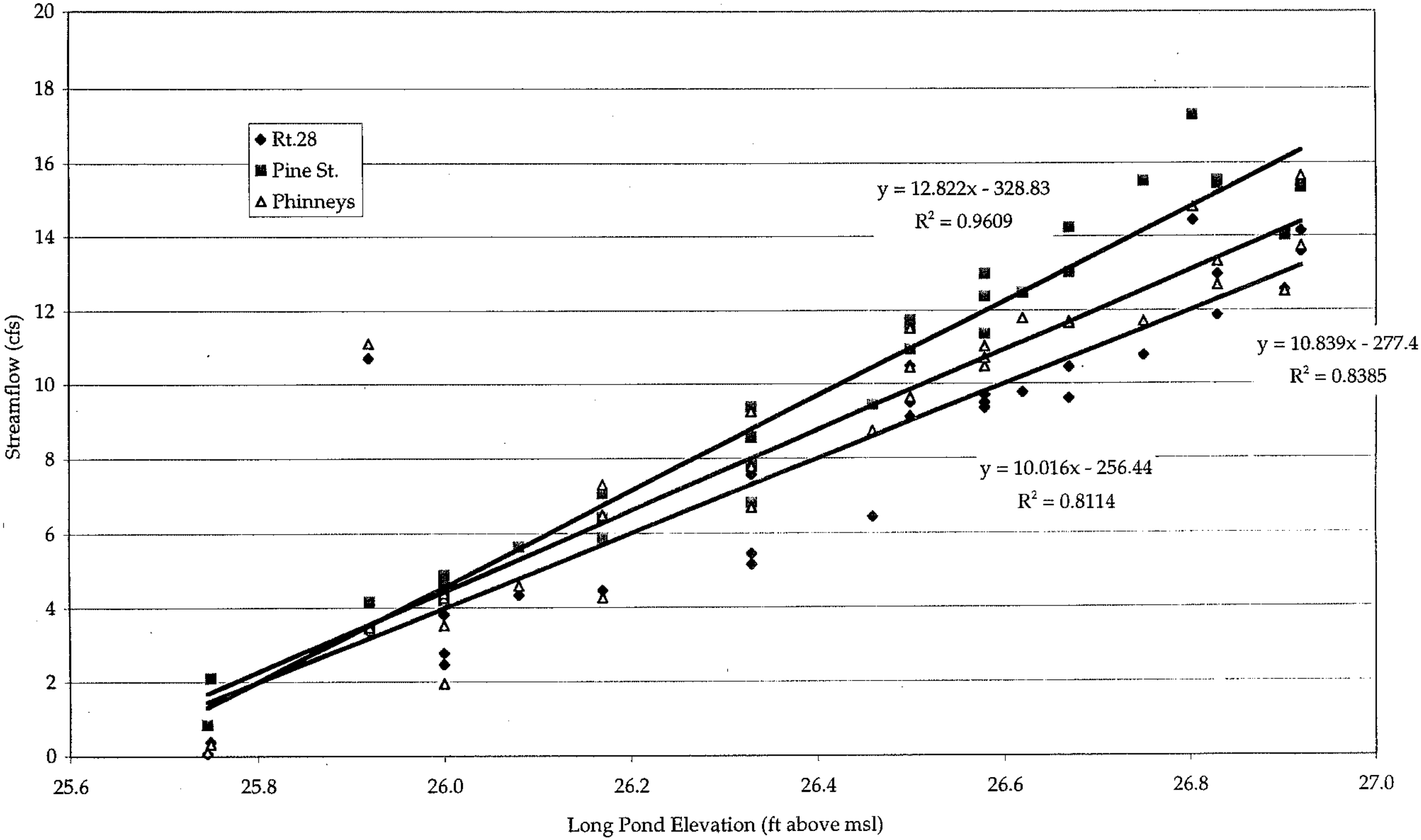


Source Data: Cape Cod Commission

Figure 20.

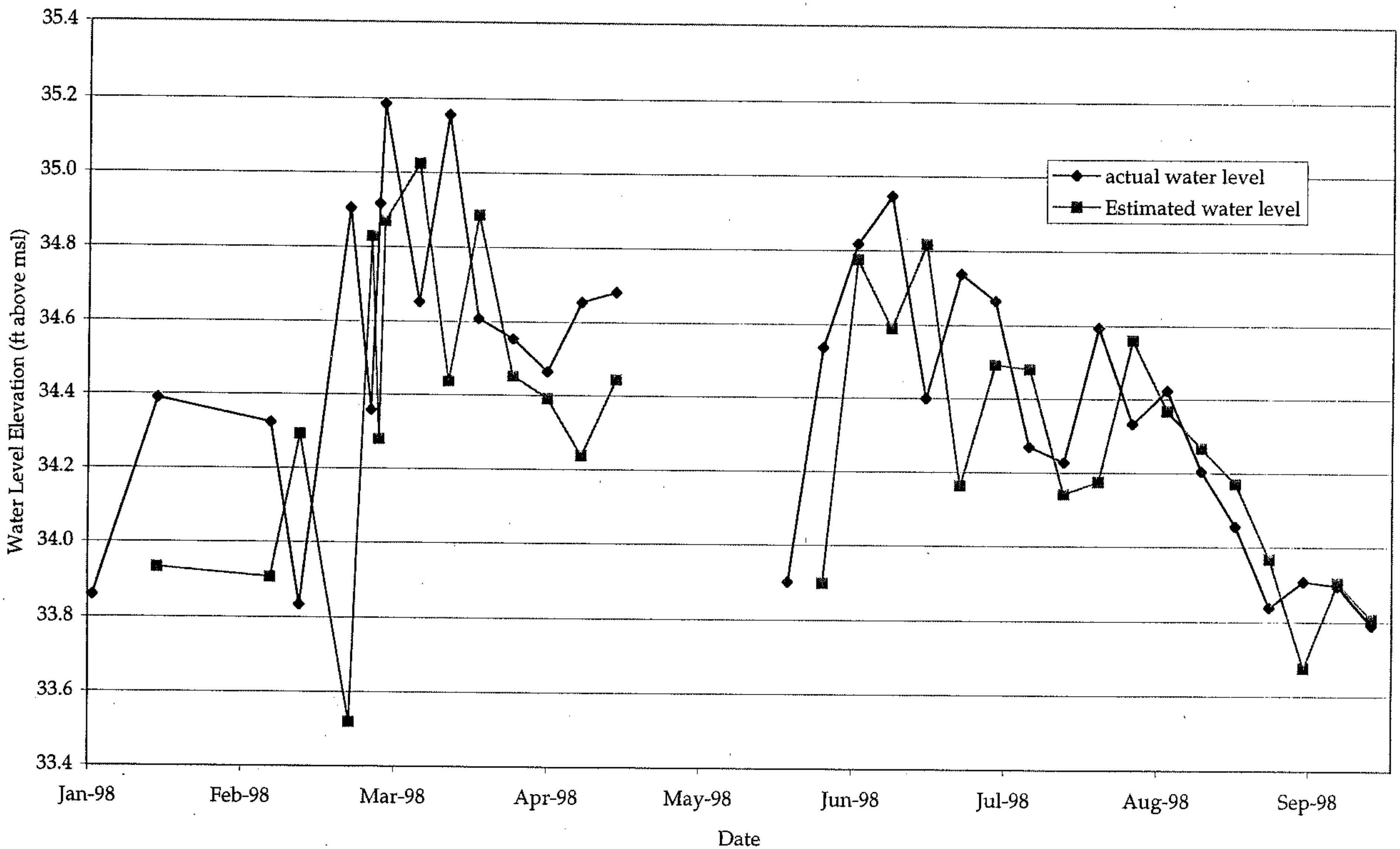
Comparison of Streamflows to Long Pond Water Levels

January to September, 1998



Source Data: Cape Cod Commission

Figure 21.
Modeled and Observed Water Levels
Lake Wequaquet, Barnstable, MA



Modeled assumes January 13, 1998
water level as starting point + precipitation- cumulative flow
(flow assumed to be linear between sampling points)

Lake Wequaquet Water Level Study
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Management Implications

The results of this study can be used to examine whether management of the boards at the Phinneys Lane outlet can be used to control the level of Lake Wequaquet. During the year of water level measurements (see Figure 6), the level of the lake fluctuated approximately 2 ft with the majority of levels within a 1 ft range between 33.8 and 34.8 ft above msl. Water levels during this period were almost always above the level of the boards and streamflow was maintained even during the drop in flow during May and June. It is difficult to say definitively on the basis of these high water conditions, what the impact of the boards might be during dry or low water conditions. However, given the relatively wide range of water levels observed during stable board conditions (see Figure 13), it appears that the level of the boards has little or no impact on the level of the lake on a yearly, monthly, or biweekly basis.

This concurs with the general concepts of groundwater pass-through and constant groundwater discharge from the lake; if the boards increase the water level of the lake, it increases the hydraulic pressure and a corresponding discharge out of the lake into the aquifer. This is why the water level of Lake Wequaquet fluctuates within a relatively small range.

The impact of the height of the board on streamflow, however, can be quite significant. As mentioned previously, removal of boards can create changes of up to 6 cfs in streamflow below Lake Wequaquet and dampened increases of up to 2 cfs below Long Pond, both of which last no more than a week (see Figure 8). Again, it is difficult to predict whether similar responses would be observed during low water conditions.

Given the profound impact that the movement of the boards can have on streamflows, especially when water levels are high, and the week to week importance of flow for maintaining the ability of alewife to utilize the herring run, the management of the board heights is still very important. During high water conditions, which were observed during the entire course of this study, maintaining flow in the run is relatively easy. However, during low water years, it is likely that the level of the boards should be kept artificially high, within the extent of existing permits, to ensure that any available head in the lake can be used to support streamflow during the use of the run by the alewife. Further evaluation of low water conditions would be necessary to quantify how well streamflow can be managed during these periods.

CONCLUSIONS

The water levels of Lake Wequaquet and Long Pond generally fluctuate together with the level of Lake Wequaquet exceeding the level of Long Pond by an average of 8 ft. The level of Lake Wequaquet fluctuates within a relatively narrow range (~2 ft) compared to the large (~6 ft) range observed in the groundwater surrounding the lake. The relative stability of the water level of Lake Wequaquet means that water inflows (groundwater and precipitation) into the lake are generally balanced by water outflows (streamflow, groundwater, and evaporation) out of the lake.

Groundwater inflows into the lake occur from the north and west sides of the lake with transient (March to September) inflows from the eastern side, due largely to seasonal groundwater mound at the Town of Barnstable WWTF. The majority of flow (~80%) comes from the western portion of its watershed.

Groundwater surrounding Lake Wequaquet was in equilibrium with the level of the lake until Fall 1996 when precipitation exceeded seasonal averages by 12 inches. Groundwater levels have remained higher than lake levels creating a relatively constant upward pressure on the level of the lake.

Even with this higher pressure, however, the level of the lake has remained fairly stable (range of ~1 ft). The greater groundwater discharge into the lake has been largely met by higher streamflow out of the lake.

Streamflows out of Lake Wequaquet (at Phinneys Lane), into Long Pond (at Route 28), and out of Long Pond (at Pine Street) generally move together (within ~0.5 cfs of each other). Streamflows out of Long Pond are generally greater than flows out of Lake Wequaquet indicating that any upward pressure on water levels in Long Pond are not due to streamflows out of Lake Wequaquet and that increases in Long Pond water levels are likely due to the same regional increases in groundwater levels that are causing the level of Lake Wequaquet to rise.

Board heights at the outflow of Lake Wequaquet (at Phinneys Lane) do not appear to have any long term impact on lake levels. However, the board heights can impact streamflows on a weekly basis. This short-term impact indicates that active management of the boards should continue to ensure that adequate flow is available for alewife movement up and down the herring run.

RECOMMENDATIONS

Long-term evaluation of board management will require continuing collection of water level, board height, and streamflow information. Although there are differences between the absolute water level heights measured by the Levelogger™ and the DNR that should be resolved, daily water level information should continue to be collected and should be sufficient for evaluating how changes in the board height effect lake water levels, especially during low water conditions. It is also recommended that the elevations on the gauge at Phinneys Lane be remeasured, marks on the gauge be numbered in tenths of feet, and board elevations be recorded on a daily basis.

Given the importance of streamflow for alewife movement and the negligible relationship measured between streamflow out of Lake Wequaquet and board height or lake level, it is recommended that streamflow be measured on a weekly basis at the Phinneys Lane culvert. Collection of this data during low water conditions will help to more fully understand the streamflow, lake level, and board height relationships.

It is also noted that further evaluation of existing data could be enhanced through the use of a groundwater model. Although use of a groundwater model was beyond the resources available for this project, a model with transient capabilities would be very helpful for evaluating groundwater and lake level interactions, especially interactions between Lake Wequaquet and Long Pond.

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