

**Aquatic Vegetation and Trophic Condition of  
Cape Cod National Seashore Kettle Ponds**

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## Preface

This manuscript has been accepted for publication in the professional journal *Hydrobiologia*. This National Park Service technical report contains the *Hydrobiologia* manuscript and data appendices that will not appear in the published paper.

## Abstract

The species composition and relative abundance of aquatic macrophytes was evaluated in five Cape Cod, Massachusetts, freshwater kettle ponds, representing a range of trophic conditions from oligotrophic to eutrophic. At each pond, aquatic vegetation and environmental variables (slope, water depth, sediment bulk density, sediment grain size, sediment organic content, and porewater inorganic nutrients) were measured along 5 transects extending perpendicular to the shoreline from the upland border into the pond. Based on a variety of multivariate methods, including Detrended Correspondence Analysis (DCA), an indirect gradient analysis technique, and Canonical Correspondence Analysis (CCA), a direct gradient approach, it was determined that the eutrophic Herring Pond was dominated by floating aquatic vegetation (*Brasenia schreberi*, *Nymphoides cordata*, *Nymphaea odorata*), and the algal stonewort, *Nitella*. Partial CCA suggested that high porewater  $\text{PO}_4\text{-P}$  concentrations and fine-grained sediments strongly influenced the vegetation of this eutrophic pond. In contrast, vegetation of the oligotrophic Duck Pond was sparse, contained no floating aquatics, and was dominated by emergent plants. Low porewater nutrients, low sediment organic content, high water clarity, and low pH (4.8) best defined the environmental characteristics of this oligotrophic pond. Gull Pond, with inorganic nitrogen-enriched sediments, also exhibited a flora quite different from the oligotrophic Duck Pond. The species composition and relative abundance of aquatic macrophytes provide good indicators of the trophic status of freshwater ponds and should be incorporated into long-term monitoring programs aimed at detecting responses to anthropogenically-derived nutrient loading.

## Introduction

Nutrient loading to lakes and ponds from adjacent residential land use, agriculture, and atmospheric sources has been a global concern for decades (e.g., Schindler & Fee, 1974; Vallentyne, 1974). With nutrient enrichment, acidification, and other water chemistry changes, both species composition and abundance of lakeshore aquatic macrophyte communities dramatically respond (Lind & Cottam, 1969; Moeller, 1985; Roelofs, 1983; Roberts et al., 1985; Arts & Leuven, 1988; Gacia et al., 1994; Srivastana et al., 1995; Toivonen & Huttunen, 1995). Pondshore vegetation is strategically positioned to intercept and assimilate nutrients transported from upgradient land uses and may serve as a valuable early warning indicator of nutrient enrichment.

This study focused on freshwater ponds on Cape Cod, Massachusetts, USA, a suburbanizing landscape where human population is expected to increase by over 40% between 1988 and 2010 (Culliton et al., 1990). This trend is not unlike other coastal areas of the northeastern US and elsewhere worldwide. In recent years, many summer cottages located adjacent to Cape Cod pond shorelines have been converted to year-round status. There is concern that the ponds will become nutrient enriched, especially from shoreline dwellings and their on-site septic systems typically located close to groundwater. Along with nutrient loading from local development, atmospheric deposition of nitrogen onto watersheds of the northeastern US has increased significantly over the last century and represents an important nutrient source (Jaworski et al., 1997). With increased nutrient loading to Cape Cod ponds and the potential for cultural enrichment, long-term monitoring strategies are required to detect changes in trophic status. To elucidate a suite of pond nutrient enrichment indicators, this paper quantifies the

floristic composition of ponds along a trophic gradient and evaluates the dependence of observed floristic differences on sediment porewater nutrients, organic content, and grain size and on topographic characteristics, such as elevation and slope. For natural resource management purposes it is important to characterize the floristic and trophic status of ponds as a benchmark for future monitoring. Changes in the flora toward a eutrophied status would be reason to consider resource management actions.

### **Description of Study Sites**

Five permanently flooded freshwater kettle ponds located within the pine-oak forested landscape of Cape Cod National Seashore (Massachusetts) were studied ( $41^{\circ}55'N$ ,  $70^{\circ}00'W$ ): Duck Pond, Gull Pond and Herring Pond in Wellfleet, Massachusetts, and Ryder Pond and Great Pond in Truro, Massachusetts. Twenty ponds of the 360 Cape Cod ponds are located within the Cape Cod National Seashore. Cape Cod's kettle ponds formed about 12,000 years ago when ice blocks left behind by the retreating continental glacier were buried by glacial drift sediments. As the ice blocks melted, the sediments collapsed to form a depression or kettle (Oldale, 1992). Cape Cod kettle ponds are within sandy substrates, mostly outwash deposits, and are often round in shape. Most ponds (e.g., Duck, Ryder and Great Ponds) are landlocked with no stream inflow or outflow, but with direct connection to groundwater. Some ponds are interconnected and discharge through human-made channels, and ultimately to the ocean through streams (Gull and Herring Ponds). The coarse, granitic, non-weathering sandy sediments confer limited buffering capacity and are nutrient poor. Although all of the 5 study ponds are within 2.5 km of the ocean and subject to marine aerosol deposition (salt spray), they remain relatively low in dissolved salts

(conductivity < 150  $\mu\text{S cm}^{-1}$ ; Table 1). Because of the low buffering capacity of sandy soils, pond pH's range from pH 4.7 to pH 6.8, with the landlocked ponds being more acidic than the ponds with surface water drainages. Natural cycles of water level fluctuation and poor nutrient availability support a distinctive flora, including rare species, which are typical for coastal plain ponds throughout southeastern New England (Sorrie, 1994).

## **Materials and Methods**

### Field Procedures

Field measurements and sampling were initiated in the summer of 1995. According to long-term records of pond water levels this was a low water or drought year throughout the Cape Cod region. At each of the five sample ponds, a gradient approach to sampling was applied by randomly choosing five permanent transects oriented perpendicular to the shoreline. Each transect originated at the upland border and continued into the pond until rooted vegetation was no longer encountered. SCUBA gear was necessary to sample in waters greater than one meter deep. All sampling was conducted within continuous 1-meter transect segments from the upland and extending into the pond. Elevation (relative to the 1929 National Geodetic Vertical Datum, NGVD), at each 1-m interval was determined by differential leveling. The slope of each 1-m segment was calculated by the elevation difference between the endpoints of each segment. At each 1-m interval water depth was determined by the relationship between land surface elevation and the lowest pond water level measured in September 1995 (relative to NGVD).

Table 1.

General characteristics of the five study ponds (from Martin et al. 1993; Godfrey et al., 1999).

$D_{max}$ , maximum depth; Cond., specific conductivity;  $\eta$ , light extinction coefficient at 0-5m depth.

Landlocked ponds are those with no stream inflow or outflow.

| Lake    | Area<br>(ha) | $D_{max}$<br>(m) | Cond.<br>( $\mu\text{S cm}^{-1}$ ) | pH<br>(Spring) | Alkalinity<br>(ppm) | $\eta$<br>(0-5m) | Land-<br>locked |
|---------|--------------|------------------|------------------------------------|----------------|---------------------|------------------|-----------------|
| Herring | 8.1          | 4                | 143                                | 6.50           | 2.75                | 0.85             | No              |
| Gull    | 44.0         | 19               | 145                                | 6.81           | 3.25                | 0.5              | No              |
| Great   | 7.0          | 11               | 126                                | 5.78           | -0.25               | 0.4              | Yes             |
| Ryder   | 8.3          | 10               | 143                                | 4.72           | -1.00               | 0.23             | Yes             |
| Duck    | 5.1          | 18               | 112                                | 4.76           | -0.50               | 0.21             | Yes             |

At the mid-point of each 1-m segment, sediment cores ( $300\text{ cm}^3$ ) were extracted by polycarbonate piston corer from the top 10 cm of sediment for the determination of bulk density, texture, and organic matter content. To assess the availability of inorganic nitrogen and phosphorous in sediment porewaters prior to seasonal macrophyte growth, interstitial water was sampled in April 1996. Inorganic nitrogen and phosphorous concentrations in the active root zone (top 10 cm) were determined by drawing triplicate samples of porewater with a 2 mm inner diameter stainless steel probe and syringe sampler (Portnoy et al., 1998). Approximately 25 ml of porewater sample was extracted and discharged directly through a  $0.45\text{ }\mu\text{m}$  filter into pre-acidified vials (0.2 ml of 2N HCl). Vials containing porewater samples were immediately put on ice and transferred to the laboratory for analysis.

The vegetation was sampled using a modified line intercept method. The presence of macrophytes and an estimate of line-cover for each species along successive 1-m segments was recorded. Rank estimates of line-cover distances were assigned on an ordinal scale from 1 to 7 to the following cover classes: less than 1 %, 1 to 5 %, 6 to 10 %, 11 to 25 %, 26 to 50 %, 51 - 75 %, and 76 to 100 %.

#### Laboratory analyses

Bulk density was measured as the oven-dried ( $105\text{ }^{\circ}\text{C}$ , 12 hrs) weight per volume of sample and expressed in  $\text{g cm}^{-3}$ . Texture was measured by dry sieve analysis (Gee & Bauder, 1986) using a set of U.S. standard sieves. The cobble and gravel fraction ( $\geq 2\text{ mm}$ ) was expressed as a percentage of the total sediment mass. The sand fraction ( $< 2\text{ mm} - 0.053\text{ mm}$ ) and a combined silt and clay fraction ( $< 0.053\text{ mm}$ ) were expressed as percentages of the  $< 2\text{ mm}$

fraction. Organic matter content was determined by the loss-on-ignition (550 °C, 2 hours) procedure (Jackson, 1974) and expressed as a percent of the < 2mm size fraction.

Inorganic nutrients were analyzed on a Lachat Auto Analyzer by flow injection analysis using the following methods (Zellweger Analytics, 1993):  $\text{NH}_4\text{-N}$  with the phenolate method,  $\text{NO}_3\text{-N}$  with the cadmium reduction method, and  $\text{PO}_4\text{-P}$  with the ascorbic acid reduction method. All results were reported in  $\mu\text{M}$ . All lab analyses were conducted in triplicate.

Nomenclature used for vascular plants and mosses is ascribed to Gleason & Cronquist (1991) and Crum & Anderson (1981), respectively. Species were assigned to growth-forms after Spence (1967).

#### Data Analyses

Physical and chemical differences among the five study ponds were analyzed separately for nine factors as dependent variables: slope, bulk density, percent cobble and gravel, percent sand, percent silt and clay, percent organic matter content, and inorganic porewater nutrients:  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$ , and  $\text{PO}_4\text{-P}$ . The response of each environmental variable to pond identity was tested using analysis of covariance, ANCOVA, using water depth as a covariate (Sokal & Rohlf, 1995). As a relative measure of gradient position, water depth served as the common basis for comparing transect segments among all ponds. Accounting for gradient position provided a more rigorous test for among pond differences. To determine which ponds differed with respect to each environmental variable, post-hoc multiple comparisons among ponds were performed using Tukey's test (Spjøtvoll & Stoline, 1973).

Species prominence at each pond was expressed as a quantity index percentage,  $Q_i$ , which was calculated as one-half of the sum of the relative frequency and relative cover. Prior to calculating  $Q_i$ , ordinal ranks of cover for each species were back-transformed to the maximum value of that class. Combining relative frequency and relative cover into a single percentage index emphasizes the "importance" of characteristic species that may contribute significantly to cover or are locally common (Dufrêne & Legendre, 1997).

Ordinations were performed using the program CANOCO (ter Braak, 1988) Version 3.15, which uses the strict convergence criteria of Oksanen & Minchin (1997). Samples with no shoreline vegetation were noted, but routinely omitted from the multivariate analysis (ter Braak, 1988). The transitional shrub zone, from the upland to the pondshore herbaceous community, was excluded from the analysis because the focus of this study was on the littoral zone of aquatic vegetation; the shrub border clearly delineates the high water mark in New England coastal plain ponds (Sorrie, 1994). The floristic variation in the aquatic vegetation was demonstrated using detrended correspondence analysis (DCA), an indirect gradient analysis technique. The pattern of floristic dissimilarity among ponds was illustrated by labeling each 1-m segment with its corresponding pond identity. In addition, pond identities were encoded as nominal variables in the analysis allowing the "centroids" to be calculated from the set of 1-m segments for each pond (ter Braak, 1987a) and plotted. The relationship between the environmental variables and floristic composition of the ponds was determined using canonical correspondence analysis (CCA), a direct gradient approach equivalent to constrained multivariate regression (ter Braak, 1988). Again, pond identity was determined by labels and encoded as nominal variables to calculate and plot pond centroids.

To determine the influence of environmental variables on the floristic composition of the ponds, the forward selection procedure of CANOCO was applied. The conditional fit of each successive variable selected was tested using a Monte Carlo unrestricted permutation procedure (ter Braak, 1995). Prior to analysis, the following data transformations were made: slope, bulk density,  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$ , and  $\text{PO}_4\text{-P}$  data were log-transformed; percent cobble and gravel, percent sand, percent silt and clay, and percent organic matter were arcsine transformed; depth to seasonal water level was not transformed.

To examine the floristic variation among ponds after adjusting for gradient position, a partial CCA was applied using water depth as a covariate. This eliminates the considerable influence that gradient position would ordinarily have in the analysis. The resulting ordination diagram emphasizes how other environmental variables besides water depth influence the floristic variation.

## **Results**

### Environmental Distinctions Among Ponds

All five study ponds exhibited environmental differences for all variables conveyed along the water depth gradient as supported by the results of the ANCOVA (Table 2). Ponds segregated differently depending upon whether physical characteristics or chemical constituents were emphasized. Based on physical characteristics of the sediments alone, Gull and Duck Ponds were distinguished from other ponds. Gull and Duck Pond sediments had the lowest fraction of organic matter and the greatest bulk density. Gull and Duck Ponds also had relatively

Table 2.

Mean environmental variables (mean  $\pm$  standard deviation in parentheses) were compared by ANCOVA among the five study ponds, and then differences were determined by Tukey's post-hoc test ( $P < 0.05$ ) as signified by letter differences. Key to variables: SLOPE (elevation change over interval, m), BULKDENS (bulk density,  $\text{g cm}^{-3}$ ), CBL&GVL (% cobble and gravel,  $\geq 2\text{mm}$  fraction of total sample weight), SAND (% sand content,  $< 2\text{ mm} - 0.053\text{ mm}$  fraction of the sample weight  $< 2\text{mm}$ ), SI&CL (% silt and clay fraction,  $< 0.053\text{ mm}$  of the sample weight  $< 2\text{mm}$ ), OM-LOI (organic matter content, % loss-on-ignition),  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$ , and  $\text{PO}_4\text{-P}$  (spring values of nutrient concentrations expressed in  $\mu\text{M}$ ).

| Variable               | POND IDENTITY         |                        |                        |                       |                          |
|------------------------|-----------------------|------------------------|------------------------|-----------------------|--------------------------|
|                        | <i>DUCK</i><br>(n=48) | <i>RYDER</i><br>(n=28) | <i>GREAT</i><br>(n=38) | <i>GULL</i><br>(n=88) | <i>HERRING</i><br>(n=26) |
| SLOPE                  | 0.10 (0.04)a          | 0.11 (0.06)a           | 0.11 (0.04)a           | 0.05 (0.04)b          | 0.09 (0.05)a             |
| BULKDENS               | 1.79 (0.08)abd        | 1.61 (0.28)bc          | 1.41 (0.25)bc          | 1.96 (0.37)ad         | 1.45 (0.36)ac            |
| CBL&GVL                | 12.34 (8.92)a         | 13.32 (12.50)a         | 9.84 (8.15)a           | 31.42 (28.35)b        | 14.44 (13.61)a           |
| SAND                   | 99.41 (0.32)a         | 99.42 (0.38)a          | 99.01 (0.52)a          | 99.81 (0.19)a         | 96.39 (5.74)b            |
| SI&CL                  | 0.59 (0.32)a          | 0.58 (0.39)a           | 0.99 (0.52)a           | 0.22 (0.26)a          | 3.61 (5.74)b             |
| OM-LOI                 | 0.38 (0.16)a          | 1.38 (1.25)bcd         | 2.04 (1.46)cd          | 0.37 (0.18)ad         | 1.50 (1.08)bd            |
| $\text{NH}_4\text{-N}$ | 14.71 (23.98)a        | 19.00 (32.08)a         | 18.18 (16.69)a         | 49.34 (48.52)b        | 19.15 (16.72)a           |
| $\text{NO}_3\text{-N}$ | 5.90 (9.55)a          | 4.54 (9.45)a           | 11.61 (10.01)a         | 29.24 (30.63)b        | 6.73 (6.18)a             |
| $\text{PO}_4\text{-P}$ | 0.22 (0.42)a          | 0.20 (0.34)a           | 0.32 (0.60)a           | 0.28 (0.42)a          | 3.28 (5.77)b             |

high sand fractions (99.81 % and 99.41 %) although the findings were only significantly greater than Herring Pond ( $\alpha = 0.05$  level). Gull Pond had the greatest fraction of cobble and gravel (31.42 %). Based on the nutrient content of porewater, Gull and Herring Ponds were distinguished from the others. Gull Pond sediments had significantly higher concentrations of  $\text{NO}_3\text{-N}$  and  $\text{NH}_4\text{-N}$  and a relatively high concentration of  $\text{PO}_4\text{-P}$ . Herring Pond had the highest concentration of  $\text{PO}_4\text{-P}$ .

In summary, based on environmental factors alone, Duck Pond was dominated by oligotrophic characteristics, such as low sediment organic content and exceptional water clarity (Table 1). Gull Pond and Herring Pond could be considered at the more eutrophic end of the gradient because of elevated porewater nutrients. Ryder Pond and Great Pond did not exhibit physical or chemical characteristics that would place them at either end of the trophic gradient, although Great Pond did have the highest sediment organic content, albeit only statistically greater than Duck Pond.

#### Floristic composition

Forty-nine macrophyte species encountered were included in the analysis (Fig. 1). The sparse vegetation of Duck and Ryder Ponds was evidenced by no vegetation encountered in 24% and 22% of the sampled 1-m segments, respectively. Only two species were common to all ponds, the pondshore emergent, *Bidens connata*, and the rosette-type plant, *Eleocharis acicularis*. Dominant species in oligotrophic ponds such as Duck Pond included the rosette-forming *Juncus pelocarpus* and *Eleocharis acicularis*, as well as the emergent, *Juncus canadensis*. Dominant species in slightly enriched ponds, such as Herring Pond, included the submerged-leafy species, *Utricularia* sp., *Najas flexilis*, *Sium suave* and floating-leaved,

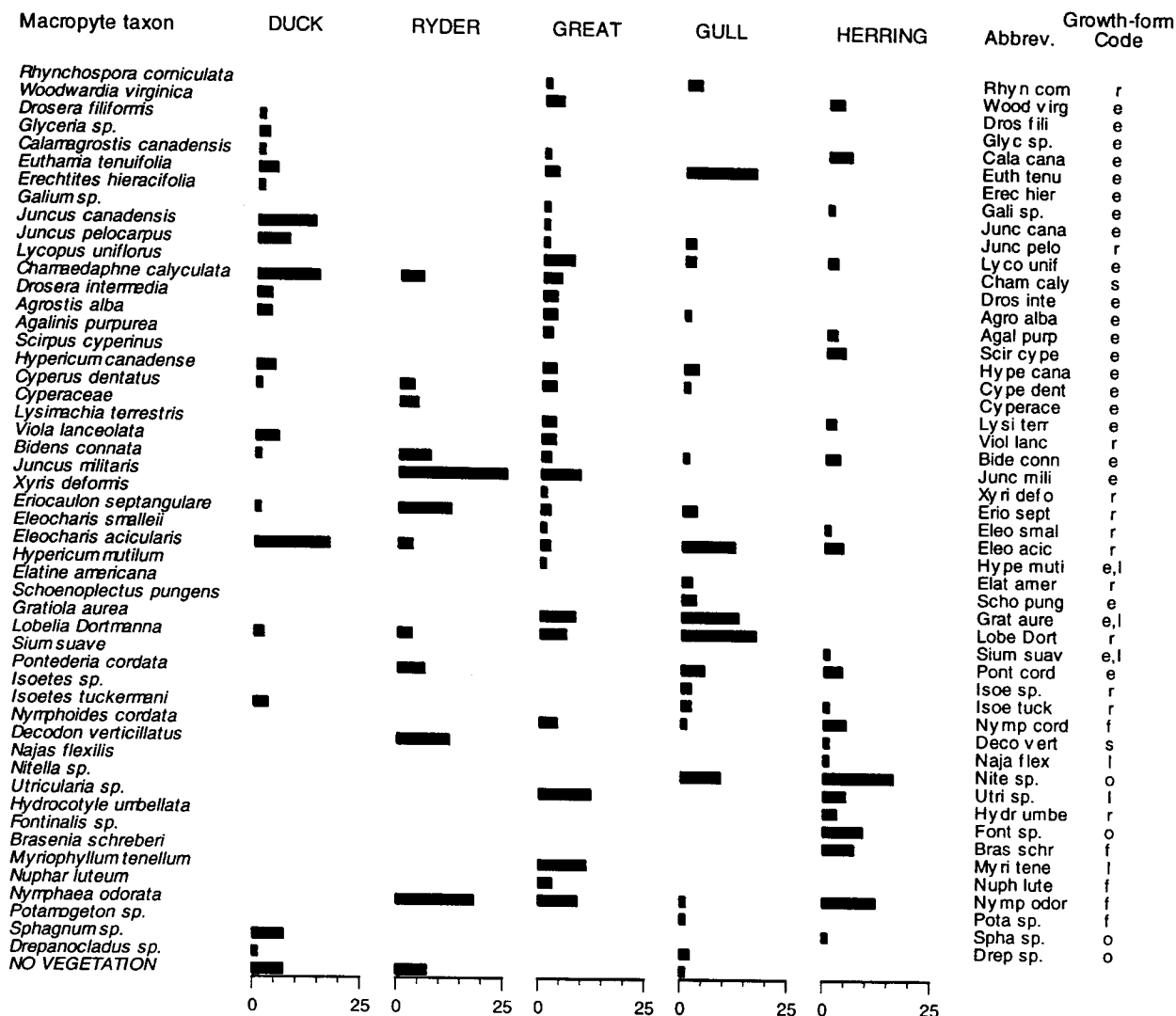


Fig. 1. Prominence of macrophyte species in each kettle pond, expressed as a quantity index percentage,  $Q_i$ , which was calculated as one-half of the sum of the relative frequency and relative cover. Species are ranked as ordered by the first DCA axis. Plant abbreviations presented in Fig. 4 are indicated along with a key to growth-form: s, suffrutescent; e, emergent; r, rosette; l, leafy-submersed; f, floating-leaved; o, other (bryophytes and charaphyte).

*Nymphoides cordata*, *Nymphaea odorata* *Brasenia schreberi*, and the algal stonewort, *Nitella cf. flexilis*.

This study was conducted during a year of drought or low water levels when compared to long-term hydrologic records. Similar to findings from coastal plain ponds in nearby Long Island, New York (Schneider, 1994), species richness was probably greater than under more flooded conditions because of plant regeneration from seeds and vegetative propagules within the exposed sediment.

Floristic differences among the five study ponds were clearly distinguishable based on the site-conditional DCA ordination plot (Fig. 2). Individual 1-m segments for each pond are plotted and differences among ponds are demonstrated by the spread of segments along the axes. The dissimilarity among the five study ponds is a direct function of the distance, along the DCA axes, between sites sampled from different ponds. The average position or centroid clearly shows how ponds were segregated. The range in floristic variation among ponds spanned 10 and 7 DCA units (*i.e.*, standard deviation units) for DCA axis I and II, respectively. A separation by 4 DCA units indicates a complete species turnover (ter Braak, 1995), meaning, for example, that many of the 1-m segments from Herring Pond had absolutely no species in common with segments from Duck Pond. Based only on vegetation composition, a trophic continuum from oligotrophic to eutrophic is represented as Duck, Great, Ryder, Gull, and Herring Ponds; similar to the gradient based on environmental variables (see Tables 1 and 2).

#### Environmental and Floristic Relationships

Seven environmental variables (water depth, organic matter, sand,  $\text{PO}_4\text{-P}$ , slope,  $\text{NO}_3\text{-N}$ , and bulk density) explained 90% of the observed variation in pond vegetation patterns (Table 3).

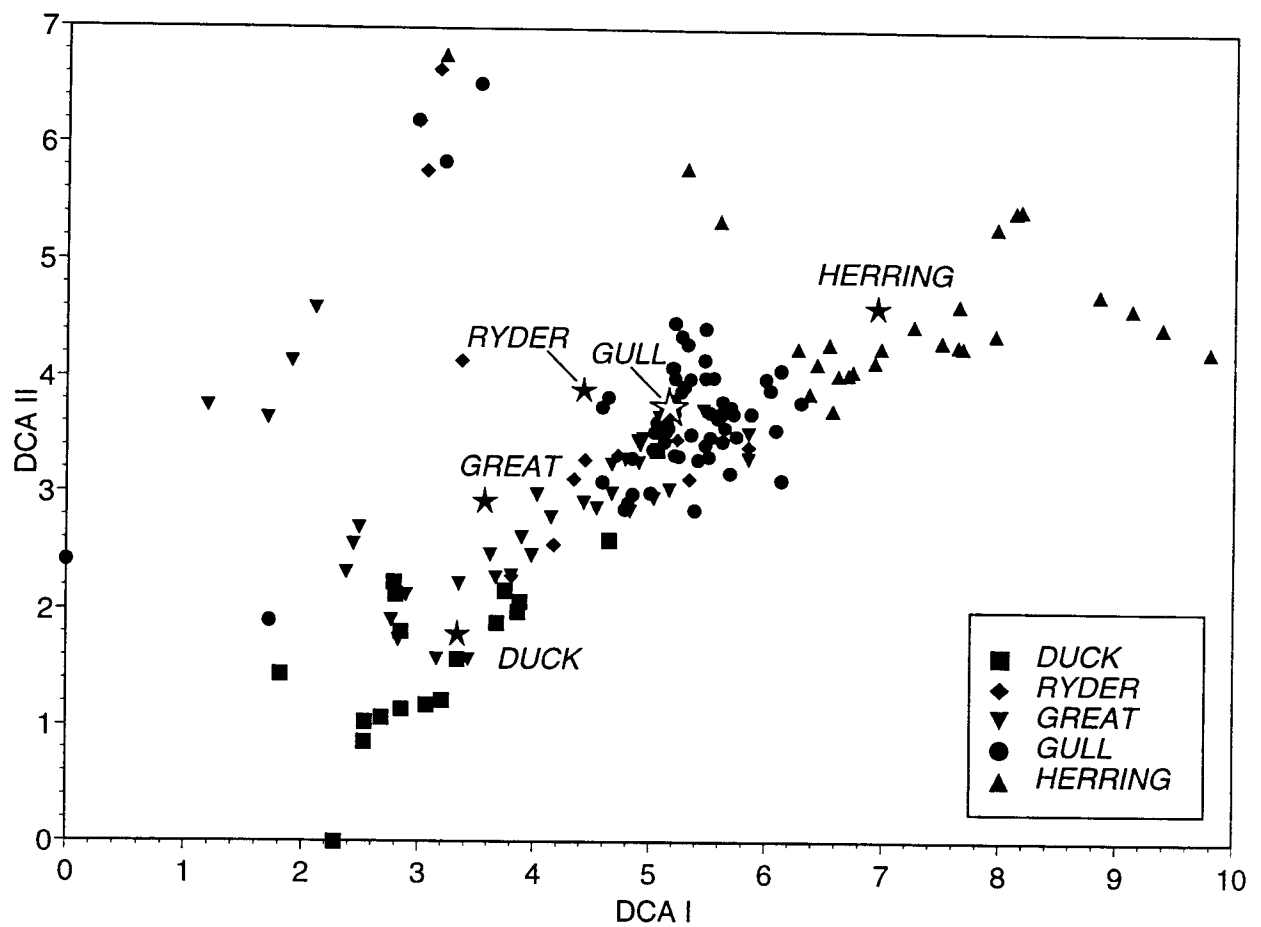


Fig. 2. Ordination diagram of DCA Axis I ( $\lambda = 0.824$ ,  $R = 0.742$ ,  $P < 0.01$ ) and DCA Axis II ( $\lambda = 0.718$ ,  $R = 0.681$ ,  $P < 0.01$ ) showing the floristic variation among the five study ponds. Individual 1-m segments are indicated by unique symbols for each pond. Centroids of each pond are designated with a star.

Not surprisingly, water depth had the largest influence on plant distributions, accounting for 31% of the variance. The overwhelming influence of water depth was anticipated because it served as a relative measure of gradient position common to all ponds. For this reason water depth was extracted as a covariate in subsequent partial CCA analyses (PCCA) in order to focus on other environmental differences among ponds that control the flora.

PCCA ordination was used to elucidate relationships between the environmental variables and vegetation patterns of the ponds along the trophic gradient. As previously discussed, on the PCCA diagrams the vegetation differences among ponds, either in terms of vegetation composition (Fig. 3) or species (Fig. 4), can be determined by the distances among centroids. The PCCA plot also presents the environmental variables as vectors or arrows. Vegetation sample plots or species that are near or beyond the tip of an arrow are positively correlated with and influenced by that variable. Those plots at opposite ends of an arrow are less affected, and thus, the arrows represent gradients of environmental influence. Some of the environmental variables are depicted as open arrows. These variables contribute, although not significantly, to the explanation of vegetation differences among the ponds. It is noted that silt & clay is an open arrow and is shown correctly as the inverse of the sand fraction. Sand was first entered into the model, and thus, the inverse silt & clay fraction was a less significant contributor to the model. The length of the arrows are proportional to the magnitude of influence that the physiochemical variable has on the vegetation (terBraak, 1987b).

The PCCA ordination plots display much information and careful interpretation reveals the following trends. The vegetation composition of eutrophic Herring Pond appears to be strongly influenced by high porewater  $\text{PO}_4\text{-P}$  concentrations and fine grained sediments (Fig. 3). The floating aquatic, *Brasenia schreberi*, the submerged *Utricularia*, and the alga, *Nitella*, all

Table 3.

Ranking the influence of environmental variables in explaining pond macrophyte vegetation patterns. The "additional fit",  $\lambda_a$ , is the change in eigenvalue explained by conditional effects of adding each additional variable to the model using a forward selection process of CANOCO; P, is the significance level obtained using a Monte Carlo unrestricted permutation test; % Cum Variance, is the cumulative fraction of the additional fit to the total model fit expressed as a percentage. Key to variable names is presented in Table 2.

| Variable           | $\lambda_a$ | P     | % Cum Variance |
|--------------------|-------------|-------|----------------|
| DEPTH              | 0.66        | 0.001 | 31             |
| OM-LOI             | 0.46        | 0.001 | 50             |
| SAND               | 0.24        | 0.001 | 61             |
| PO <sub>4</sub> -P | 0.19        | 0.001 | 69             |
| SLOPE              | 0.17        | 0.001 | 77             |
| NO <sub>3</sub> -N | 0.15        | 0.001 | 84             |
| BULKDENS           | 0.13        | 0.003 | 90             |
| CBL&GVL            | 0.09        | 0.067 | 95             |
| NH <sub>4</sub> -N | 0.07        | 0.220 | 98             |
| SI&CL              | 0.02        | 0.970 | 99             |

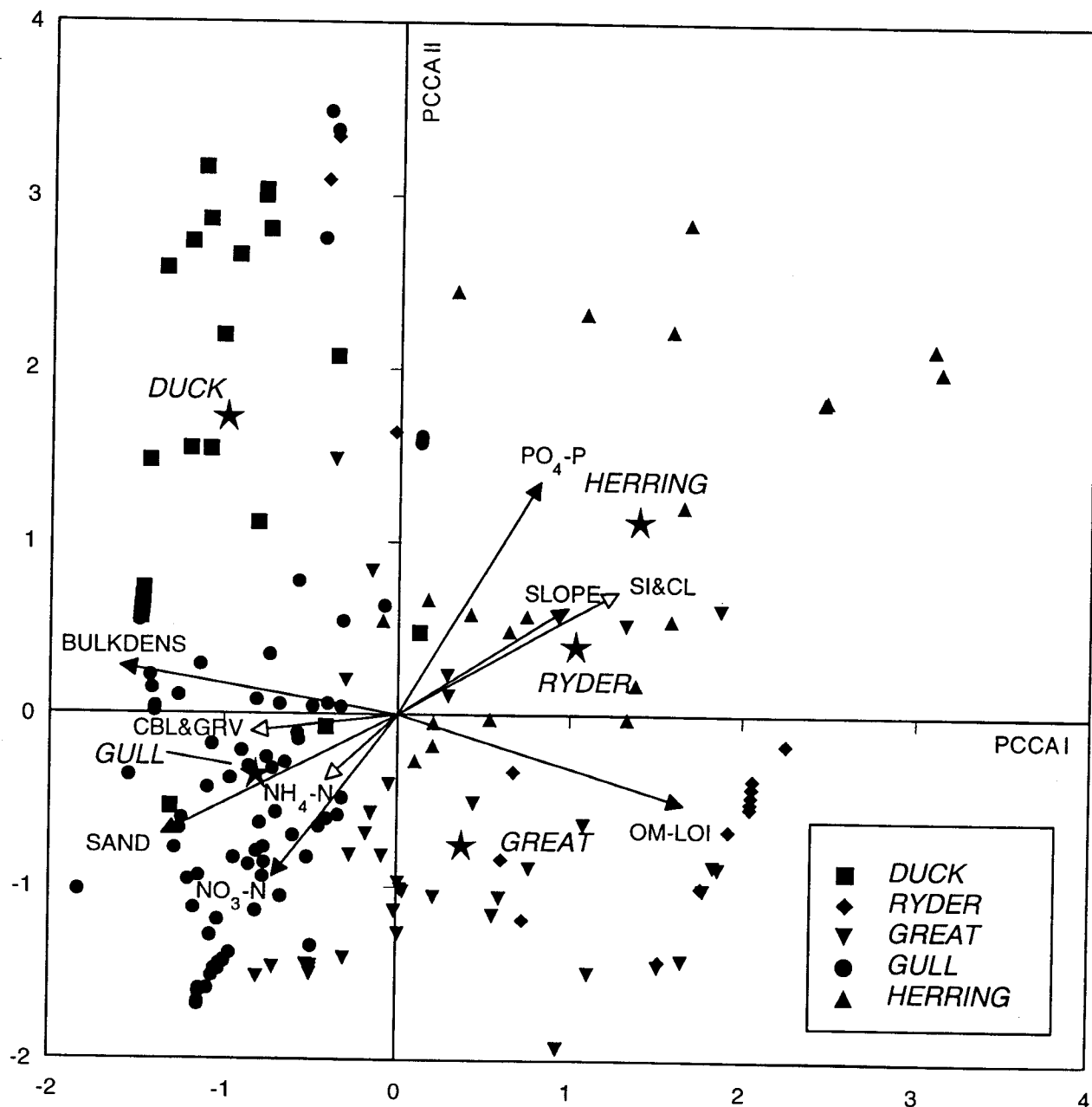


Fig. 3. Ordination diagram of PCCA Axis I ( $\lambda = 0.449$ ,  $R = 0.847$ ,  $P < 0.01$ ) and PCCA Axis II ( $\lambda = 0.253$ ,  $R = 0.683$ ,  $P < 0.01$ ) showing the relationship between floristic composition of the ponds and gradients of environmental factors (see Table 2 for key to environmental factors). Centroids for each pond are designated with a star. Solid arrows indicate a significance of  $P < 0.05$ ; open arrows indicate factors that tested not significant in the forward selection model.

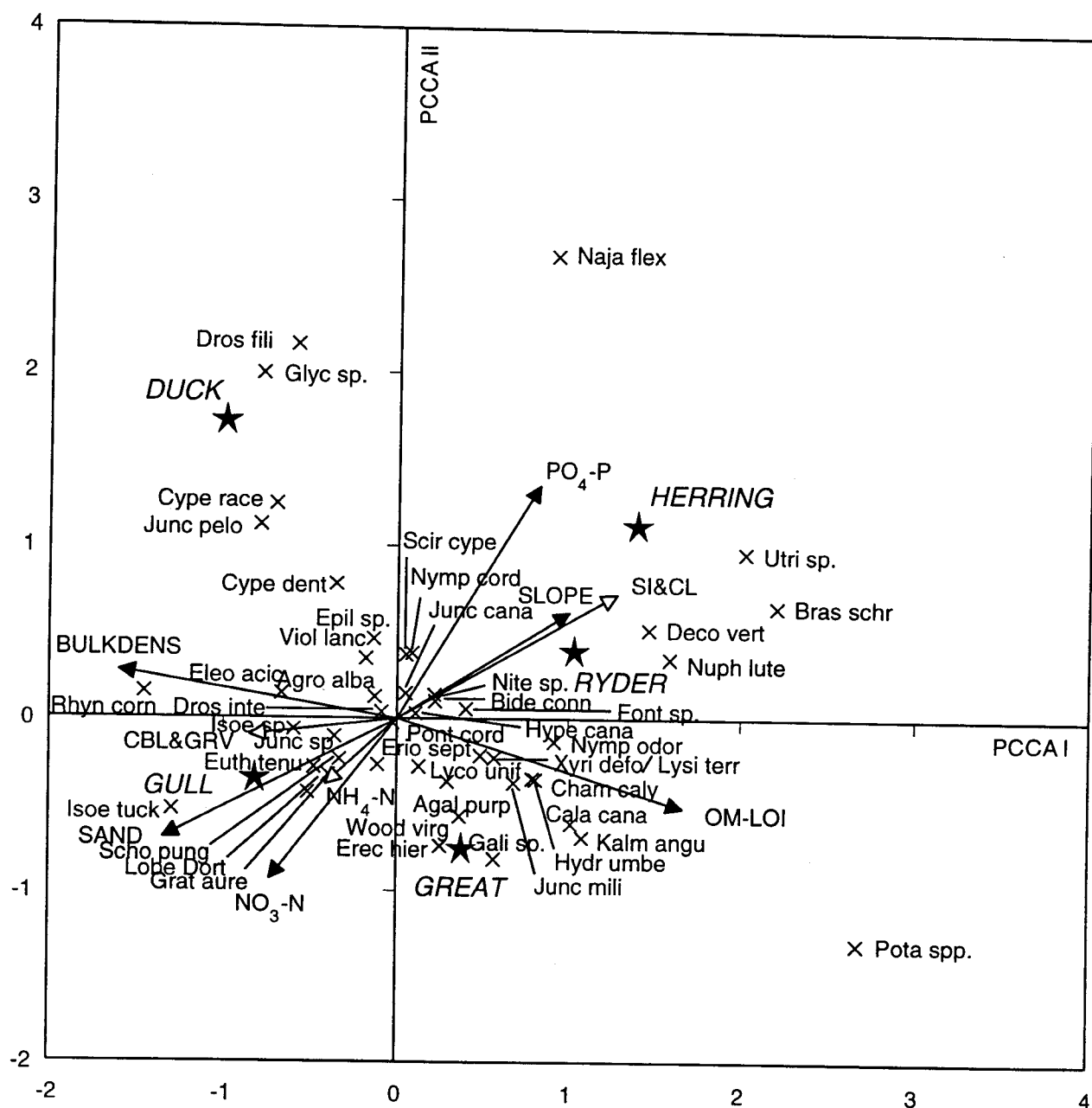


Fig. 4. Ordination diagram of PCCA Axis I ( $\lambda = 0.449$ ,  $R = 0.847$ ,  $P < 0.01$ ) and PCCA Axis II ( $\lambda = 0.253$ ,  $R = 0.683$ ,  $P < 0.01$ ) showing the relationship between the flora of different ponds and gradients of environmental factors (see Table 2 for key to environmental factors). See Fig. 1 for key to plant species abbreviations.

dominate at Herring Pond (Fig. 4). The PCCA plots confirm that vegetation of the eutrophic Gull Pond is strongly influenced by porewater  $\text{NO}_3$  concentrations and a sand substrate. Species such as *Lobelia dortmanna*, and the emergents, *Gratiola aurea* and *Euthamia tenuifolia*, dominate at Gull Pond. The centroid of the oligotrophic Duck Pond is well-separated from the other ponds and the vegetation seems strongly influenced by low sediment organic content and high sediment bulk density. No floating aquatics occur in Duck Pond, instead the emergents appear to dominant. The PCCA plots support our previous data presentations suggesting that Ryder and Great Ponds are intermediate along the trophic gradient.

## Discussion

The species composition and growth form of aquatic macrophytes differed significantly between oligotrophic Duck Pond and the more eutrophic Herring Pond. This trend was best defined by the predominance of floating-leaved plants in the eutrophic pond and their complete absence in the oligotrophic pond (Fig. 1). Moreover, the vegetation of the oligotrophic pond was sparse in comparison to the more eutrophic pond. Canonical correspondence analysis, a widely used and effective multivariate direct gradient technique for elucidating relationships between vegetation and environmental variables (Palmer, 1993), suggests that high sediment porewater  $\text{PO}_4\text{-P}$  level is an important variable influencing the vegetation of eutrophic Herring Pond (Figs. 4 & 5). A study of coastal plain lakes in Nova Scotia revealed the same trend, with floating plants dominating nutrient enriched lakes (Srivastava et al., 1995). Roelofs (1983) reported suppression of rosette-type plants under phosphorous-enriched conditions, a trend found at the eutrophic Herring Pond where rosette species were present, but not prominent (Fig. 1).

Based on environmental variables alone, Gull Pond was classified toward the eutrophic end of the gradient, due to elevated porewater nitrogen levels (Table 2). However, physical characteristics, such as grain size, sediment organic content, and dominant plant growth forms differed from the eutrophic Herring Pond. Floating aquatics were only a minor component of the Gull Pond flora (Fig. 1). Rosette species, *Lobelia dortmanna* and *Eleocharis acicularis*, were a dominant part of the Gull Pond macrophyte community, yet these and other rosette plants generally occur in non-enriched or oligotrophic waters (Hutchinson 1975; Gacia et al., 1994; Srivastava et al., 1995; Toivonen & Huttunen, 1995). The PCCA ordination plots (Figs. 3 and 4) demonstrate that high porewater nitrate levels influenced Gull Pond vegetation, but other factors, such as sandy, cobble, and gravel substrate and a low-gradient slope were also important and probably major determinants of Gull Pond vegetation.

It is obvious that our quantitative multivariate analyses did not include all of the major environmental factors that could be important to explaining pond shoreline vegetation along trophic gradients. However, the relevance of these factors to our findings is evaluated. Keddy (1983) studied the role of exposure or wave energy in defining lakeshore vegetation patterns and found that *Lobelia dortmanna* and other rosette-type plants were most abundant on wave-exposed shores, while floating species (*Brasenia schreberi*, *Nymphaea odorata*) were restricted to sheltered shores. As noted in Table 1, the 44 ha Gull Pond was the largest of the ponds studied, presumably with the greatest wave energy, favoring *Lobelia* and other rosette plants along the shore.

Light represents another, and perhaps the most important, factor controlling pond shoreline vegetation patterns. Herring Pond's high chlorophyll *a* levels and a high light extinction coefficient, compared to the other study ponds (Table 1), suggests that light limitation may be a

mechanism that is restricting the prominence of emergent and rosette growth forms. Studies have documented that in nutrient-enriched lakes, high densities of phytoplankton or floating-leaved macrophytes reduce water clarity to the point where insufficient light is available for submersed plants (Sand-Jensen & Søndergaard, 1981; Roelofs, 1983; Srivastava et al., 1995; Toivonen & Huttunen, 1995). In contrast, submerged bryophytes, *Sphagnum cf. subsecundum* and *Dreplanocladus exannulatus*, were collected to a depth of 14m in oligotrophic Duck Pond with typical summer Secchi transparencies of 8-10m. Deep-water bryophytes are well adapted to the acidic and oligotrophic conditions of Duck Pond and have reportedly occurred there since deglaciation, 11-12,000 years before present (Winkler, 1985; Farmer, 1988).

The significance of lake pH to aquatic macrophyte composition has been emphasized by the acidification of lakes caused by acid deposition and subsequent declines in species richness and changes in plant growth forms. Studies of acidified systems have reported mats of *Spaghnum* replacing isoetid taxa, or more subtle changes related to declines in species richness (Grahn, 1977; Roelofs, 1983; Roberts et al., 1985; Arts & Leuven, 1988; Jackson & Charles, 1988). However, as noted in the literature, it is often difficult to attribute macrophyte changes directly to pH. Changes in acidity can affect the availability and form of nutrients and inorganic carbon which are critical to determining macrophyte species composition (Roelofs et al., 1984; Roberts et al., 1985; Srivastava et al., 1995). pH clearly plays a fundamental role in defining pond macrophyte communities, but because of the difficulty in differentiating direct from indirect effects, and following the recommendations of others (Toivonen & Huttunen, 1995; Srivastava et al., 1995), pH was not considered as an environmental factor in our quantitative analyses.

Having identified this qualifier regarding pH and acidification, it should be noted that Great Pond was limed in 1975 and again in 1985 in efforts to artificially raise pH to enhance stocked

fish survival. Liming of acidic pond and lake waters has been a common practice globally (Olem, 1991). Great Pond had the greatest species richness (Fig. 1) and the macrophytes were represented by a variety of growth forms, ranging from emergents and rosettes to floating-leaved aquatics and submerged bryophytes. This diversity may be related, at least in part, to the human-influenced fluctuations in pH over the past few decades between pH 6 and 7. It has been demonstrated that after liming, lake and pond vegetation is altered, especially with declines or disappearance of submerged *Sphagnum* (Hultberg & Anderson, 1982; Eriksson et al., 1983).

#### Implications for monitoring

With increasing suburbanization of Cape Cod and associated increased density of on-site septic systems, groundwater is becoming nutrient enriched (Persky, 1986). Significant discharge of groundwater-borne nitrogen directly to shallow estuaries of Cape Cod, and elsewhere throughout the northeastern US where aquifers are sandy and highly permeable, has been demonstrated and the ecological responses specifically related to shifts in primary producers have been documented (Lee & Olsen, 1985; Valiela et al., 1990; Short & Burdick, 1996; Portnoy et al., 1998). Discharge of nutrient-enriched groundwater to freshwater kettle ponds and associated ecological effects have been less studied, but is a major concern to natural resource managers.

Primary production in freshwater environments is phosphorous limited (Schindler, 1977), although nitrogen limitation is also reported (Vitousek et al., 1997). Acidic sediments generally retain or remove phosphorous by adsorption, and thus, transport of groundwater-borne phosphorous to fresh surface waters is not considered a problem (Cantor & Knox, 1985), particularly in sandy, aerobic coastal aquifers. A study of nutrient transport in septic effluent

within the sandy substrate of southeastern Massachusetts confirms the high removal of inorganic phosphorous in groundwater, but inorganic nitrogen transport and discharge to surface waters was substantial (Weiskel & Howes, 1992). However, septic systems located close to pond shorelines may leach low-redox and high phosphate effluent into phosphorous-limited kettle ponds. Introduction of inorganic phosphorous by visiting seabirds (gulls) may also represent a significant source of this limiting nutrient to freshwater ponds, as demonstrated at Gull Pond (Portnoy, 1990). Nitrogen loading can increase primary production in normally phosphorous-limited freshwaters once the phosphorous supply exceeds the needs of primary producers (Esler et al., 1990; Downing and McCauley, 1992).

It is important to develop long-term monitoring programs for kettle ponds that include assessment of nutrient loading from various sources along with a suite of environmental and biotic factors that describe pond trophic status. From the data presented in this paper, we suggest that long-term quantification of aquatic macrophyte species composition should become an integral part of a comprehensive pond monitoring program. The aquatic macrophyte community of oligotrophic and naturally acidic ponds, such as Duck Pond, is best characterized by relatively sparse vegetation that is dominated by narrow-leaved rosette and emergent plants. Submerged bryophytes also indicate acidic and oligotrophic conditions. As ponds tend toward a more eutrophic status caused by nutrient enrichment, altered pH, or a combination of other factors, our research indicates that floating-leaved plants may increase in relative abundance, along with an overall increase in the density or cover of aquatic macrophytes.

## **Acknowledgements**

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## APPENDICES

### **Appendix 1: Location of pond vegetation transects**

At each of the five sample ponds, a gradient approach to sampling was applied by randomly choosing five permanent transects oriented perpendicular to the shoreline. A small monument (constructed of a concrete-filled schedule 40 PVC pipe of 7 cm-diameter and 40 cm-length) was placed near the shoreline at the upland-wetland shrub border as a permanent reference for each transect. Each monument was affixed in advance with a small brass plate stamped with a four character code to designate each transect. The location of each monument was referenced using a global positioning system (GPS; Trimble Geoexplorer).

Because some trampling of vegetation occurred when the monuments were installed, the starting location of each transect was offset a random number of meters to the right of the monument as the investigator faced the pond.

Appendix 1 Table. Identification and location of pond transects.

*Monument ID* – Each PVC/concrete marker has a stamped ID on the top

*Bearing* – Each transect extended perpendicular to the shore at a bearing, relative to True North

*Random Offset* – Each transect was offset a random number of meters to the right of the monument, as the investigator faces the pond.

*UTM coordinates* are references to NAD83.

| Transect  | Monument ID | Bearing | Random Offset | UTM Coordinates |         |
|-----------|-------------|---------|---------------|-----------------|---------|
| Duck 1    | AFS9        | 260     | 16.0          |                 |         |
| Duck 2    | PGL5        | 274     | 4.2           |                 |         |
| Duck 3    | PGH6        | 50      | 6.2           | 416899          | 4642519 |
| Duck 4    | CHB1        | 114     | 14.6          | 416906          | 4642656 |
| Duck 5    | PGL10       | 162     | 6.8           | 416983          | 4642719 |
| Gull 1    | CMB10       | 221     | 34.5          | 416533          | 4645507 |
| Gull 2    | CHB4        | 242     | 15.8          | 416828          | 4645270 |
| Gull 3    | AFS2        | 343     | 14.4          | 416482          | 4644847 |
| Gull 4    | AFS4        | 15      | none          | 414606          | 4646497 |
| Gull 5    | BAB3        | 110     | 28.0          | 416094          | 4645450 |
| GreatT 1  | NLB4        | 244     | 3.3           | 414749          | 4647208 |
| GreatT 2  | PGH3        | 32      | 3.0           | 414567          | 4647100 |
| GreatT 3  | BAB1        | 144     | 1.1           | 414414          | 4647160 |
| GreatT 4  | AFS1        | 140     | 11.2          | 414544          | 4647295 |
| GreatT 5  | BAB9        | 340     | 11.8          | 414745          | 4647270 |
| Herring 1 | AFS3        | 314     | 11.5          | 416119          | 4645832 |
| Herring 2 | CHB7        | 14      | 12.2          | 414898          | 4645899 |
| Herring 3 | AFS5        | 4       | 8.5           | 415856          | 4645910 |
| Herring 4 | NHB9        | 180     | 9.1           | 416057          | 4646068 |
| Herring 5 | AFS5        | 275     | 5.5           | 416158          | 4645964 |
| Ryder 1   | PGL8        | 74      | 11.0          | 414422          | 4646352 |
| Ryder 2   | PGL3        | 174     | 11.0          | 414534          | 4646616 |
| Ryder 3   | MCB7        | 256     | 5.1           | 414422          | 4646351 |
| Ryder 4   | CHB5        | 314     | 1.7           | 414661          | 4646281 |
| Ryder 5   | AFS6        | 26      | 5.9           | 414527          | 4646203 |

## Appendix 2: Pond Vegetation Maps

In the summer of 1978 (June through August), Coe and Soukup (technical report to the NPS, North Atlantic Region, "Macrophyte vegetation of freshwater kettle ponds of Cape Cod National Seashore," *no date*) conducted a qualitative survey of macrophytes for seventeen of the Seashore's twenty kettle ponds. In addition to species lists for each pond, they prepared field maps indicating the distribution of major aquatic macrophytes within the pond shoreline. Coe and Soukup obtained maps (scale 1"=200') that outlined the pond shoreline. In the field, the distribution of "densest aquatic macrophyte vegetation" was sketched onto the base map "by eye."

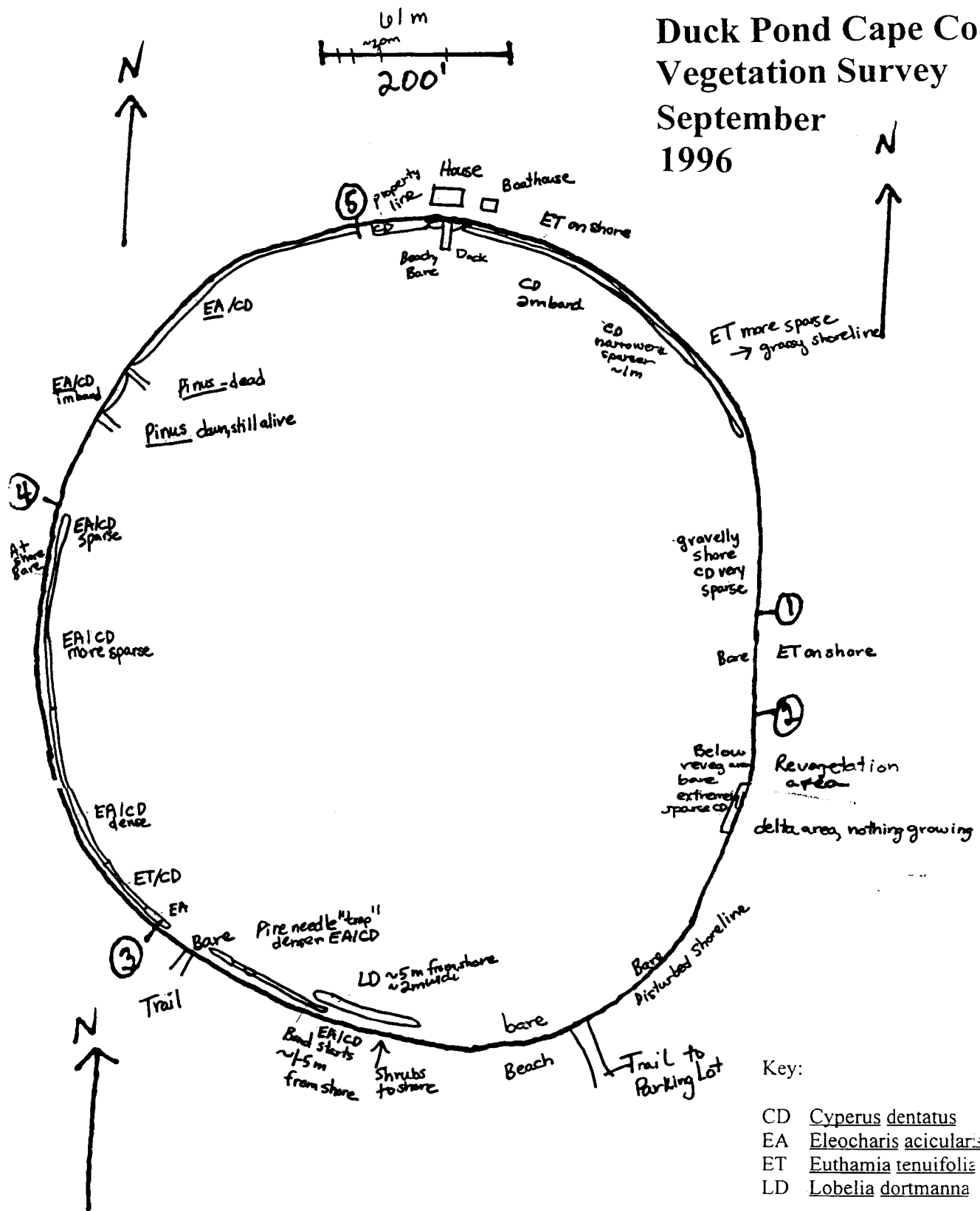
In September 1996 we produced aquatic macrophyte vegetation maps of the five study ponds (Duck, Great-Truro, Gull, Herring, Ryder). Our methods were as follows. Park boundary/ownership maps (scale 1"=200') were used as a base map. Property boundaries, permanent features (e.g., docks, trails, streams), and our permanent transects were located on the base maps. All maps were created from a canoe. Boundaries of various vegetation polygons and dimensions of the polygons were estimated and drawn to the base map by reference to permanent features and marked property boundaries. Also, the length of the canoe was used as scale to judge dimensions of the polygons. In the laboratory, a planimeter was used to estimate the area of each vegetation polygon that was displayed on the map (see Table).

Our original intent was to compare the Coe and Soukup maps with those of the present study. However, because of the unknown errors associated with the production of these maps, it seems prudent to only use the maps as general guides and not for comparative purposes. Aerial photography, at an appropriate scale to map pond-shore macrophyte, was not available.

### Key to Pond Vegetation Maps

1. Abbreviations for macrophyte cover types are listed on each map. Abbreviations such as BS/NO indicate that *Brassenia schreberi* and *Nymphaea odorata* are co-dominants. BS/NO indicates that *Brassenia* and *Nymphaea* co-exist, but that *Brassenia* is the dominant.
2. Location of the permanent vegetation transects are indicated by circled numbers 1-5.
3. Enlarged portions of the pond shoreline are presented on separate sheets.
4. Property boundaries are indicated as lines originating from the pond shore and extending away from the shore.

**Duck Pond Cape Cod  
Vegetation Survey  
September 1996** N



Key:

CD Cyperus dentatus  
EA Eleocharis acicularis  
ET Euthamia tenuifolia  
LD Lobelia dortmanna

Canada geese have been pulling up Eleocharis acicularis

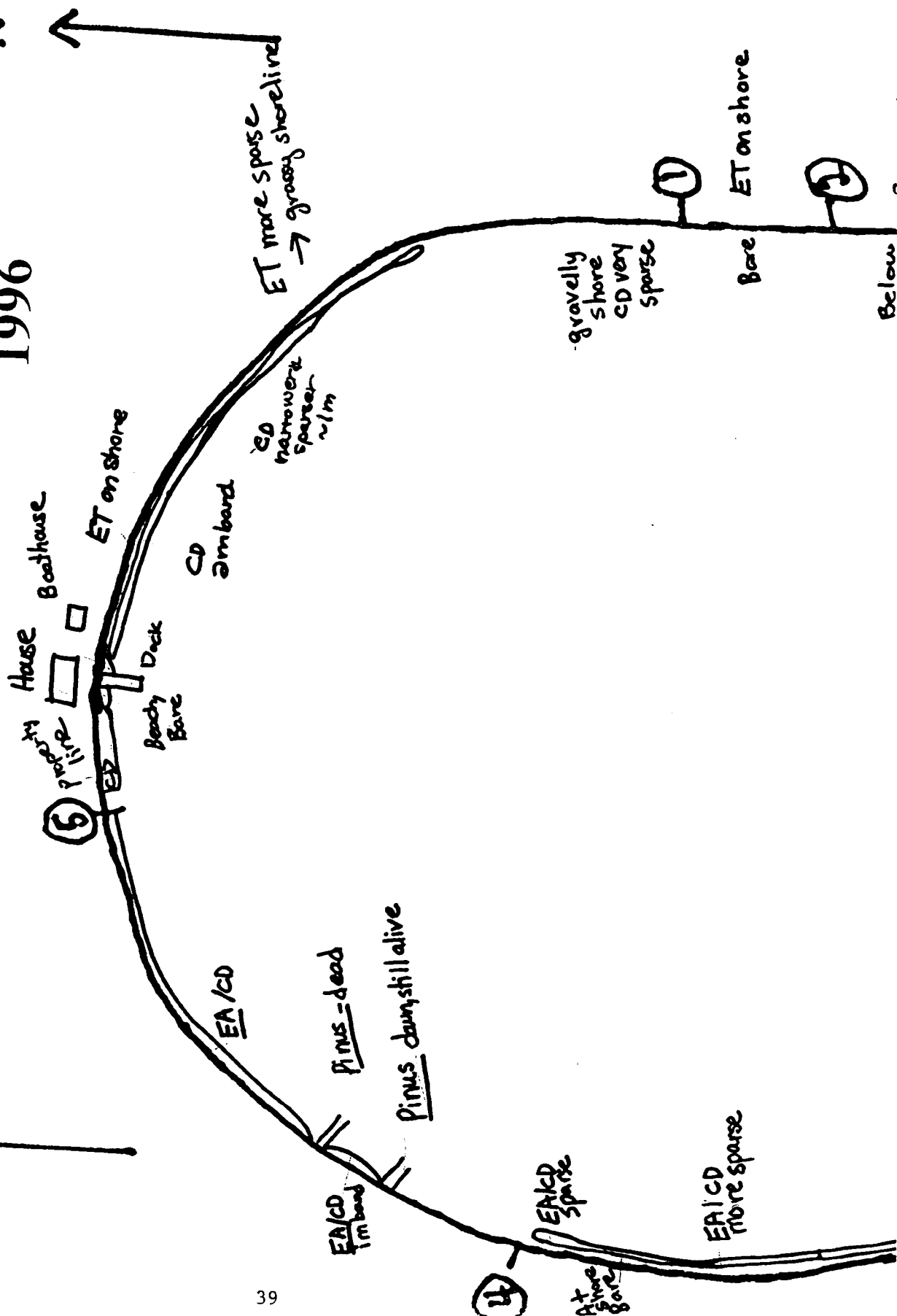
# Duck Pond Cape Cod Vegetation Survey

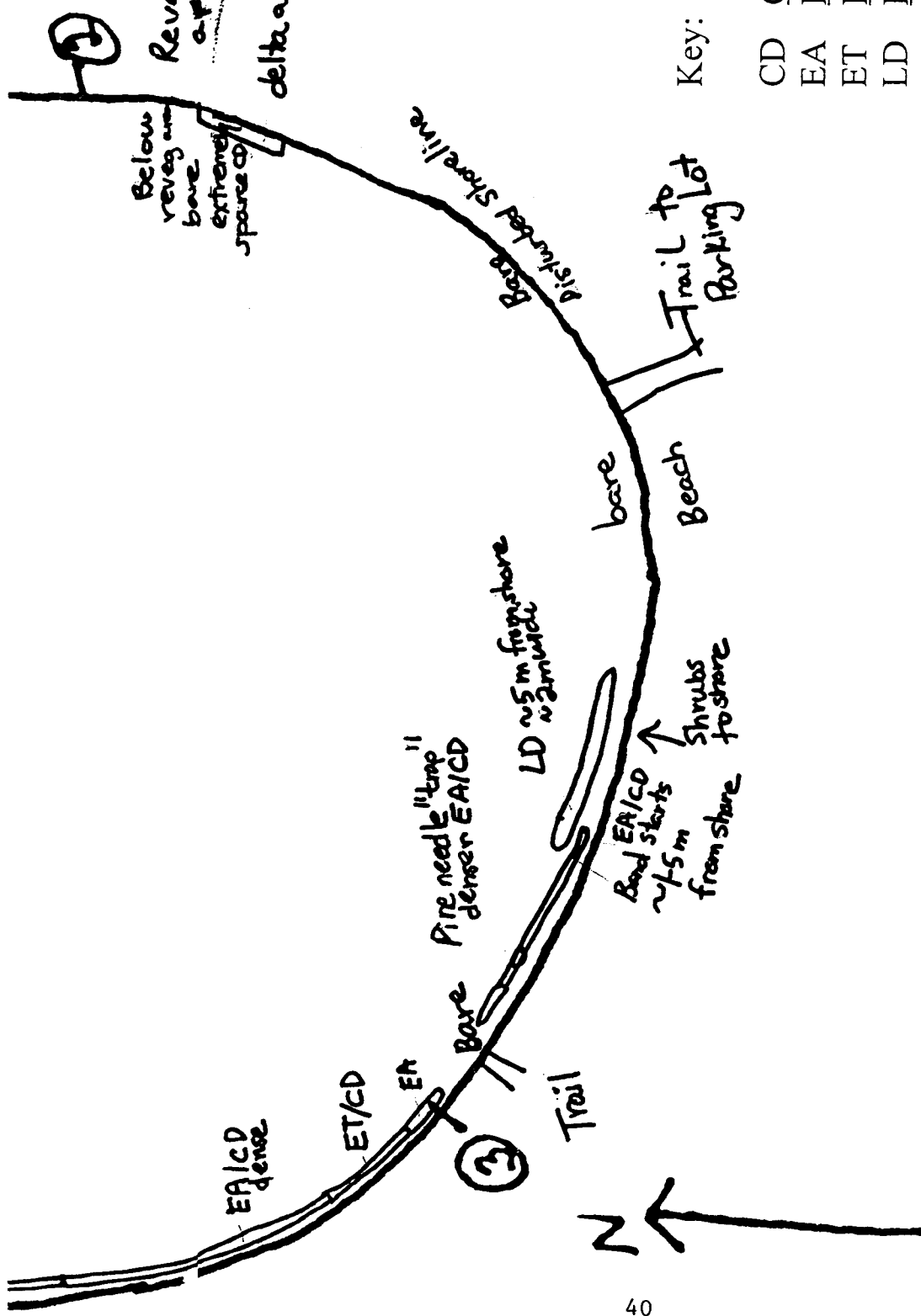
September  
1996

60 m  
200'

N

N





Key:

- CD Cyperus dentatus
- EA Eleocharis acicularis
- ET Euthamia tenuifolia
- LD Lobelia dortmanna

200'

Canada geese have been pulling up Eleocharis acicularis

Water level high-up to base of bank



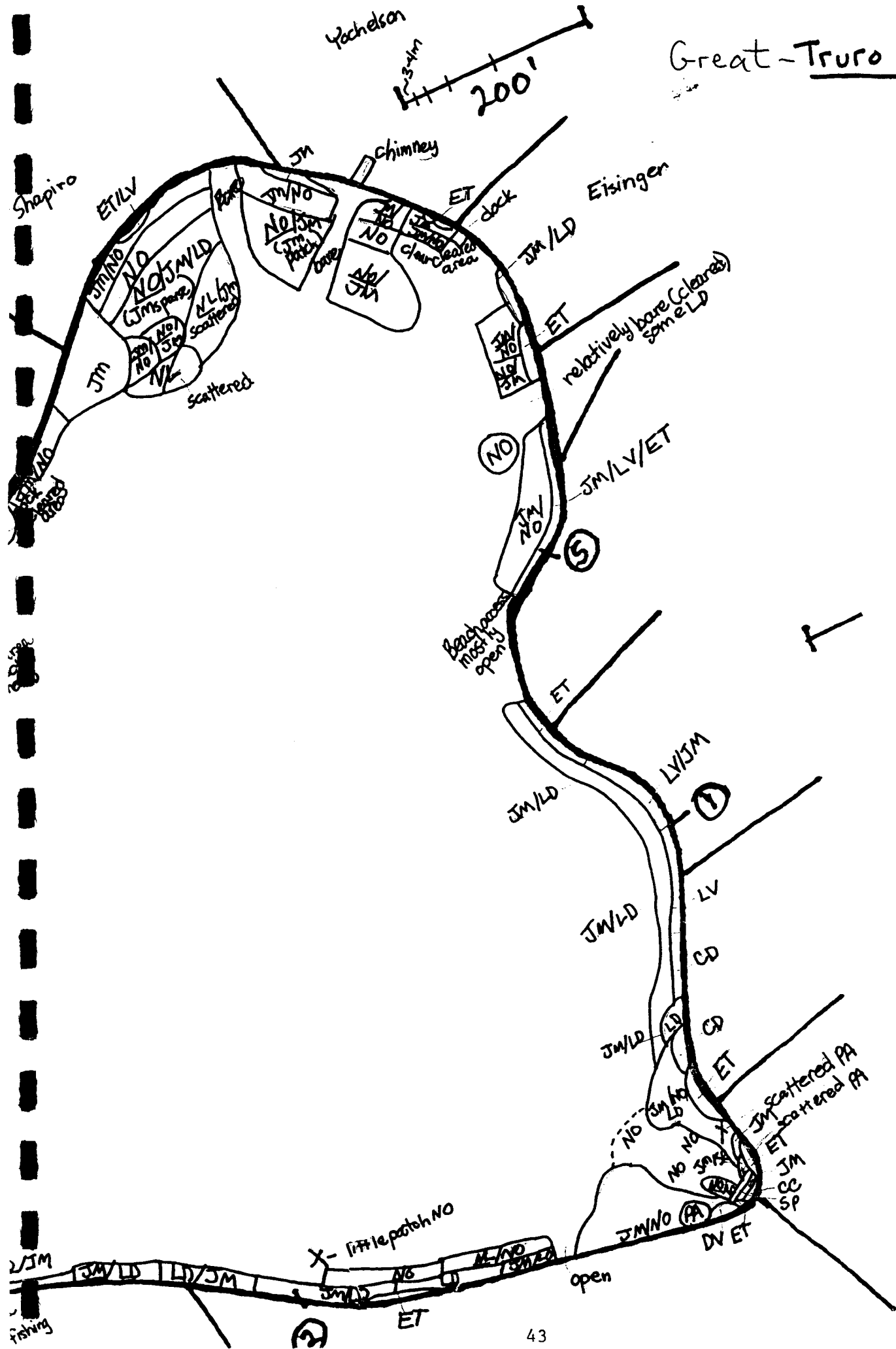
## Map 1

Key:

- 

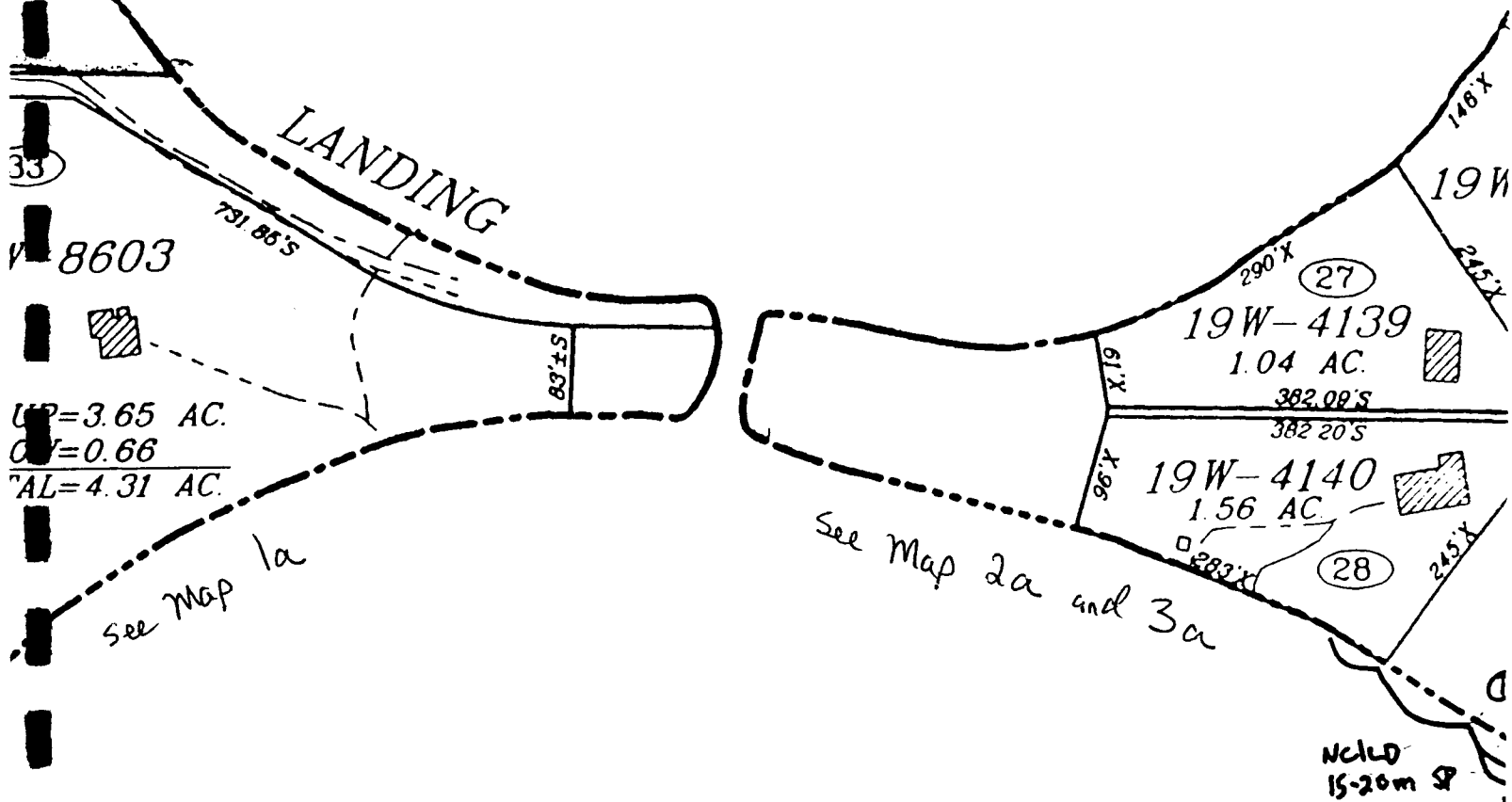


## Great-Truro Map 2





# Gull Pond Map 2

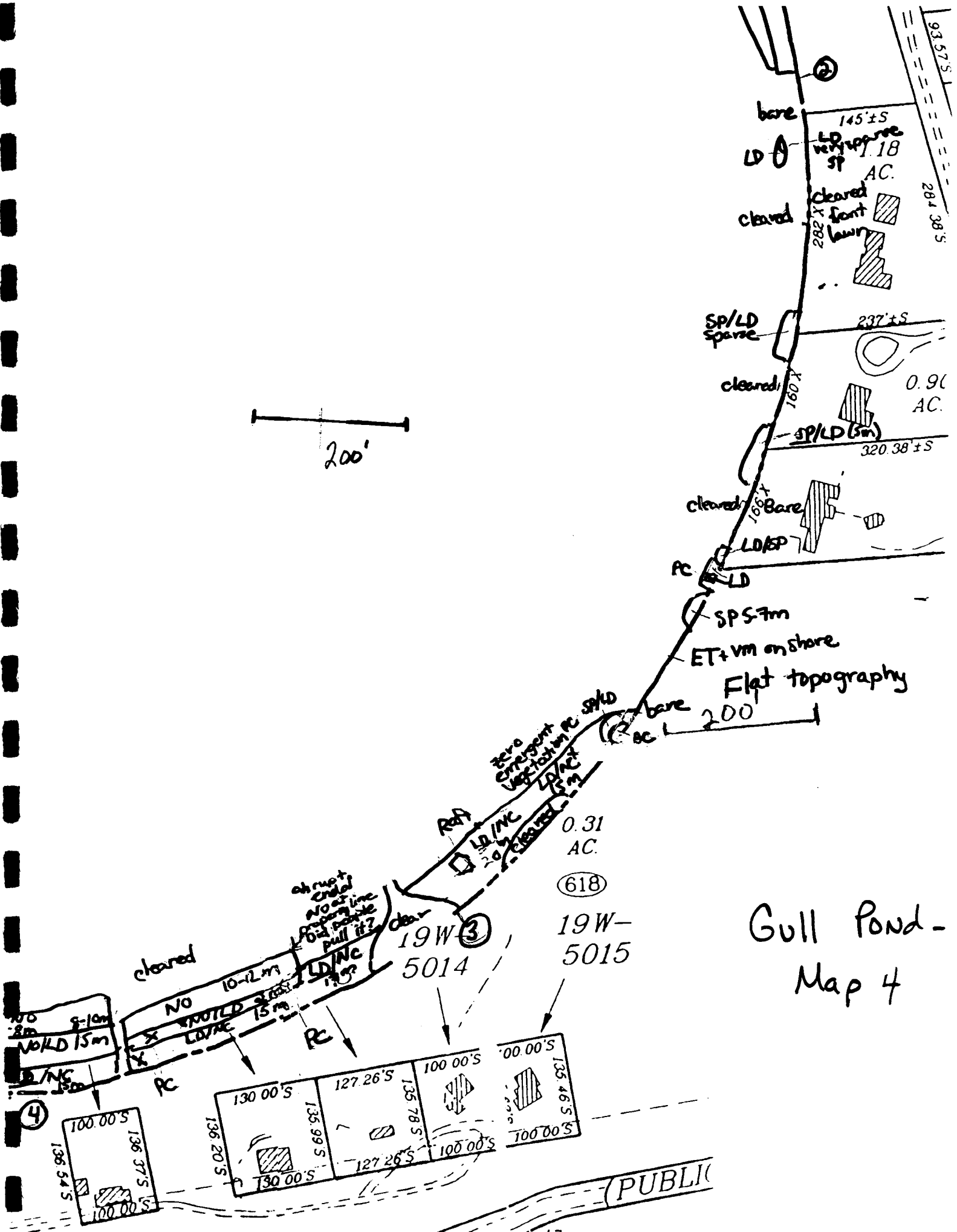


GULL POND  
(A GREAT POND)

200'



200'

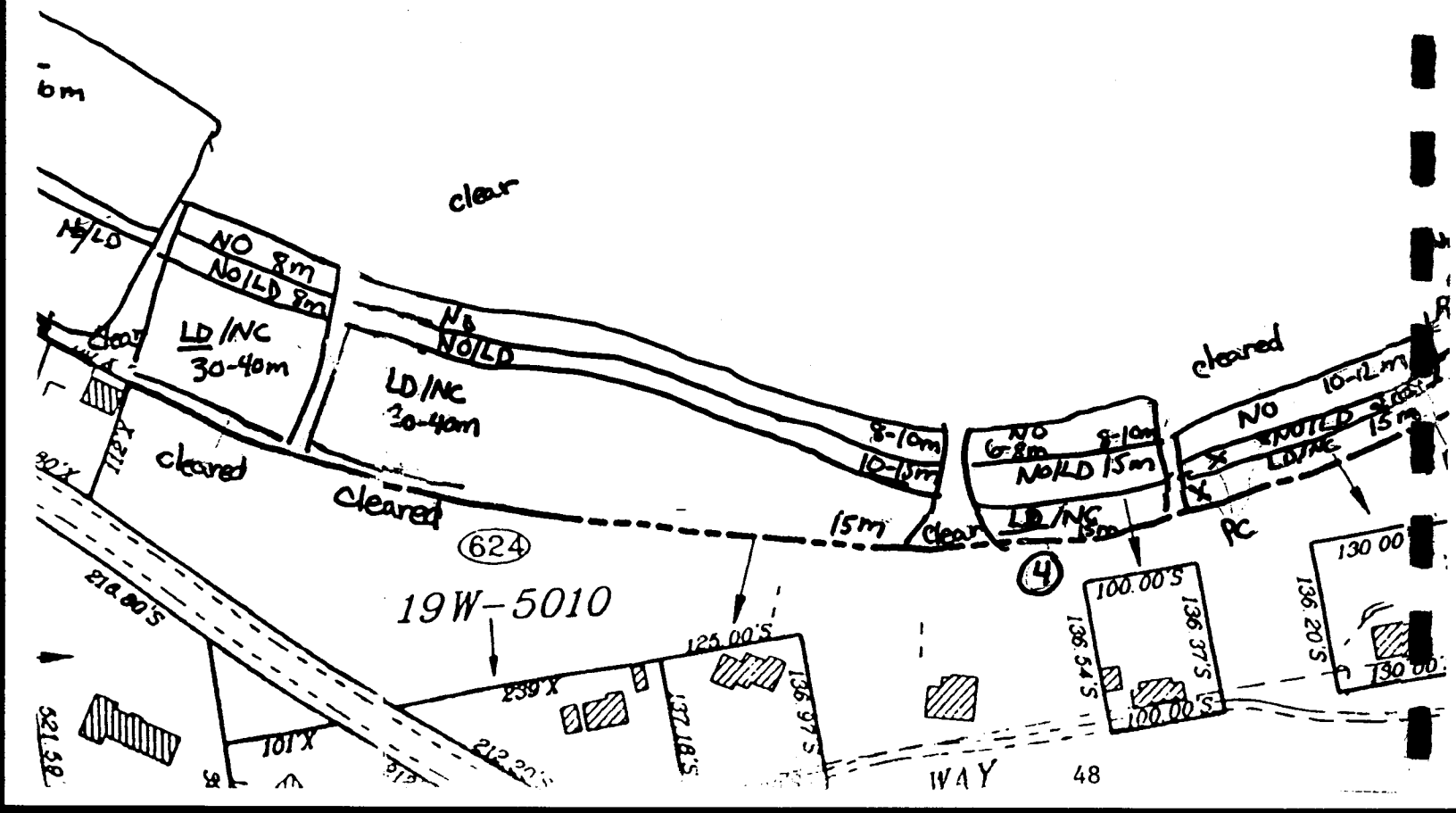


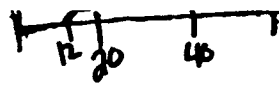
Gull Pond - Map 4

# GULL POND - Map 5

## (A GREAT POND)

200'





# Gull Pond Map 6

eroded trail  
comes down

ET/4D/SP

GA 1m

SP

250'x  
75'x

LD sparse  
5m

40m x 12m

LD  
LD

(637)

W-418

5.21 AC.

SP/PC/GA

Public Beach

Bare

Beach

(630)

new poles

1.78 AC.

19W-4189

640'x

(631)

19W-4191

1.43 AC.

368'x  
275'

(PUBLIC)

61m

LD/NC  
30-40m

X-No

PC/D

102'x

180'x

0.53 AC.

215'x

WAY

180'x

115'x

100'x

180'x

180'x

180'x

180'x

180'x

180'x

180'x

180'x

NO  
30-40m

LD/NC  
30-40m

NO/LO

NO 8m  
No/LO 8m

LD/NC  
30-40m

cleared

19W-5007

521.58'

101'

Higgins Pond



MA

GULL POND  
(A GREAT POND)

Filamentous green algae  
on LD throughout area

**Key:**

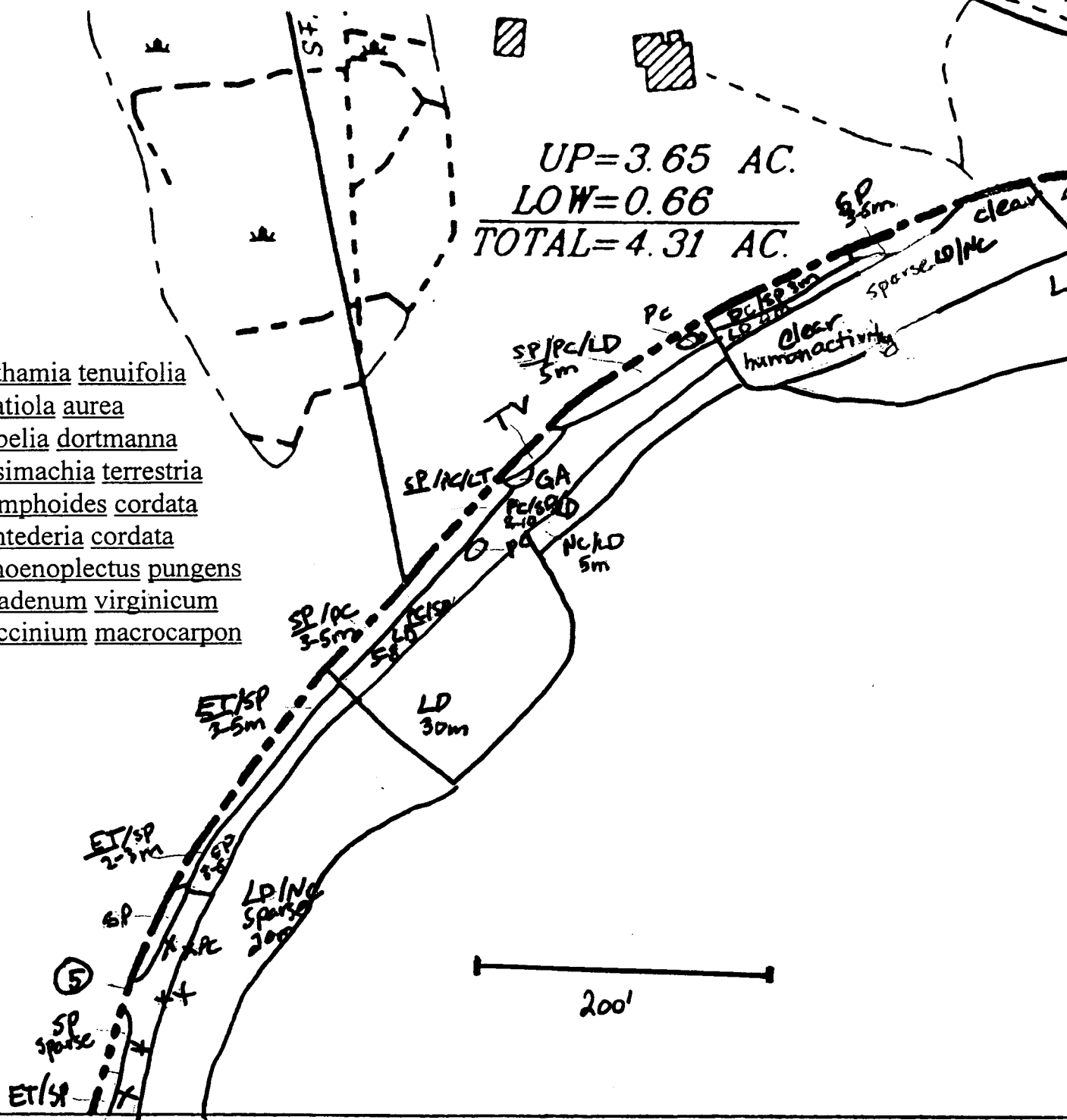
- |    |                               |
|----|-------------------------------|
| ET | <i>Euthamia tenuifolia</i>    |
| GA | <i>Gratiola aurea</i>         |
| LD | <i>Lobelia dortmanna</i>      |
| LT | <i>Lysimachia terrestris</i>  |
| NC | <i>Nymphoides cordata</i>     |
| PC | <i>Pontederia cordata</i>     |
| SP | <i>Schoenoplectus pungens</i> |
| TV | <i>Triadenum virginicum</i>   |
| VM | <i>Vaccinium macrocarpon</i>  |

# Gull Pond

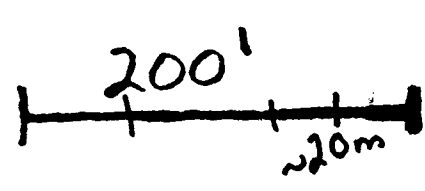
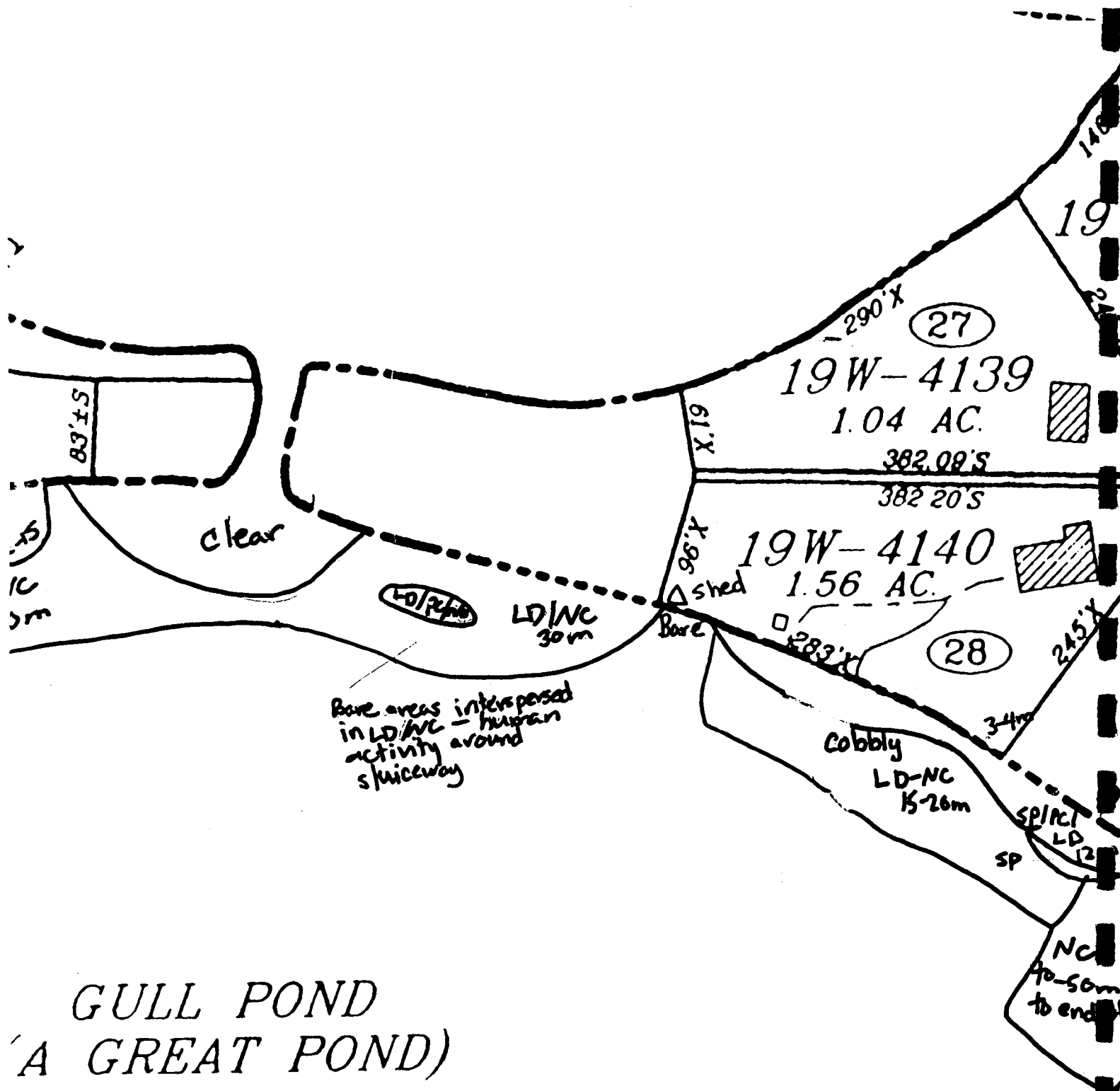
## Vegetation Survey, September 1996

Key:

ET Euthamia tenuifolia  
 GA Gratiola aurea  
 LD Lobelia dortmanna  
 LT Lysimachia terrestria  
 NC Nymphoides cordata  
 PC Pontederia cordata  
 SP Schoenoplectus pungens  
 TV Triadenum virginicum  
 VM Vaccinium macrocarpon



Gull Pond-Map 1a





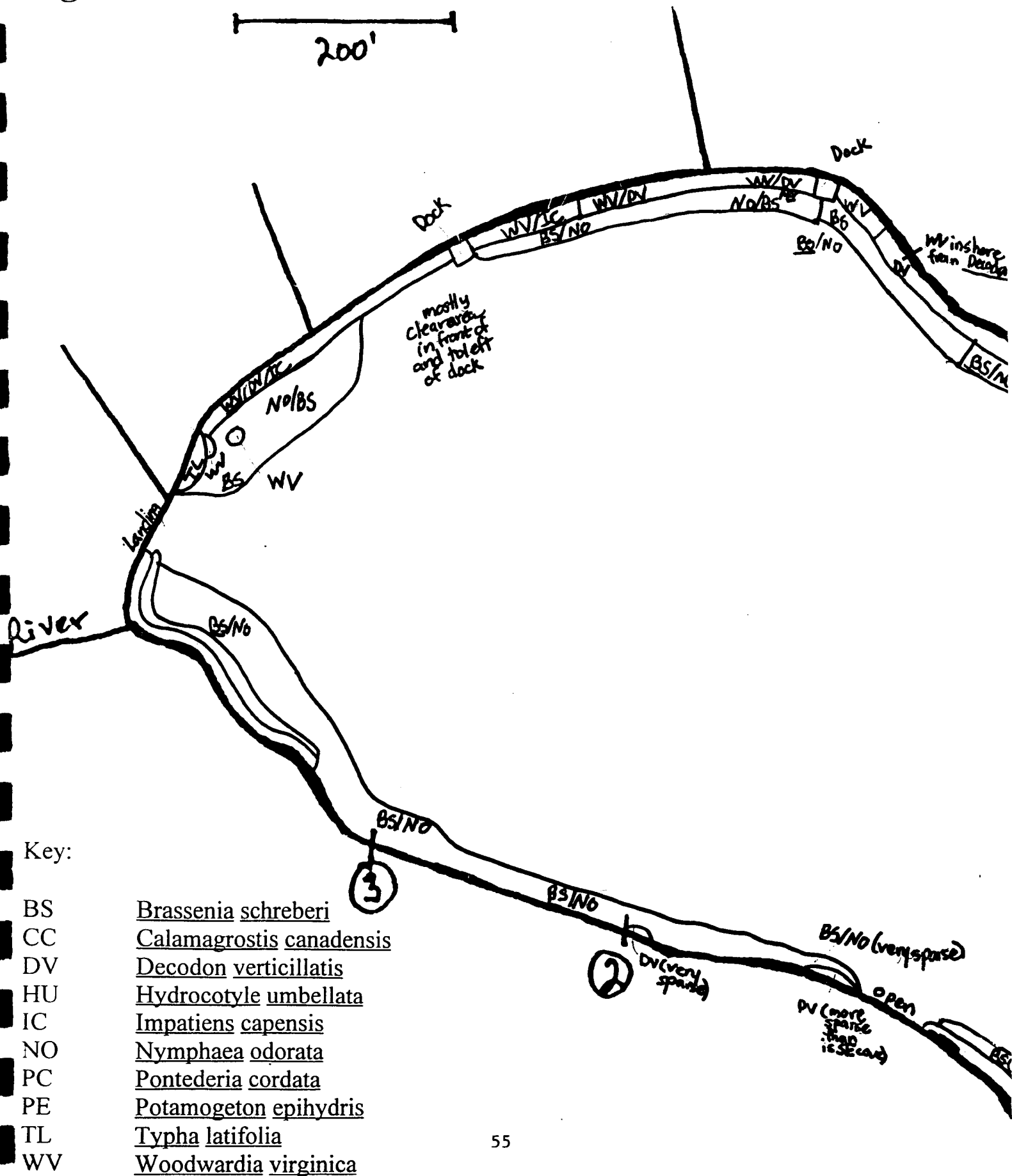


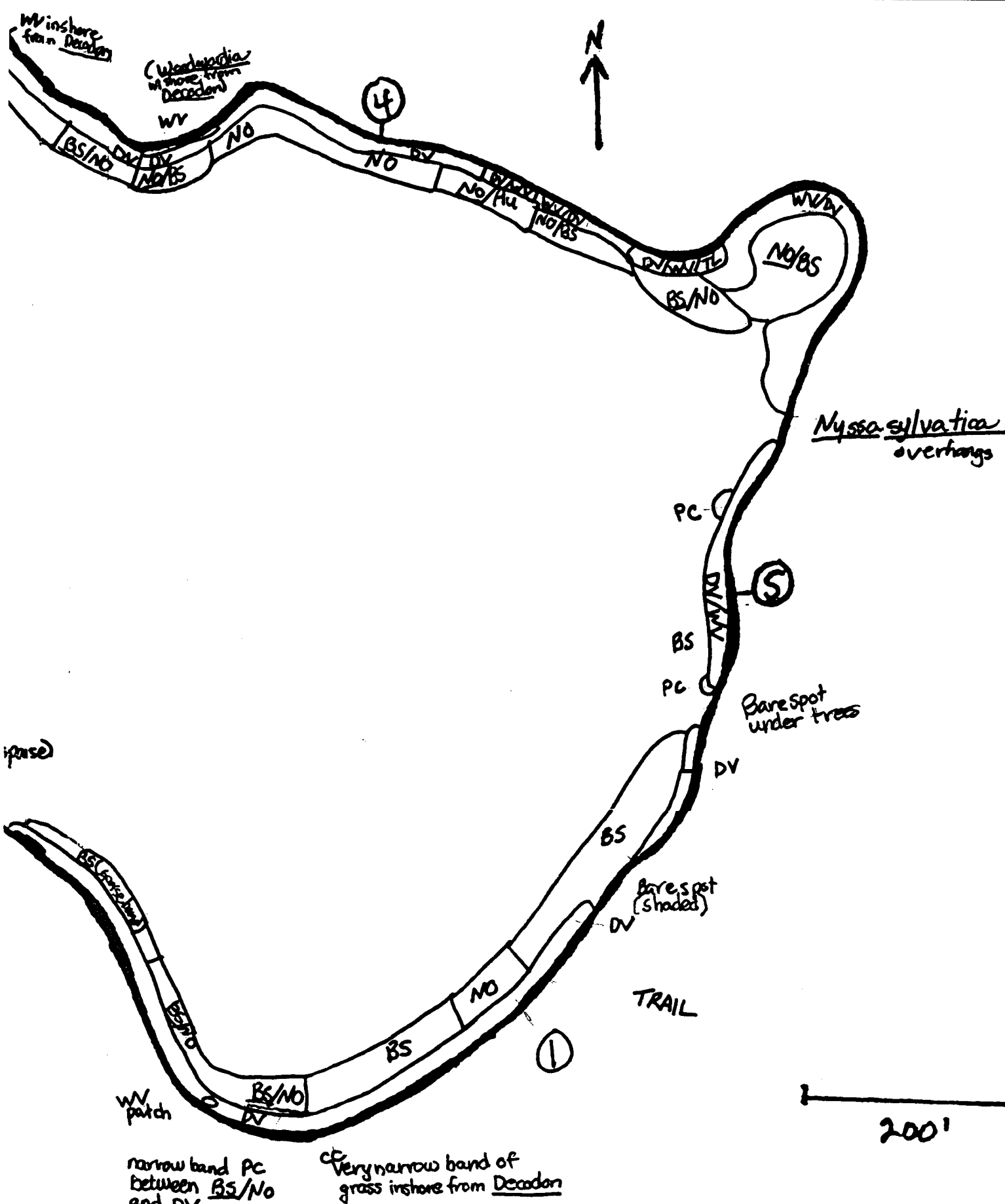
# Herring Pond, Cape Cod

## Vegetation Survey, September 1996

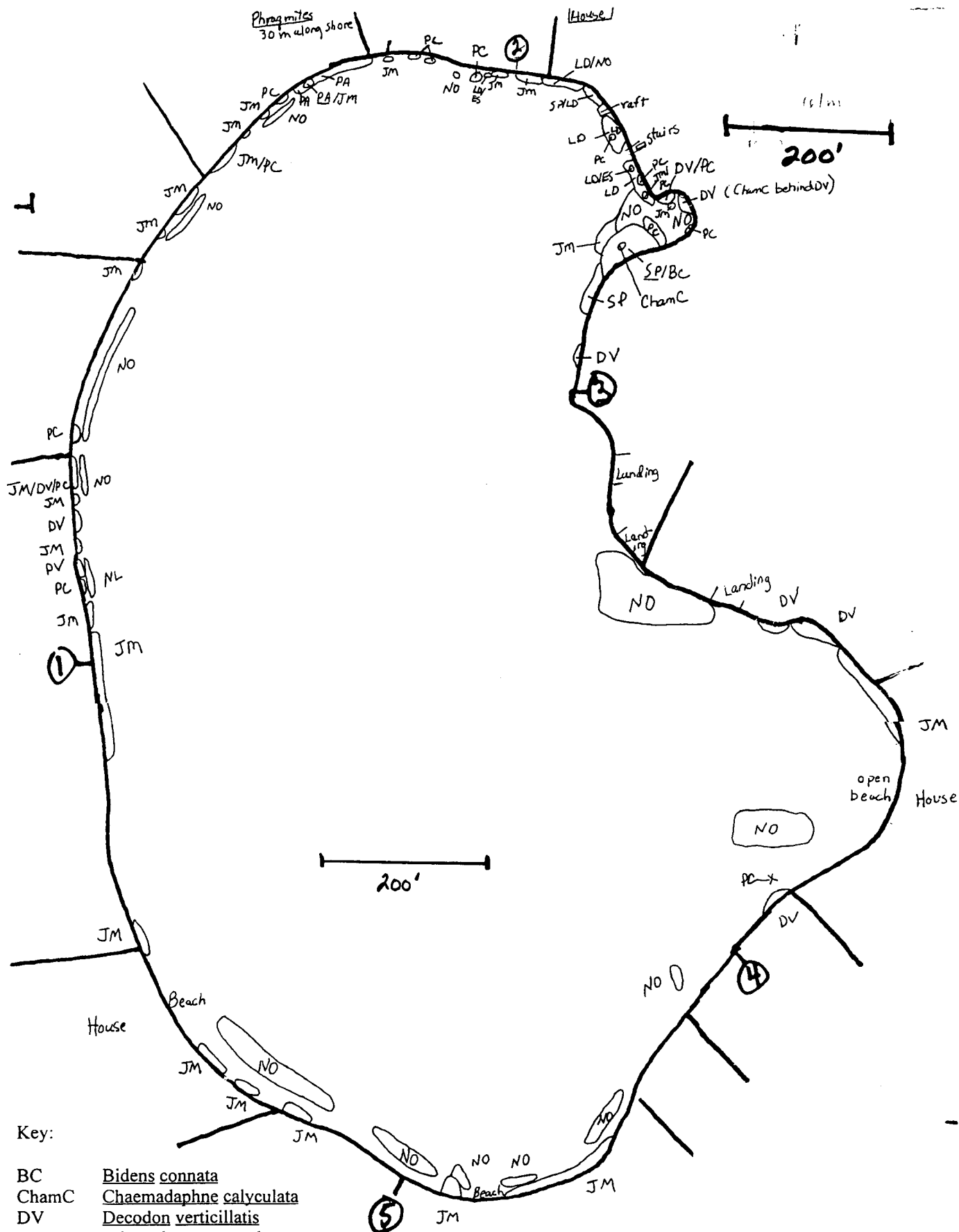
MAP #1

200'

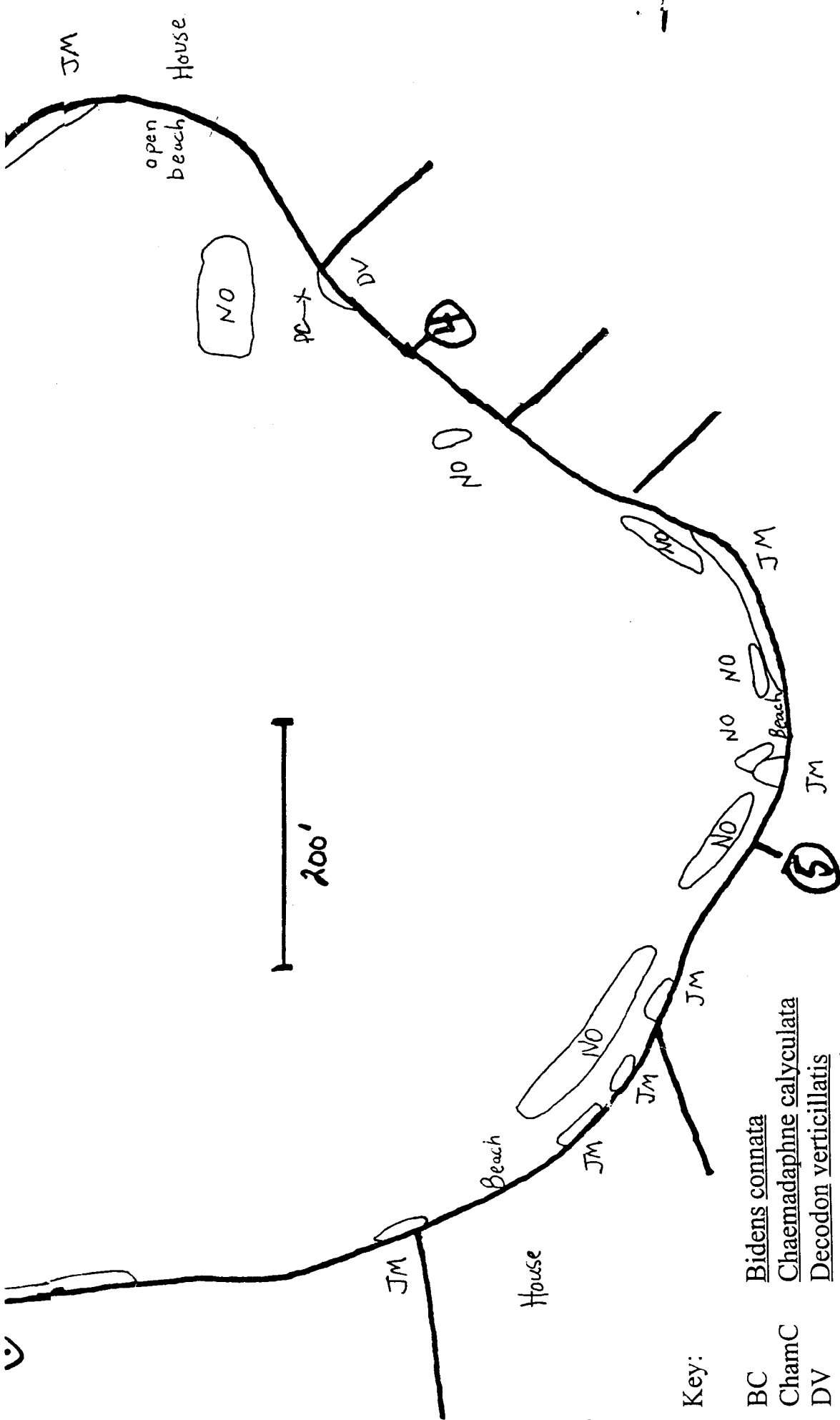




Herring Pond, Cape Cod  
MAP #2



# Ryder Pond, Truro Vegetation Survey, September 1996



# Ryder Pond, Truro Vegetation Survey, September 1996

Key:

- BC Bidens connata
- ChamC Chaemadaphne calyculata
- DV Decodon verticillatis
- ES Eriocaulon septangulare
- JM Juncus militaris
- LD Lobelia dortmanna
- NL Nuphar luteum
- NO Nymphaea odorata
- PA Phragmites australis
- PC Pontederia cordata
- SP Schoenoplectus pungens

2AP #2



# AREA STATISTICS FOR 1996 KETTLE POND VEGETATION MAPS

| SITE       | VEGETATION TYPE  | TOTAL AREA (m2) |
|------------|------------------|-----------------|
| Duck Pond  | CD               | 204.400         |
| Duck Pond  | EA               | 9.300           |
| Duck Pond  | EA/CD            | 315.900         |
| Duck Pond  | <u>EA</u> /CD    | 144.000         |
| Duck Pond  | ET/CD            | 18.600          |
| Duck Pond  | LD               | 102.200         |
| Great Pond | CC               | 46.500          |
| Great Pond | CD               | 97.500          |
| Great Pond | DV               | 13.900          |
| Great Pond | ET               | 357.700         |
| Great Pond | ET/LV            | 13.900          |
| Great Pond | JM               | 856.500         |
| Great Pond | JM/LD            | 970.800         |
| Great Pond | <u>JM</u> /LD    | 120.800         |
| Great Pond | JM/LV/ET         | 130.100         |
| Great Pond | JM/NO            | 1904.400        |
| Great Pond | <u>JM</u> /NO    | 1384.200        |
| Great Pond | JM/NO/LD         | 315.900         |
| Great Pond | JM/SP            | 18.600          |
| Great Pond | LD               | 139.400         |
| Great Pond | <u>LD</u> /JM    | 65.000          |
| Great Pond | LV               | 88.300          |
| Great Pond | LV/JM            | 102.200         |
| Great Pond | NL               | 622.400         |
| Great Pond | <u>NL</u> /JM    | 315.900         |
| Great Pond | <u>NL</u> /NO    | 148.600         |
| Great Pond | NO               | 1161.300        |
| Great Pond | <u>NO</u> /JM    | 1003.300        |
| Great Pond | <u>NO</u> /JM/LD | 511.000         |
| Great Pond | NO/LD            | 13.900          |
| Great Pond | <u>NO</u> /LD    | 46.500          |
| Great Pond | PA               | 41.800          |
| Great Pond | SP               | 18.600          |
| Gull Pond  | BC               | 19.600          |
| Gull Pond  | ET               | 29.400          |
| Gull Pond  | ET/LD/SP         | 58.800          |
| Gull Pond  | ET/LT            | 294.000         |
| Gull Pond  | ET/SP            | 67.580          |
| Gull Pond  | <u>ET</u> /SP    | 120.770         |
| Gull Pond  | GA               | 24.245          |
| Gull Pond  | LD               | 1692.905        |
| Gull Pond  | <u>LD</u> /NC    | 8696.390        |
| Gull Pond  | LD/NC            | 20343.160       |
| Gull Pond  | LD/PC/NC         | 92.900          |
| Gull Pond  | LD/SP            | 261.755         |
| Gull Pond  | LT               | 88.200          |
| Gull Pond  | NC               | 1725.680        |
| Gull Pond  | NO               | 5821.200        |
| Gull Pond  | NO/LD            | 2861.600        |
| Gull Pond  | <u>NO</u> /LD    | 303.800         |
| Gull Pond  | PC               | 72.950          |

# AREA STATISTICS FOR 1996 KETTLE POND VEGETATION MAPS

| SITE         | VEGETATION TYPE  | TOTAL AREA (m2) |
|--------------|------------------|-----------------|
| Gull Pond    | PC/LD            | 117.600         |
| Gull Pond    | <u>PC</u> /LD    | 323.400         |
| Gull Pond    | PC/SP            | 161.500         |
| Gull Pond    | <u>PC</u> /SP/LD | 798.940         |
| Gull Pond    | SP               | 1157.350        |
| Gull Pond    | <u>SP</u> /LD    | 127.400         |
| Gull Pond    | <u>SP</u> /PC    | 83.610          |
| Gull Pond    | SP/PC/GA         | 39.200          |
| Gull Pond    | <u>SP</u> /PC/LD | 1096.220        |
| Gull Pond    | TV               | 47.470          |
| Herring Pond | BS               | 1700.100        |
| Herring Pond | BS/NO            | 3167.900        |
| Herring Pond | <u>BS</u> /NO    | 817.500         |
| Herring Pond | DV               | 1500.300        |
| Herring Pond | <u>DV</u> /WV    | 46.500          |
| Herring Pond | DV/WV            | 1216.950        |
| Herring Pond | DV/WV/TL         | 92.900          |
| Herring Pond | NO               | 594.600         |
| Herring Pond | <u>NO</u> /BS    | 715.300         |
| Herring Pond | <u>NO</u> /HU    | 176.500         |
| Herring Pond | PC               | 34.400          |
| Herring Pond | TL               | 46.500          |
| Herring Pond | WV               | 127.300         |
| Herring Pond | <u>WV</u> /DV    | 79.000          |
| Herring Pond | <u>WV</u> /DV/IC | 297.300         |
| Herring Pond | WV/IC            | 111.500         |
| Ryder Pond   | Cham C           | 4.600           |
| Ryder Pond   | DV               | 145.900         |
| Ryder Pond   | DV/PC            | 9.300           |
| Ryder Pond   | JM               | 689.900         |
| Ryder Pond   | JM/DV/PC         | 23.200          |
| Ryder Pond   | LD               | 120.800         |
| Ryder Pond   | LD/ES            | 5.600           |
| Ryder Pond   | LD/NO            | 37.200          |
| Ryder Pond   | NL               | 27.900          |
| Ryder Pond   | NO               | 2170.100        |
| Ryder Pond   | PA               | 83.600          |
| Ryder Pond   | <u>PA</u> /JM    | 9.300           |
| Ryder Pond   | PC               | 100.300         |
| Ryder Pond   | SP               | 55.700          |
| Ryder Pond   | <u>SP</u> /BC    | 185.800         |
| Ryder Pond   | SP/LD            | 18.600          |

