KETTLE POND DATA ATLAS
FOR CAPE COD NATIONAL SEASHORE:
PALEOECOLOGY AND MODERN WATER CHEMISTRY

April 2001

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“The National Park Service cares for special places saved by the American people so that all can experience our heritage.”

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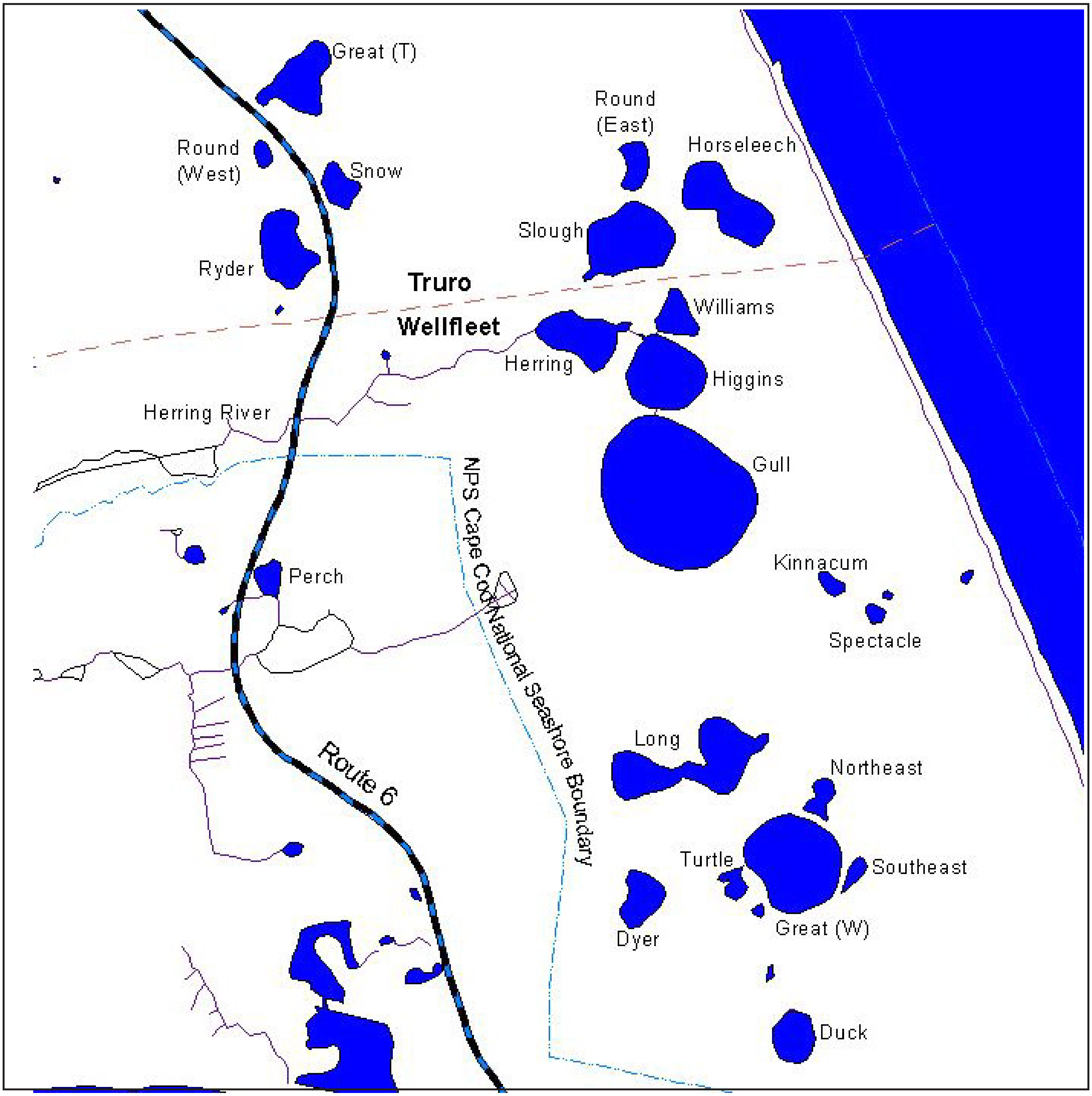

Figure 1-1. Kettle ponds of Cape Cod National Seashore included in this data atlas and report.

Chapter I. Introduction

Kettle Pond Environments

Twenty permanently flooded freshwater ponds (technically "lakes" [1]) occur within the pine-oak forested landscape of Cape Cod National Seashore (CCNS) in the townships of Wellfleet and Truro (Fig. 1-1). They range from one to 44 hectares (2.5 to 100 acres). Although all are within 2.5 km of the ocean and have been subjected to thousands of years of marine aerosol deposition (salt spray), they remain low in dissolved salts (conductivity < 150 µS/cm) (Table 1-1). The shallow-water (littoral) sediments of most ponds are a nearly white sand, reflecting the granite-based soils of the outer Cape peninsula.

The Seashore ponds range in trophic condition from oligotrophic, i.e. clear and nutrient-poor, to eutrophic, i.e. naturally or culturally enriched with nutrients and organic matter. Though all ponds have a similar developmental history, hydrogeology and limnology, each is unique. Together they provide a diversity of habitats for plant, animal and microbial communities, some of which are rare elsewhere in New England.

Clear, warm water and white sandy shorelines attract seasonal recreation and have encouraged summer home construction along the shoreline. Hundreds of people swim or sunbathe at the most accessible ponds during a typical summer day. Visitation is encouraged at several ponds by the Town of Wellfleet and CCNS, who provide parking areas and restrooms. Throughout the year, people fish the ponds from shore and from boats for both native and introduced species; ice-fishing and even skating is common during cold winters. Private homes, each with an on-site wastewater disposal system, border most of the ponds; in recent years occupancy has begun to extend beyond the traditional June to September summer season.

In addition to their value to native biodiversity and human recreation, the ponds represent an irreplaceable resource for researching the environmental history of outer Cape Cod and the northeast region. This is because kettle ponds not only <u>respond</u> to changes in the surrounding environment, but also <u>record</u> environmental changes occurring both within the water column and in the surrounding landscape. Kettle pond sediments are a systematically stratified repository for pollen, charcoal, algae and zooplankton remains and chemical substances. Sediment analyses have produced detailed chronologies of local post-glacial vegetation, fire history, and pond water chemistry, as well as regional trends in climate and atmospheric pollution (Winkler 1985a, 1988, 1997a).

Threats to Water Quality

Because of the scarcity of nutrients and base cations in local soils (granitic glacial outwash), most ponds are naturally clear (low phytoplankton biomass) and acidic with low pH-buffering capacity. These conditions make the ponds sensitive to anthropogenic loading of either nutrients (phosphorus and nitrogen) or mineral acids, as from acid deposition. Over the past few centuries of European settlement, and particularly over the past 100 years of industrialization, both local and regional land uses have drastically increased the delivery of nutrients, acidity and metals (see Fig. 2-17) to the ponds. As a local example, a growing proportion of the 5 million annual visitors to CCNS is now visiting the ponds. Because human use is usually accompanied by shoreline soil erosion and waste disposal, increased use may degrade those pond features, e.g. water clarity, attractive plants and animals, that people most value. It is clear that pond visitation and human use in general will have to be managed. Thus, important management concerns center on: 1) human activities and land uses that can increase nutrient loading, e.g. through residential wastewater disposal, swimmer use and shoreline soil erosion; and 2) atmospheric inputs of acids and metals.

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[1] Ponds are shallow and/or clear enough that light is sufficient to support plant growth along the bottom. The deepest sediments of true lakes receive so little light that vegetation cannot survive. It is a New England tradition to call lakes "ponds". We use these terms interchangeably here.

Besides nutrient loading, local cultural influences on water quality have included eighteenth and nineteenth century deforestation followed by forest regrowth, hydrologic changes, twentieth century fish stocking with exotic species, and liming to artificially neutralize the ponds' naturally acidic waters for exotic fish survival. Deforestation caused lake production and pH to increase, probably because of increased runoff of nutrients and base cations from shoreline soils. Conversely, forest regrowth has been followed by decreased pond production and pH, as indicated by sediment analyses, as more nutrients and base cations are captured by the upland vegetation and soils before leaching into the ponds (Winkler 1988). Hydrologic alterations, like the digging of channels to connect otherwise landlocked ponds to the sea, has increased access to anadromous fishes and, combined with the introduction of exotic species, probably altered pond trophic structure (Sanford 1993), i.e. the relative abundance and ecological role of organisms that comprise the food web. In this way the species composition, size distributions and biomass of the plankton community can be affected. Additions of agricultural limestone to acidic Cape ponds, though not always well documented, can cause major changes in plankton, invertebrates and fish (Stross & Hassler 1960, Kitchell & Kitchell 1980, Britt & Fraser 1983, Shortelle & Colburn 1986, Leavitt et al. 1989,).

Another factor impacting all of the Cape ponds is the recent increase in UV-β (ultra-violet-beta) radiation reaching the ponds (Schindler et al., 1996). The increase has been caused globally by depletion of the protective ozone layer in the atmosphere by human use of fluoro-chloro-carbons and polychlorinated compounds. In the pond biota, diatoms are the organisms most sensitive to UV-β radiation (Vinebrooke and Leavitt, 1999). In the more acid Seashore ponds, planktonic diatoms decrease and are replaced by littoral diatoms that grow on and among the aquatic vegetation in shallow waters. It is possible that the littoral diatoms that remain in the pond secrete heavy mucilaginous coatings which protect them somewhat from UV-β radiation (Winkler, 1997b). If this is true, this is an example of outside pollutants forcing large biotic replacements in lakes.

Although Cape Cod has little local industry, the ponds receive industrial pollutants that are transported by prevailing winds from a large area of the industrialized northeastern U.S. This fact, and the ponds' natural acidity, makes pond life vulnerable to toxic metals. Some metals, like aluminum and manganese, are naturally occurring in the Cape environment and can be leached from soils and sediments into pond water by high acidity. Other toxic metals like lead and mercury are transported in the atmosphere from distant sources. There is evidence of recent increases in both lead and mercury in kettle pond sediment (Chapter II, Winkler 1997b) and fish tissue (Haines 1999).

Report Objectives

Limnological and ecological research and water quality monitoring have long been appreciated as essential components of CCNS kettle pond management (Soukup 1977). The Cape ponds have also been a focal point for paleolimnologic investigations demonstrating the importance of climate, soils, vegetation and human activities on pond development and modern pond chemistry and biology (Winkler 1994, 1985a, 1988, 1994). Thus, CCNS kettle ponds have both a long history of water quality monitoring and an excellent paleoecological record that can be merged to explain current conditions and reveal water quality trends. It also can be used by land managers to assess the ponds' sensitivity and likely response to current and future disturbance.

This report summarizes both regional (outer Cape Cod) and pond-specific paleoecology, and then, with this post-glacial developmental background, presents a brief history of research and monitoring by the National Park Service (NPS) and others, describes pond water quality in a regional context, synthesizes and interprets recent water quality data for each of the 20 kettle ponds, recommends future monitoring and research, and discusses the management implications of monitoring results.

	Distance (r ocean	Max depth (m)	Area (ha)	Shoreline ʼ es	Public beach	pH	Alkalinity (uE	Conductivity	April Secchi m)	Color (Pt-Co units)
Duck (W)	1667	18	5.1	1	X	5.0	-12	95	15	0
Dyer	2154	10	4.8	3		4.9	-14	79	>10	0
Great (T)	1897	11	7	6		5.6	1	126	9.7	2
Great (W)	1282	16	17.8	8	X	4.9	-23	108	16	0
Gull	949	19	44.0	21	X	6.7	75	130	3.5	0
Herring	1154	4	8.1	2		6.6	75	130	3.2	7
Higgins	923	6	11.3	7		6.7	71	130	4.7	2
Horseleech	308	5	10.0	4		5.9	7	157	4.5	0
Kinnacum	769	2	0.8	1		5.0	-10	77	1.6	12
Long	1410	15	15.0	22	X	5.0	-12	85	8.3	0
Northeast	1179	4	1.7	3		5.1	-6	96	3.4	5
Round (east)	718	8	2.6	1		5.4	-1	121	7.3	0
Round (west)	2410	9	0.8	0		5.0	-12	65	7.3	0
Ryder	2384	10	8.3	7		4.7	-26	131	6.6	0
Slough	795	8	11.9	9		5.1	-9	119	6	0
Snow	2102	8	2.3	0	X	5.6	-1	82	4.2	14
Southeast	1231	4	1.1	1		5.4	4	95	3.3	10
Spectacle	641	7	0.5	0		5.1	-5	128	6.2	0
Turtle	1846	2	1.6	2		4.6	-30	94	>1.3	5
Williams	846	2	3.6	3		6.0	16	134	>1.5	14

Table 1-1. Some general characteristics of Cape Cod National Seashore kettle ponds. Data are from surface samples from April 1999.

Chapter II. Geologic Origins and Paleoecology

All of the Seashore ponds are set in non-calcareous, granitic, coarse outwash sands deposited about 17,000 to 14,000 years ago during the retreat of the last glacial (Laurentide) ice sheet to cover North America. All occupy depressions in the outwash sands left by stagnant ice blocks that were left behind as the glacier receded. Despite their common glacial origin, their subsequent evolution has differed depending on: the depth of the original ice block; the clay content of outwash in their drainage basins; and their topographic position relative to landscape changes caused by sea-level rise, barrier beach formation, and salt marsh development. Some of the ponds are presently connected to the sea, a feature that greatly changed their limnology in comparison to completely land-locked ponds.

In order to study the history of the kettle ponds, sediment cores taken from the deepest basins have been radiocarbon-dated, chemically analyzed, and microscopically examined for pollen, diatoms and other algae, cladocera (crustacean water fleas), and charcoal. Microscopic remains and chemical changes document environmental changes to both the pond and its watershed, throughout the life of the pond. By comparing sediment cores among ponds, we find ponds with similar histories and also discover ponds that have a unique past.

Geologic Setting

The French scientist Louis Agassiz demonstrated in 1840 that there was evidence for ice ages and ice sheets in northern Europe; he then came to North America to look for similar evidence. By 1846 it was clear to him that most of the southern New England and Cape Cod landscape, as well as the present topography of the northern part of North America, was shaped by the activity of glacial ice (Shelton 1966). The glacial history of coastal New England includes climate warming, ice sheet retreat, rebound of the land as the ice melted, and sea level changes. Current models of movements of the Laurentide ice sheet suggest that ice overran New England and terminated south of Cape Cod on Long Island and on the continental shelf between Cape Cod and Nova Scotia (Denton and Hughes 1981, Dyke and Prest 1987). Thickness of the ice at glacial maximum was over 1700 m (5600 feet); both the White Mountains in New Hampshire and Mt. Katahdin in Maine were entirely covered. The coastal morainal belt (Martha’s Vineyard, Nantucket, and Long Island) represents the maximum extent of the glacial ice in the northeast laid down sometime between 26,000 and 21,000 years before present (yr B. P.). Moraines forming the Cape Cod mainland were deposited north of this belt after 17,000 yr B. P. These moraines are ridges of granitic glacial till from which material eroded to form the sandy outwash plains of the lower Cape (Strahler 1966, Oldale 1968, 1992). The Wellfleet, and Truro outwash plains were deposited by meltwater streams from the South Channel Lobe of the ice sheet and slope to the west. Ice plates and blocks that remained in outwash as the ice sheet retreated subsequently melted leaving hollows and ponds (collapse features) and sandy ridges. These outwash plains are “pitted” by the collapse features and have an undulating “knob and kettle” topography today. Hollows that were underlain by coarse sands and gravel are presently either dry or contain peatlands, while hollows underlain by clay-rich sands contain the kettle ponds. The outwash plains are broken by valleys formed by larger meltwater streams that drained from the moraines. These valleys are called pamets or hanging valleys because the valley heads to the east have been eroded by sea-level rise (Strahler 1966). While the lower Cape was forming, much windblown silt and fine sand covered till, meltwater-borne sands and gravels, and parts of the ice itself (Cameron 1976). Plants adapted to cold exposed conditions, high winds, and drought colonized the raw deposits. Debris layers found at the bottom of sediment cores from Duck Pond in Wellfleet (hereafter DuckW) and Great Pond in Truro (GreatT) are evidence of the first vegetation after deglaciation more than 12,000 years ago (Winkler 1985a, 1989). The time of the most recent major interglacial warming is the Holocene epoch dating from 10,500 yr B. P. to the present day.

Sea level during late glacial time (older than 10,500 yr B. P.) was much lower than at present. At the glacial maximum, the sea was between 117 meters (384 feet) (Strahler 1966; Denton and Hughes 1981) and 90 meters (295 feet) (Dyke and Prest 1987) below its current level. Much more of the earth's water was then tied up in ice and snow. Large coastal plains exposed by lowered sea level provided land south of the glacier for colonization by vegetation. Forests of spruce and jack pine covered these coastal shelves (Watts 1979, Maxwell and Davis 1972, Sirkin et al. 1977) and provided a ready seed source for rapid colonization of land that became available as the glacier retreated.

The burden of ice depressed the land surface under the glacier. When the ice melted, the land surface rebounded at the same time that sea level rose. Thus, the local rate of sea level rise depended upon the rate of melting of the ice, the slope of the land and the balance between concurrent land uplift and sea-level rise. Dyke and Prest (1987) indicate that sea level was about 35 meters (115 feet) below current levels between 11,000 and 8400 years ago and 15 meters (49 feet) below current levels by 5000 years ago.

The Seashore kettle ponds have been found to differ in their evolution, reflecting local differences in geologic history. Those that date from the late-glacial, prior to 9500 yr B.P. (Group I ponds, Fig. 2-1) have continuous sediment deposition (Winkler and Sanford 1995). Group II ponds (Fig. 2-1) formed in the middle Holocene (after 5000 yr B. P.) when the freshwater lens was pushed upward by sea-level rise to intersect the ponds' previously dry kettle holes.

Paleoecology as a Tool for Study of Seashore Kettle Ponds

Study of the development of the Seashore ponds was initiated because modern environmental problems such as acid precipitation, toxic atmospheric deposition, trophic (nutrient) enrichment leading to eutrophication, and pollution of ground and surface waters have degraded freshwater systems throughout the world. To know how the Seashore ponds have responded to local and regional environmental impacts, it is important to compare recent changes in the ponds with past (pre-European settlement) changes. In the absence of historical records, only paleoecological study of lake sediment cores can provide this long-term perspective. The goals of the paleohistoric investigation of the kettle ponds were: 1) to document evolutionary changes in the ponds and in the uplands around the ponds; 2) to provide evidence for local and regional changes within the ponds in the years since European settlement (about 360 years ago on the lower Cape); and 3) to determine the direction and rate of recent chemical and biological changes in the ponds in the context of local and regional environmental change throughout their development.

Lake sediment deposited since deglaciation provides an anoxic, water-logged environment in which fossils such as pollen, charcoal, algae (diatoms), and zooplankton (cladocera), are so well-preserved that they can be separated and concentrated from the sediment by laboratory chemical and mechanical procedures and identified and quantified by microscopic examination. The pollen and charcoal analyses provide evidence of vegetation, fire disturbance, water level and other climatic change on the outer Cape since deglaciation, while diatom and cladocera analyses provide evidence of within-lake changes in lake morphometry, pH, salinity, trophic state, etc. over time.

Lake sediment chemistry measures several processes. Organic and inorganic sediment loads (analyzed by LOI, loss-on-ignition) indicate changes in the uplands. High inorganic deposition suggests erosional events while high organic sediment accumulation indicates nutrient increases. Increased metal and nutrient concentrations in the top sediments of the cores indicate recent changes in surface runoff and in atmospheric deposition to a pond. Other chemical analytic techniques, such as mass spectrometry of stable carbon isotopes in both bulk lake sediment and in charcoal isolated from lake sediment, identify the source of carbon in the analyzed sample. This technique can separate freshwater marsh from salt marsh sediments using the fact that most upland trees and herbs are C3 plants while some saltmarsh grasses are C4 plants. C3 and C4 plants utilize different metabolic pathways for photosynthesis and have

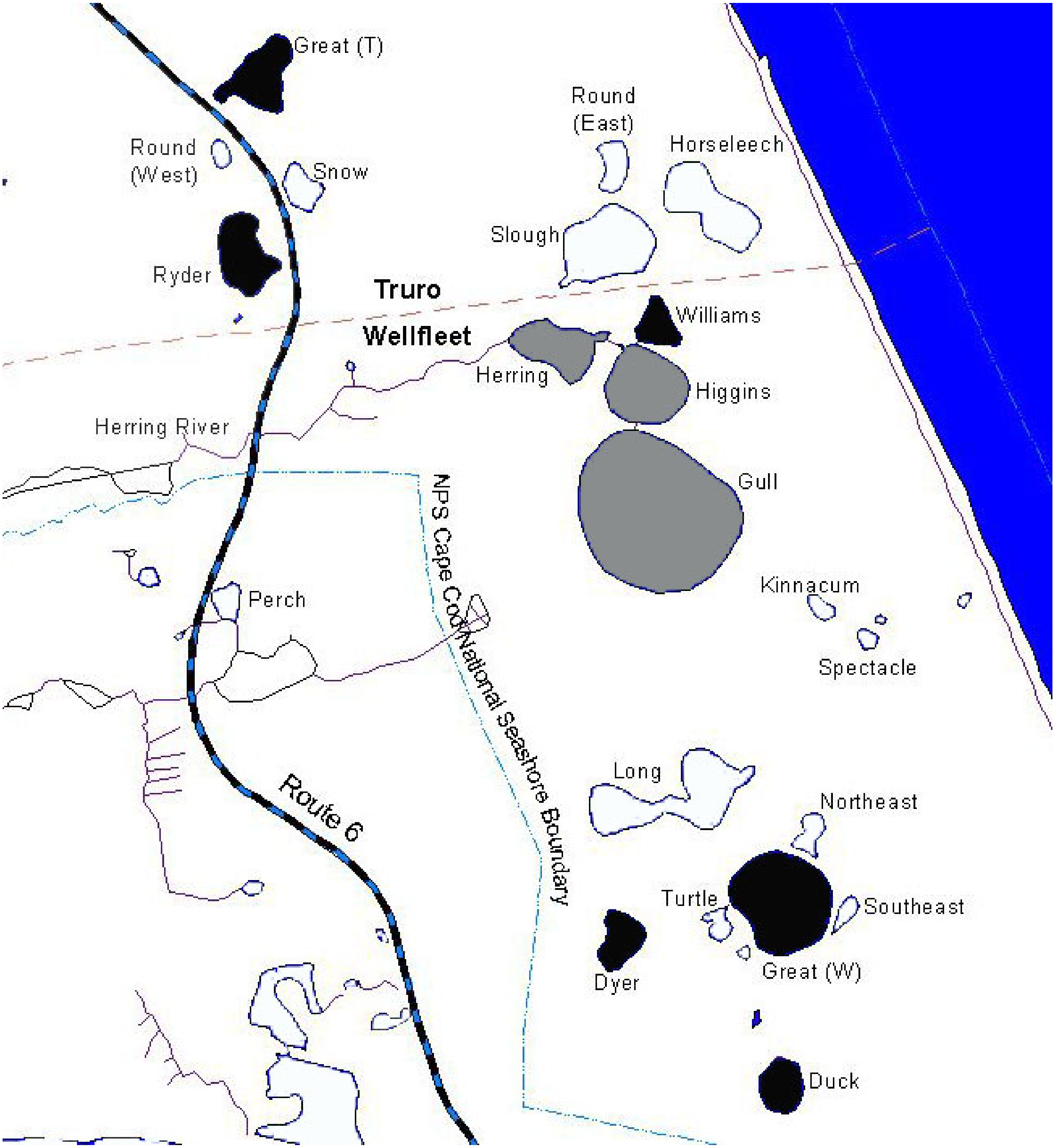

Figure 2-1. Map of the Wellfleet-Truro kettle ponds that have been cored for paleoecological study. Older ponds (Group I, see text) are shaded black; younger ponds of the Gull Pond and Herring River system (Group II) are shaded gray. Long and Snow Pond have some paleoecological data but complete cores have not been taken; other unshaded ponds have not been cored.

C4 plants can inhabit extreme environments: arid prairies, tropical deserts, and saline marshes while the trees and herbs most familiar to us in our temperate environment are generally C3 plants. The stable isotope signatures of these two classes of plants are recognizably different by mass spectrometric analysis. Changes within the lake, mediated by changing chemistry and/or food webs, are interpreted from the expansion, decline, or replacement of species of planktonic (deepwater) or littoral (shallow-water dwelling) organisms including diatoms, cladocera, dinoflagellates, and others.

In order to determine the temporal relationship among the ponds, a chronology was constructed. Radiocarbon-dating of bulk lake sediments and/or Accelerator Mass Spectrometric radiocarbon-dating (AMS) of smaller sediment samples or discrete objects (seeds, wood, or charcoal fragments isolated from the sediment), are used to provide dates for the initiation of lake sediment deposition in a pond and for inter-stratigraphic comparison. Radiocarbon dates are reported as yr B. P. (years before present, by convention “present” is 1950 A.D.). To obtain a chronology for the last 150 years two pond sediment cores were radiometrically-dated using the ^{210}Pb isotope technique.

Sediment Cores and Sedimentation Rates

We obtained cores of kettle pond sediment using a hand-operated piston core rig set up on a raft anchored over the deepest part of each of the ponds. Cores of the typically highly organic lake mud (gyttja, see below) were retrieved meter by meter until resistant sediments such as dense sand or clay was reached and hand-driven core retrieval was no longer possible. These latter deposits represent the original post-glacial soil surface. The depth of lake sediment found in each pond varied (Fig. 2-2). Some ponds, such as Dyer and Great ponds in Wellfleet (GreatW) contained close to 7 meters of organic lake sediment, while other ponds such as Great Pond in Truro (GreatT) and Duck Pond in Wellfleet (DuckW) contained only 4 meters of organic lake sediment. All of the ponds in the Herring River basin in Wellfleet (Gull, Higgins, and Herring) held less than 3 meters of sediment; below this depth sands and gravels interfered with the coring procedure.

In 1997, short cores for a eutrophication study were obtained from the east basin of Long Pond and from the deepest part of Snow Pond. The sediments of Long and Snow ponds were dated by ^{210}Pb to provide time control for the last 150 years. The basal sediments of the short cores from Snow and Long ponds were also AMS radiocarbon-dated to provide a chronology for the truncated stratigraphies (6000 +/- 50 yr B. P. for Snow Pond and 2550 +/- 45 yr B. P. for Long Pond). Therefore we have some mid- to late Holocene information about these two ponds, but no data about their initiation.

Upon retrieval of the cores, sediment differences indicating differences in pond development were immediately apparent. Both sediment depth and gross appearance differed substantially from pond to pond. There was continuously deposited dark gyttja (highly organic lake sediment containing mainly the detritus of within-lake organisms) in the cores from DuckW, Dyer, GreatT, and Williams ponds, while deposition of gyttja was interrupted by lenses of sand and gravel in Gull, Higgins, Herring, and Ryder Ponds (Fig. 2-2). The radiocarbon dates of the bottom sediments of these ponds supported the sediment findings and documented the fact that DuckW, DyerW, GreatT, GreatW, and probably Williams were indeed kettle ponds dating from deglaciation of the Cape about 14,000 yr B. P. (Group I ponds). The GreatW sediment core differed from the others because the lowest organic sediment (older than 11,670 +/- 100 yr B. P.) consisted of 24 cm of iron crust that was dark black when retrieved from the pond and turned red and friable upon oxidation soon after. Above the crust was about 60 cm of mottled reddish-yellow and gray sediment. These complex layers contained no diatoms and about 30% organic matter (by LOI). These findings suggest a bog origin for GreatW. Gull, Higgins, and Herring were much younger and therefore had different geomorphic and/or climatic origins (Group II ponds) (Fig. 2-2). Snow Pond had a bog origin like GreatW, but is much younger and is therefore a unique pond that will be discussed separately.

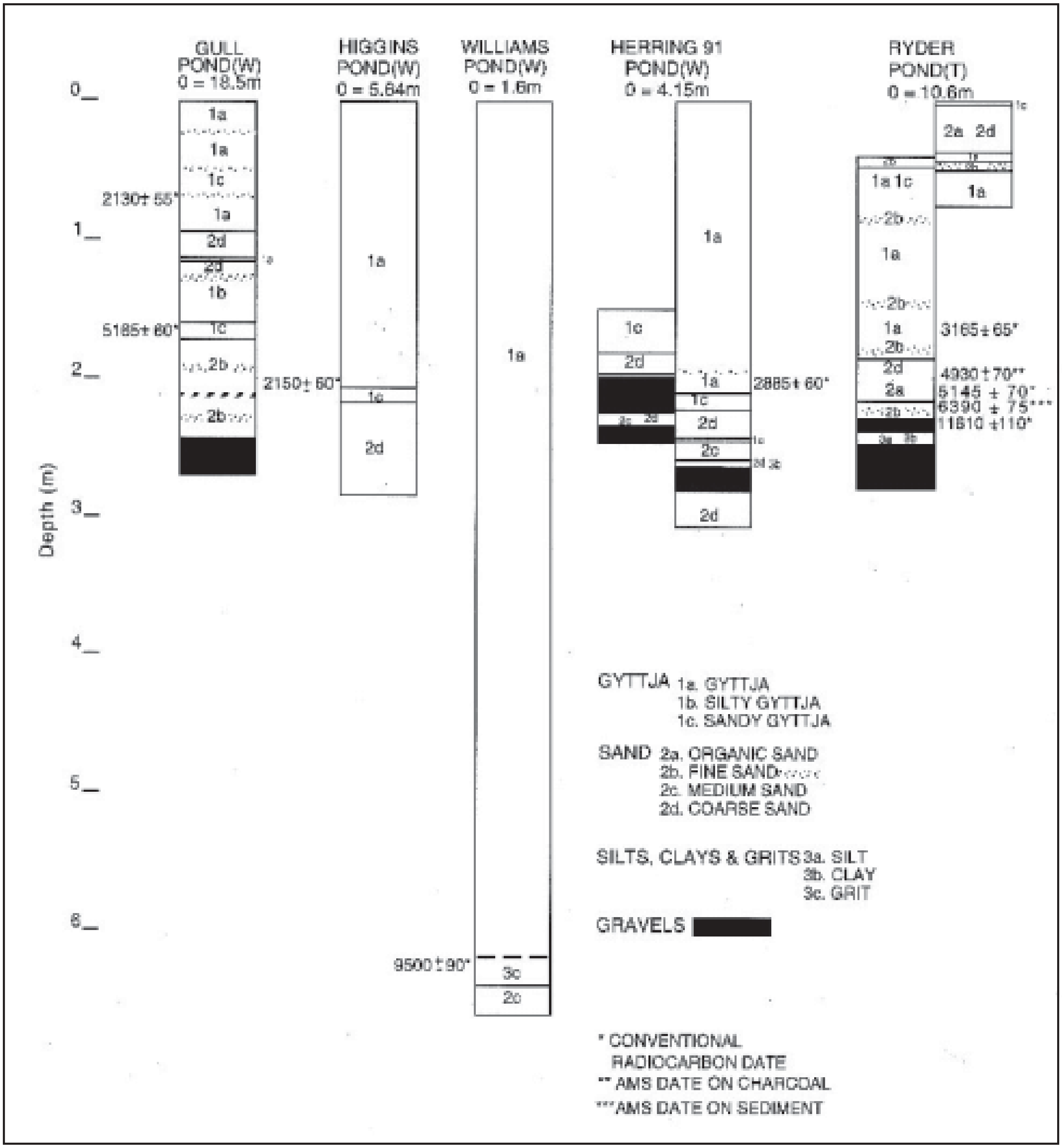

Figure 2-2. Sediment stratigraphy, radiocarbon (yr B.P.) and 210Pb (A.D.) dates, for the pond sediment cores referred to in this chapter. Note depth scale change from meters to centimeters for Snow and Long ponds. Refer to legend (1a., 1b., etc.) for sediment type changes. W = Wellfleet, T = Truro.

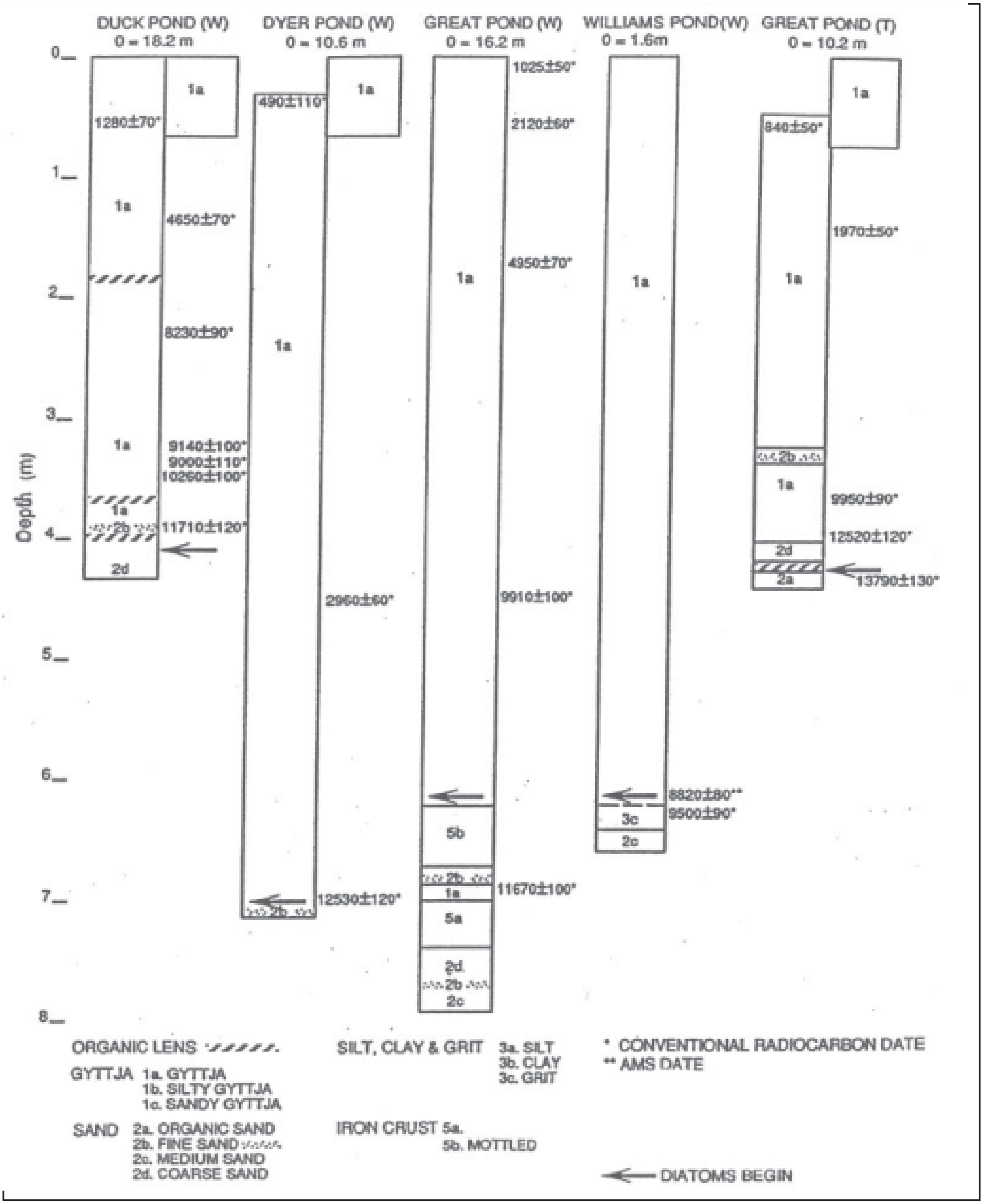

Fig. 2-2 continued

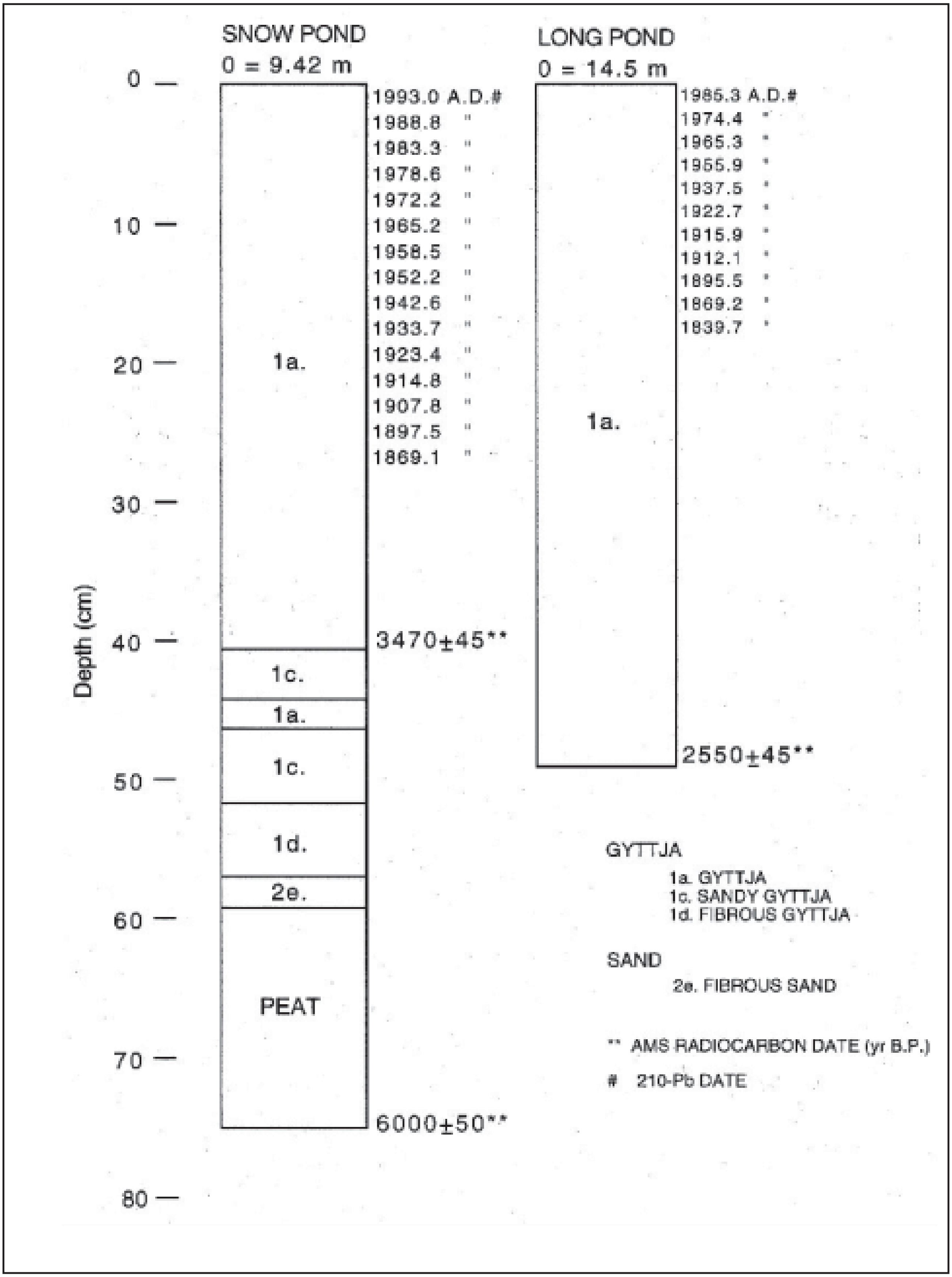

Fig. 2-2 continued

Regional Vegetation Changes Since Deglaciation

The most complete reconstruction of the vegetation and climate history of the Outer Cape is derived from study of pollen in pond sediments dating from deglaciation of the Outer Cape (Group I ponds). Pollen from many different species of plants is windborne to the ponds. It is abundant in the sediments and well preserved by the anoxic environment of the wet bottom muds. The pollen of different species of plants is distinctly different (Fig. 2-3a); identification of the relative abundance of pollen types in space and time provides a history of ancient vegetation.

From pollen and charcoal analyses of DuckW, Dyer, and GreatT sediments we have obtained a record of the changes in Cape Cod vegetation from 14,000 yr B. P. (Figs. 2-3b and 3c). Before 12,000 yr B. P. the earliest pollen assemblages in the pond sediments indicate tundra, *Hudsonia* (poverty grass), and spruce-willow parklands. In addition to pollen evidence, “trash” layers were found at the bottom of the sediment cores from both DuckW and GreatT. This litter, consisting of twigs, leaves, seeds, mosses, insect remains, and bits of aquatic vegetation, is thought to be evidence for the persistence of stagnant ice blocks and the vegetation that grew on them before they melted to form kettle lakes (Florin and Wright 1969). The litter from Duck Pond contained aquatic mosses and fruits of cattail, sedges, *Potentilla*, and *Epilobium*, suggesting a cold tundra environment with shallow meltwater pools (Winkler 1985a). The litter layer found in the GreatT core broadened the picture of the late-glacial environment on the Cape (Winkler and Sanford 1995). There were several very small twigs from a dwarf willow, one with an intact bud and several with *in situ* scale insects, black spruce needles, *Najas* seeds and many *Nitella* oospores (Fig. 2-4). Cattail seeds were also found, as were seeds of St. John’s-wort *(Hypericum* spp.). The upland vegetation at the time was dominated by an arctic species of scrub willow and by spruce trees. In this parkland also grew tundra herbs, *Lycopodium* (ground pines), and mosses. These sediments also contained pollen from *Littorella*, a wetland plant that grows today on sandy and gravelly shorelines of lakes above latitude 45° N (e.g. northern Maine). The pollen, algae, and plant litter evidence in these Group I late-glacial ponds indicate that they were relatively shallow, nutrient-rich, and species-poor.

As the climate warmed somewhat and the ice blocks melted to form ponds and/or dry hollows, the spruce-parkland was replaced by a boreal forest of spruce, jack pine, and green alder between 12,000 and 10,500 yr B. P. There was initiation, expansion, and retreat of heathlands between 11,000 and 10,000 yr B. P. and, as fires began to sweep the landscape more frequently, the development of a northern conifer forest of jack pine and white pine between 10,500 and 9000 yr B.P.

After 9000 yr B. P. the Cape oak and pitch pine barrens vegetation was established. This vegetation assemblage is typical of the Cape today. The Cape shrubs and herbs such as bayberry, sweet gale, sweetfern, winterberry holly, and rose species, increased between 9000 and 5000 yr B. P. and the Cape heathlands that had been abundant before about 9,500 yr B. P. decreased dramatically. At this time white pine became the dominant tree on the Outer Cape while the boreal trees and shrubs—spruce, fir, green alder, and jack pine—disappeared. In the next 500 years, pitch pine replaced jack pine, and beech, hemlock, and oak appeared. Maple, ironwood, and other hardwoods grew in moist hollows. Abundant microscopic charcoal in the sediment (Winkler 1997a) and the changes in diatom composition and in other sediment characteristics indicate lowered freshwater levels between 9000 and 5000 yr B. P. caused by decreased precipitation on the Atlantic coastal plain. The frequency of charcoal particles in pond sediment is directly related to forest fire.There is a dramatic decline in hemlock and beech pollen at about 4700 yr B. P. The disappearance of hemlock has been found in pollen records concurrently throughout the northeast and is thought to have been caused by a pathogen or insect infestation that followed the more arid climate. After 5000 yr B. P. charcoal abundances decreased somewhat (Winkler 1997a) and pine barrens (pitch pine and oak) alternated with more moisture-loving forest trees (white pine and hardwoods such as hickory and elm) as the dominant vegetation. After about 3000 yr B. P. white pine and pitch pine shared conifer dominance in the

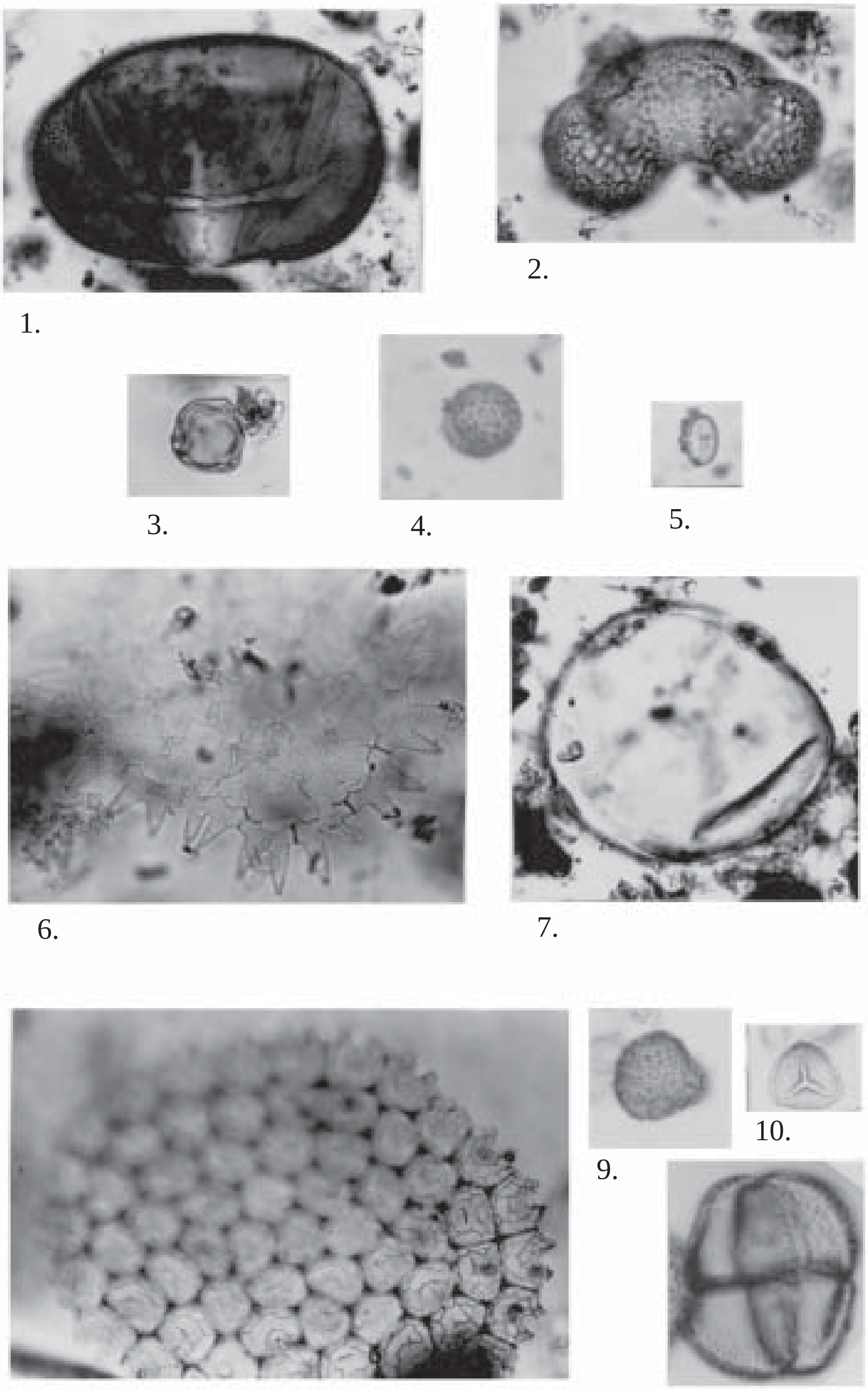

Figure 2-3a. Pollen, spore, and *Pediastrum* colony types commonly found in Cape Cod kettle pond sediments. 1) Spruce (*Picea*), 100 µm x 60 µm. 2) White pine (*Pinus strobus*), 68 µm. 3) Birch (*Betula*), 19 µm. 4) Ragweed (*Ambrosia*), 19 µm. 5) Chestnut (*Castanea dentata*), 14 µm. 6) *Pediastrum* duplex, 119 µm. 7) Corn (*Zea mays*), 80 µm. 8) *Pediastrum* cf. *araneosum*, 125 µm. 9) Bracken fern (*Pteridium*), 33 µm. 10) *Sphagnum*, 30 µm. 11). Cat-tail (*Typha latifolia*), 40 µm.

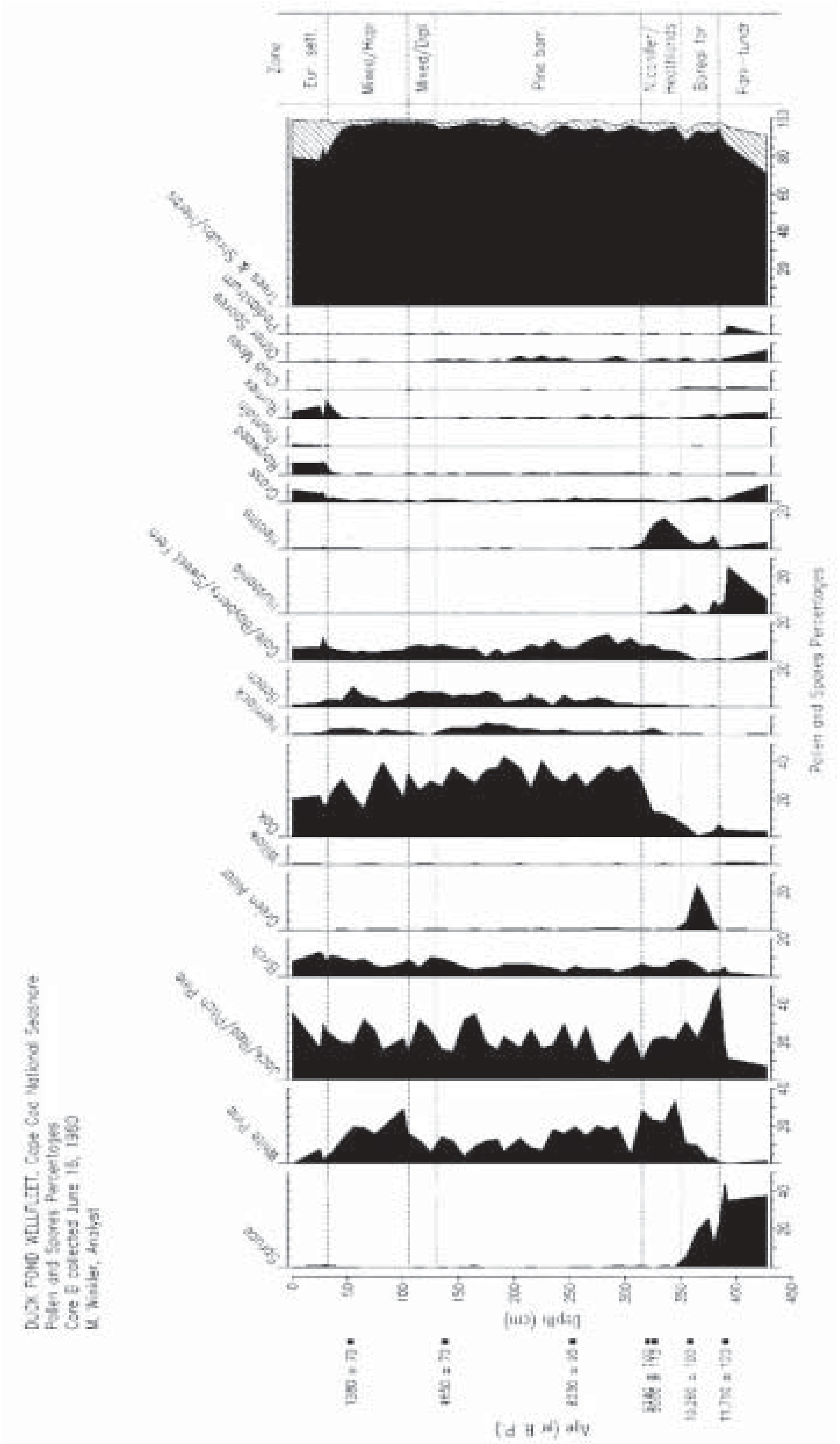

Figure 2-3b. Pollen and spores percentage diagrams for Duck Pond Wellfleet. Radiocarbon dates (yr B.P.) and depth (cm.) are to the left of the diagrams and vegetation zones interpreted from pollen are to the right of the diagrams. More than 300 pollen grains were counted for each level in the two diagrams. The proportions of the green colonial alga *Pediastrum* is also shown on each diagram.

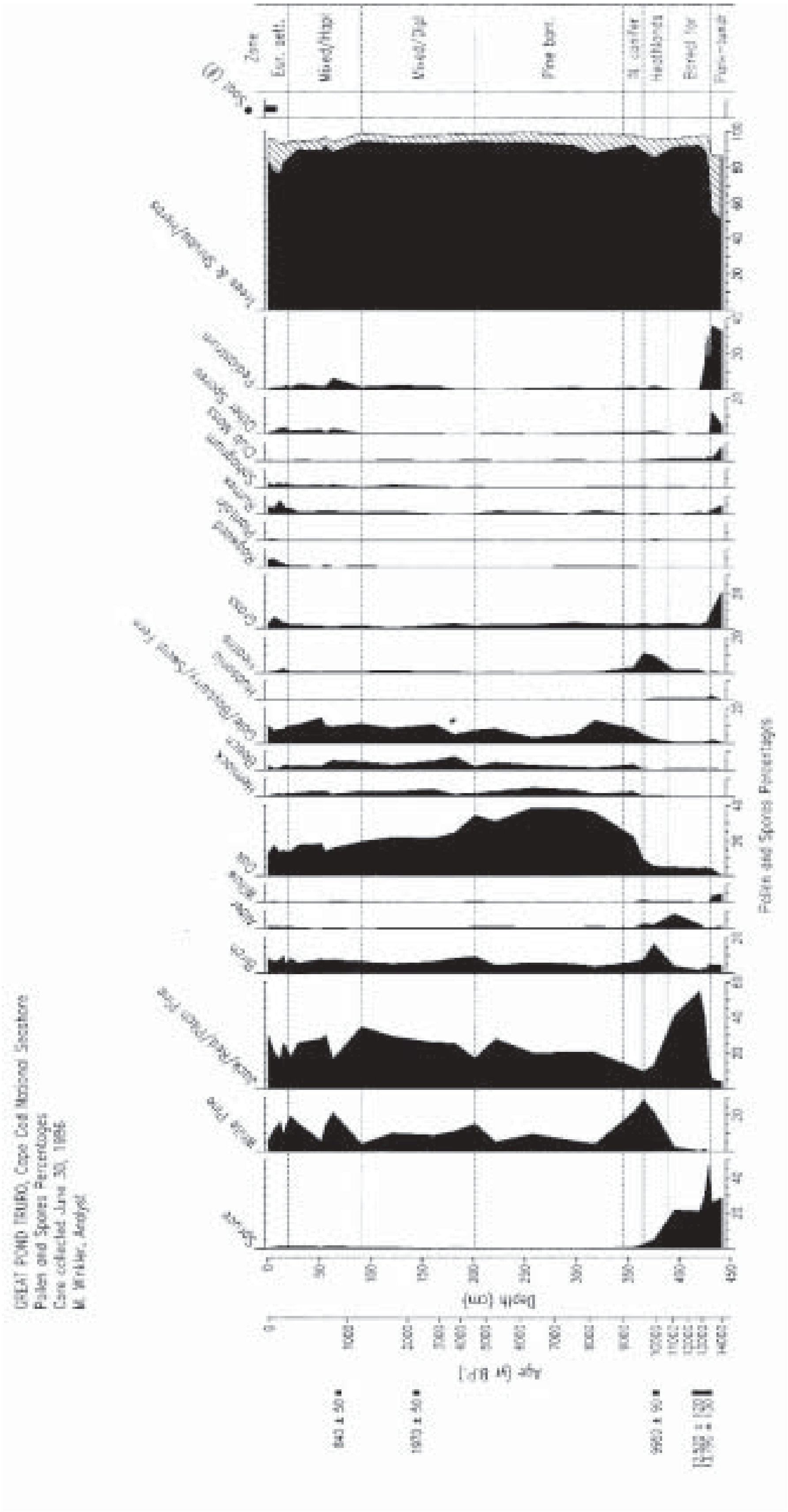

Figure 2-3c. As in 2-3b but for Great Pond Truro. Soot, an industrial indicator, is plotted. Soot does not appear until after the Industrial Revolution.

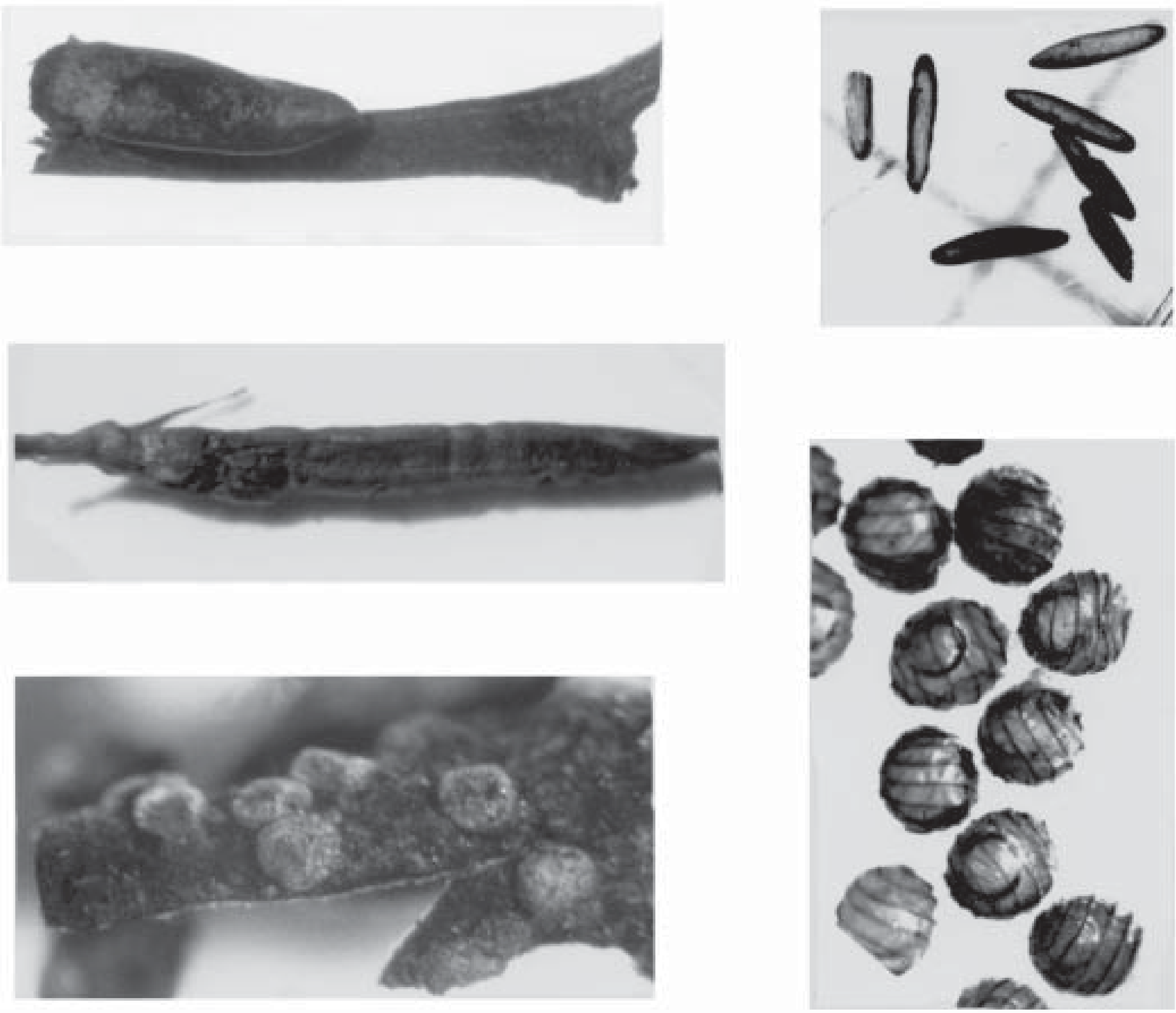

Figure 2-4. Macrofossils from Great Pond Truro sediments dated c. 13,000 B.P. a) willow bud, 1.5 mm. b) *Najas* seeds, c. 2.5 mm. c) spruce needle, 3 mm. d) *Nitella* oospores, 500 µm. e) scale insects on twigs, 0.16 mm diameter.

Corn pollen (*Zea mays*), evidence of Native American cultivation of food plants, was found in sediment deposited prior to European settlement at four ponds on the Outer Cape. Of the four ponds, No Bottom Pond in Brewster, Duck Pond in the Provincelands, Herring Pond in Wellfleet, and Snow Pond in Truro, only Herring and Snow Ponds are discussed in this Atlas. Other pollen possibly indicative of Native American cultivation before the colonists arrived is *Rumex* (sorrel, dock). This pollen type increases at all the Cape sampling sites about 200 years before European settlement and may be associated with Native American agriculture since *Rumex* was a known food source for several tribes.

European settlement impacts (post 1620 A.D.) such as logging and land clearance for villages and farms resulted in clear vegetation changes. Pollen from herbaceous species, especially ragweed and other aster family plants, grass, sorrel, and plantain, increased while the pollen from most commercially important tree species (especially white pine and Atlantic white cedar) decreased. Corn, rye, and buckwheat pollen grains were found in the post-settlement sediments of many of the ponds – especially those ponds in the Gull Pond chain. Pitch pine and oak increased in recent decades on abandoned farmland. In Herring Pond, a change from larger-sized grass pollen grains (*Spartina*, cordgrass) to smaller-sized grass pollen grains (*Phragmites*) documents the diking of the Herring River in the early 1900s and the consequent replacement of salt marsh by freshwater marsh (Winkler 1994).

Charcoal analyses of the pond sediments (see Winkler 1985b for analytical technique) were used to construct a fire history for the outer Cape dating from deglaciation (Fig. 2-5). A composite of high, medium, and low charcoal values from four ponds in the Seashore provides evidence of regional fire frequency and/or intensity. The charcoal values in the sediments were low before 9500 yr B. P., very high between 9000 and 5000 yr B. P., and mostly medium values between 5000 yr B. P. and 500 yr B. P. The fire history supports a climatic cause for most of the vegetation changes interpreted from pollen (Winkler 1997a). In addition, soot balls formed from incomplete combustion of fossil fuels were found in sediment dating from the Industrial Revolution in several ponds.

Development of the Seashore Ponds Since Deglaciation

Paleoecological study also provides a history of the development of the aquatic biota and water chemistry of the Seashore ponds. The sediments contain the remains of within-lake biota – the plankton that form the base of the food chain in aquatic habitats – and these remnants of organisms when isolated from the sediment and examined microscopically tell the ponds' environmental history. By identifying species assemblage changes, species abundance, and species deposition rates from the parts of organisms that are preserved in these anoxic muds, we can document changes in pH, salinity, nutrient inputs, water levels, etc. Here we present some of the important changes in the Cape Cod National Seashore ponds from analysis of diatoms (unicellular algae with silica cell walls that are part of the phytoplankton of the ponds, Fig. 2-6) and cladocera (zooplankton, water fleas, Fig. 2-7).

Environmental Changes in the Ponds from Diatom Analyses

Diatoms are algae with silica, glass-like, cell walls. The living diatoms contain chloroplasts and produce carbohydrates by photosynthesis using sunlight for energy and carbon dioxide gas as a carbon source. Diatoms are usually abundant in most fresh, brackish, and saltwater aquatic habitats and are also found in moist hollows of trees, springs, and seeps throughout the world. These single-celled algae are very small and have to be viewed for analysis with high magnification (usually higher than 1000 x) under oil immersion with a transmission light microscope. Diatoms are identified by shape and their silica cell wall decoration among other attributes (number of septa, size, etc.) (Fig. 2-6). Freshwater diatoms in lakes are planktonic, floating in the water column, or epiphytic, clinging to plants in shallow water (the littoral zone). Some diatoms live among sand grains (psammon) and can be found on the shore of ponds and also in sands in deeper water. Other diatoms (benthic forms) live on or in the bottom mud. Lithic diatoms cling to rocks and gravel in the water. Some diatoms are aerophils and can be blown into the pond from moist, terrestrial habitats.

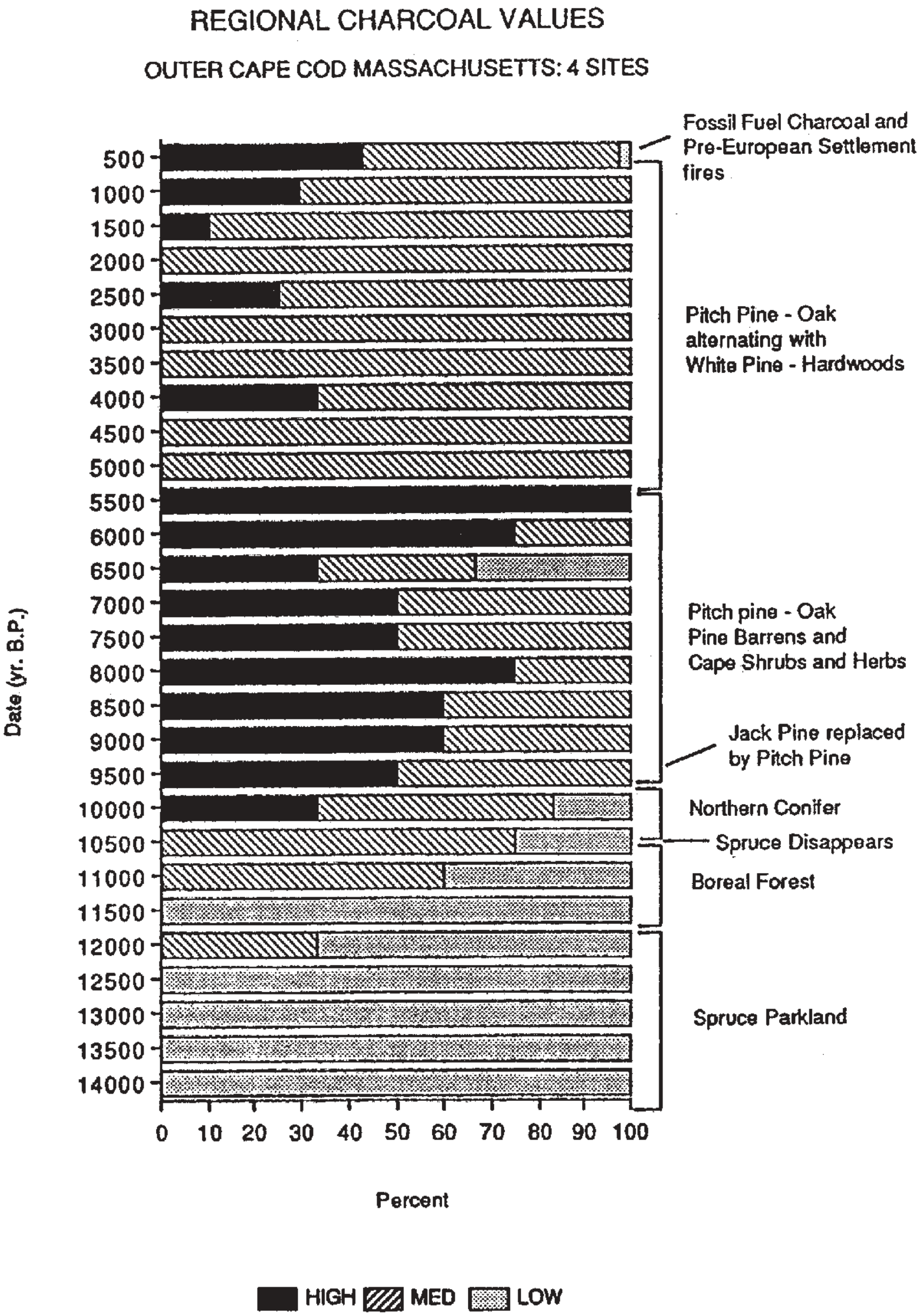

Fig. 2-5. Regional charcoal since deglaciation, Cape Cod National Seashore ponds, Outer Cape Cod, Massachusetts (modified from Winkler, 1997a). A composite of high, medium, and low charcoal values from four sites (DuckW, Dyer, GreatW, GreatT). Timescale is derived from radiocarbon chronologies. Regional plant community changes are interpreted from pollen analyses (Winkler 1985a, b and Winkler and Sanford 1995).

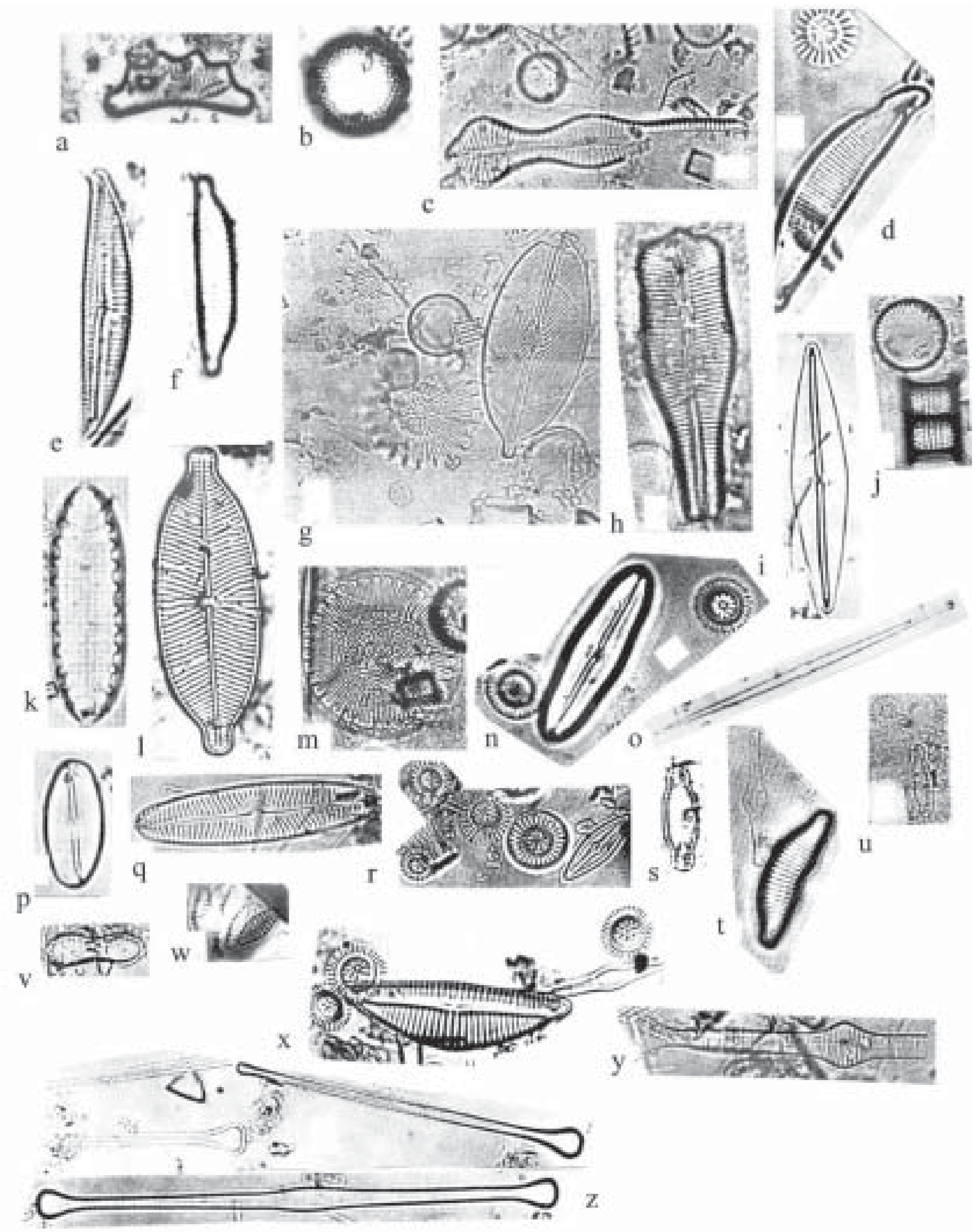

Fig. 2-6. Representative Diatoms from Cape Cod kettle ponds. a. *Eunotia serra v. diadema*, b. *Aulacoseira perglabra*, valve view, 14 µm diameter, c.*Gomphonema acuminatum*, 45 x 10 µm and *Fragilaria virescens v exigua* ~ 14 µm long, d. *Eunotia incisa*, 34 x 6.5 µm and *Cyclotella stelligera v* ~10 µm diameter, e. *Cymbella lunata* ~35 µm long, f. *Eunotia c.f. carolina* 30 x 5 µm, g. *Navicula placenta,* 40 x 15 µm, also *Cyclotella cf bodanica/comta* spp., h. *Gomphonema truncatum v turgidum* 46 x 17.5 µm, i. *Frustulia rhomboides v saxonica* 41 x 8 µm, j. *Aulacoseira distans* (girdle view) 5 x 8 µm, *A. perglabra v*. valve ~ 12 µm diam., k. *Surirella* sp., l. *Navicula cf anglica v subsalsa* 46 x 14 µm, m. *Cyclotella cf bodanica v* 25 µm diameter, n. *Caloneis ventricosa v alpina* 30 x 8 µm, also *Cyclotella stelligera v tenuis* ~ 10 µm diameter. o. *Synedra rumpens v familiaris* 50 x 2 µm, p. *Achnanthes flexella*, raphe valve 20 x 9 µm, q. *Pinnularia brebissonii* 36 x 8.5 µm, r. *Anomoneis serians v brachysira* 14 x 3.75 µm and *Cyclotella stelligera v* 6-11 um in diameter, s. *Pinnularia cf burkii* 16 x 5 µm, t. *Eunotia cf sudetica* 22 x 5 µm and *Tabellaria flocculosa* III 20 um long, u. *Fragilaria virescens v exigua* ~12 µm long, v. *Tabellaria binalis* ~14 µm long, w. *Fragilaria pinnata v lancettula* on a sand grain ~8 µm long, x. *Cymbella minuta v silesiaca* 35 x 10 µm and *Cyclotella stelligera v tenuis*, y. *Tabellaria fenestrata* fragment, z. top diatoms *Asterionella ralfsii v americana* 52 x 2 µm, bottom diatom *Tabellaria flocculosa v linearis* 80 x 4 µm.

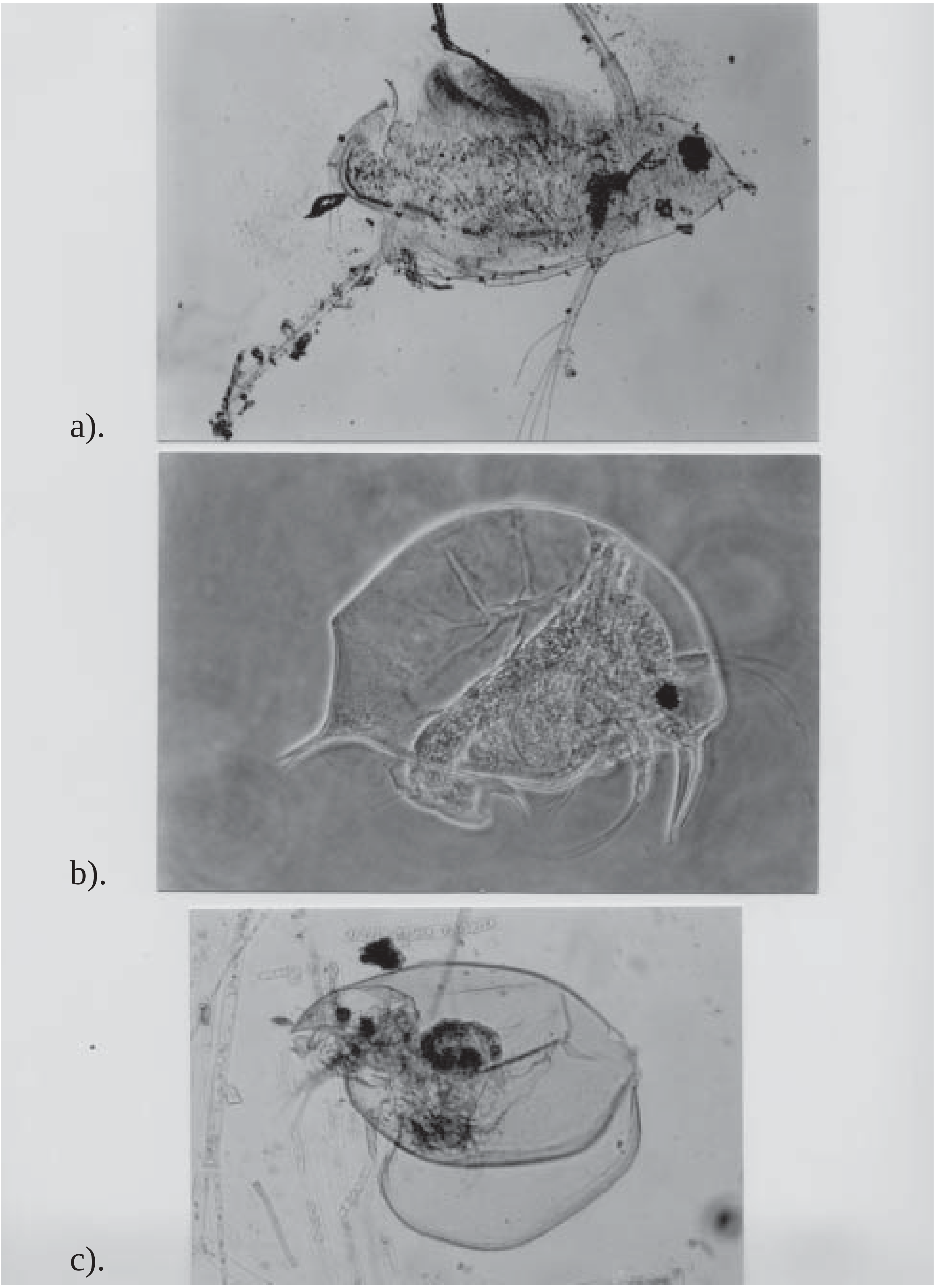

Figure 2-7. Common cladocera zooplankton of Cape Cod kettle ponds. a) *Daphnia ambigua*, 0.93 mm. b) *Neobosmina tubicen*, 0.4 mm, c) *Chydorus brevilabris*, 0.4 mm.

As the diatoms die, their highly resistant glass-like cell walls are deposited in the sediment and are well preserved for stratigraphic analysis. By treatment with strong oxidants (hydrogen peroxide and potassium dichromate) the sediment matrix can be digested and the diatom frustules (cell walls) which remain are mounted on slides for microscope viewing (see Winkler 1985c, 1988 for further discussion and references pertaining to diatom preparation, identification, and the theory of diatom analysis).

Diatom assemblages integrate pH changes, salinity changes, and nutrient changes. The sediment cores from the Cape Cod National Seashore ponds have been analyzed for these environmental fluctuations using diatoms as a proxy. There are stratigraphic diatom species percentage diagrams (Fig. 2-8), habitat change diagrams (Fig.2-9), and pH reconstructions (Fig. 2-10) for most of the ponds discussed in this atlas (Winkler 1985c, 1988, 1989, 1994, 1997b, and unpubl. data). Diatom-inferred pH reconstruction (see Winkler 1988) to describe the acid/base changes in a pond during its history is calculated by a transfer function equation developed from modern diatom assemblages assigned to pH groups and their modern pondwater pH measurements (Fig. 2-11). The diatom pH groups (Fig. 2-9) (Hustedt 1939) include acidobionts (diatom taxa that occur at pH lower than 5.5), acidophils (diatoms found primarily below pH 7), circumneutral (diatoms occurring at pH 7), alkaliphils (diatom taxa found primarily above pH 7) and alkalibionts (diatoms that occur only above pH 7). It is evident in the Gull Pond diatom diagrams (Fig. 2-8 and 2-9) that periods of pH greater than 7.0 have increased in recent times (30 cm to surface).

Diatom analysis of the Seashore pond sediments separates the ponds on the basis of within-pond biota into two groups that coincide with the Group I and Group II ponds based on age and sediment-type discussed above. The diatoms of the Group I ponds are dominated by acid- and circumneutral-dwelling plankton species (*Aulacoseira distans*, *A. lirata*, *A. perglabra* and varieties, *Cyclotella stelligera* and varieties, and *Tabellaria flocculosa III and IV*) and acid-dwelling littoral species such as *Eunotia* (Fig. 2-12). The Group II ponds are dominated by small *Fragilaria* species, ubiquitous diatoms found in a wide range of habitats and tolerant of more alkaline conditions. It is interesting to observe that these differences have been present throughout the life of each pond. The diatom-pH reconstruction (Table 2-1) for the length of record of each pond shows that the Group I ponds had a mean geometric pH of 5.4 while the Group II ponds within the Herring River drainage had a mean geometric pH of 6.2. Diatoms in the Long Pond core are similar in species assemblage to those in the Group I ponds. Diatoms in the Snow Pond core change from small *Fragilaria* dominance as the pond deepened in the middle Holocene to dominance by *Cyclotella stelligera* and varieties and acid *Eunotia* diatoms during the last two centuries.

Diatoms are an important component of a pond's primary producers. They, along with other algae, are the basis of the food chain in lakes. When the diatom assemblages change certain species indicate major water quality changes. Since European settlement, there have been diatom changes in each pond examined that document increased nutrient loading as well as increased acidification. Diatoms that indicate increased nutrients such as *Asterionella formosa* and *Fragilaria crotonensis* appear or increase in the top sediments (Fig. 2-8 and 2-12). In addition taxa typical of large alkaline, algae-choked lakes (*Cyclotella meneghiniana*, *C. michiganiana*, and more alkaline *Aulacoseira* species, Fig. 2-12) are found in recent sediments of Seashore ponds. These diatoms indicate a trend toward eutrophication in most of these ponds. Ponds affected by acidification have more abundant littoral diatoms and more acid *Eunotia* species. However, periods of low pH have also been found in the past history of the ponds and the reversal of this condition is a testament to the resiliency of the Seashore ponds to buffer acid deposition to some extent.

Although the Seashore kettle ponds are naturally acid (varying between pH 6 and 4) and have been for millennia (Table 2-1), the acid diatoms that were present in pre-settlement sediments are, in part, different from the acid species dominating the ponds today. In addition, the nutrient-tolerant taxa of modern alkaline assemblages are different from alkaline assemblages in the past (Fig. 2-12). This is an interesting observation that needs to be explored further.

Environmental Changes in the Ponds from Cladocera Analyses

Cladoceran assemblages for 10 Seashore kettle ponds have been studied by analysis of lake sediment. Cladocera, branchiopod crustaceans, commonly called water fleas (Fig. 2-7), are among the most likely of freshwater invertebrates to leave quantitatively meaningful remains in lake sediments (Frey 1964, Binford et al. 1983, Frey 1986, Hann 1990, Dodson and Frey 1991), because their chitinized exoskeletons are readily preserved in anaerobic sediments. Some species are primarily limnetic (free-swimming in open water), while others are littoral, i.e. benthic or epiphytic (bottom dwelling or living on or among plants in the shallow water littoral zone). A cladoceran assemblage for any given period of time integrates lake morphometry, lake chemistry, and lake nutrient status. Cladocera are an important part of the food web of lakes transferring energy from primary producers (algae) up the food web to higher trophic levels (e.g. fish). Therefore presence/absence of planktivorous invertebrates or planktivorous or piscivorous fish can be inferred from changes in cladoceran assemblages and changes in morphology of certain cladoceran species.

Table 2-1. Diatom-reconstructed pH for outer Cape Cod ponds. Means and standard deviations are for the length of the sediment record.

	pH (geom. mean)	Standard Deviation
Duck Pond	5.20	± 0.30
Great Pond, Wellfleet	5.30	± 0.25
Dyer Pond	5.19	± 0.27
Great Pond Truro	5.84	± 0.70
Ryder Pond	5.60	± 0.50
Gull Pond	6.00	± 0.20
Higgins Pond	6.50	± 0.30
Herring Pond	6.30	± 0.30
Williams Pond	6.10	± 0.20

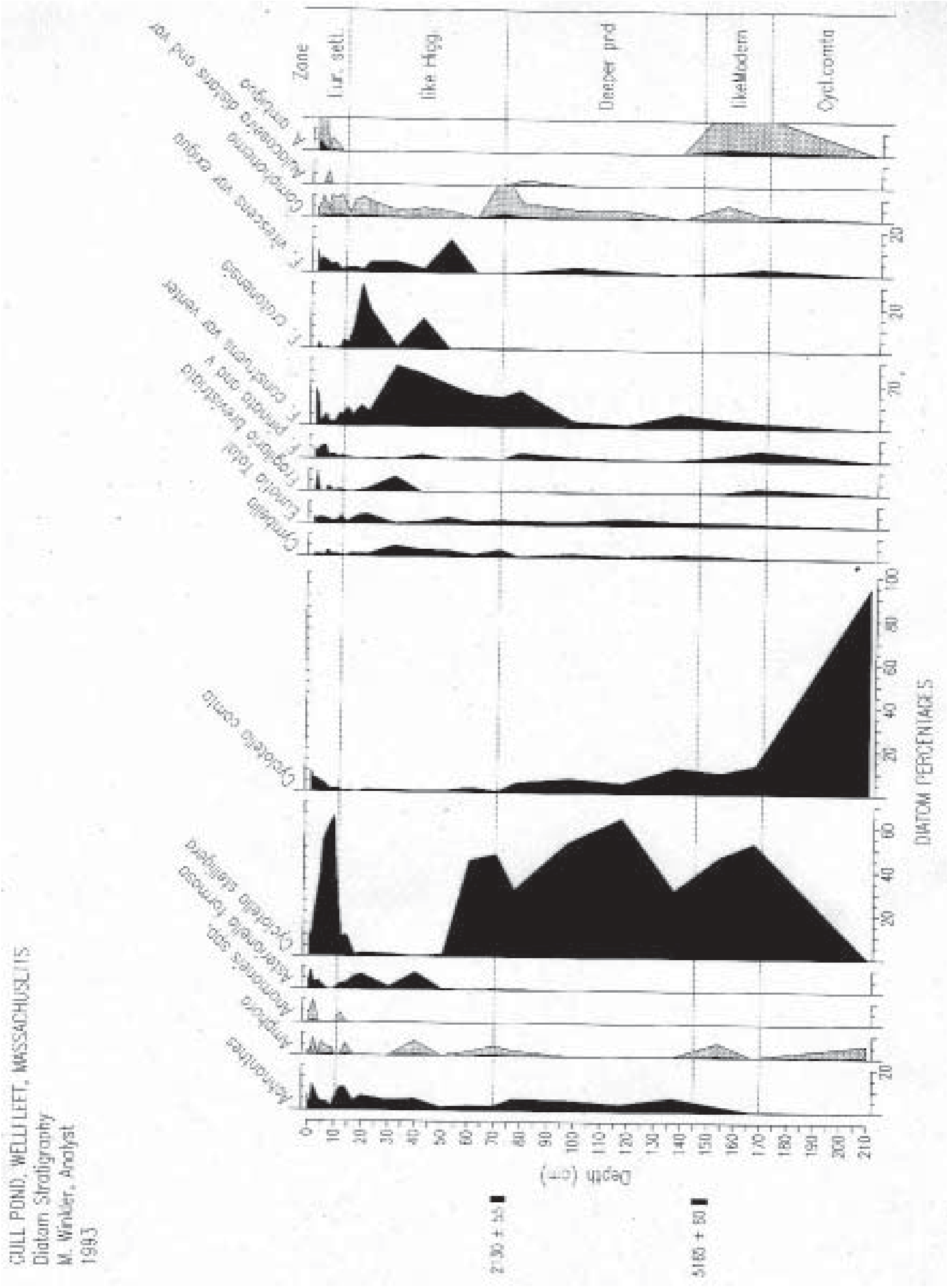

Figure 2-8. Changes in diatom assemblages through time in Gull Pond. The depth scale in centimeters reads from the bottom up. Radiocarbon dates in yr B. P. are on the left side of the diagram. The names of the diatom species counted are on the top of the diagram (the x-axis). Along the bottom of the x-axis is a percentage scale for each taxon. One scale unit equals 5%. The 20% unit is marked. The total diatom sum presents the number of diatoms counted for each level in the core. Solid fill represents actual percentages, while shaded areas represent 10X exaggeration. In this figure the abundance changes of *Cyclotella stelligera* and its replacement by small *Fragilaria* species after 2000 yr B. P. document a connection of Gull Pond with Higgins Pond and an increase of nutrients to Gull Pond (Winkler 1994).

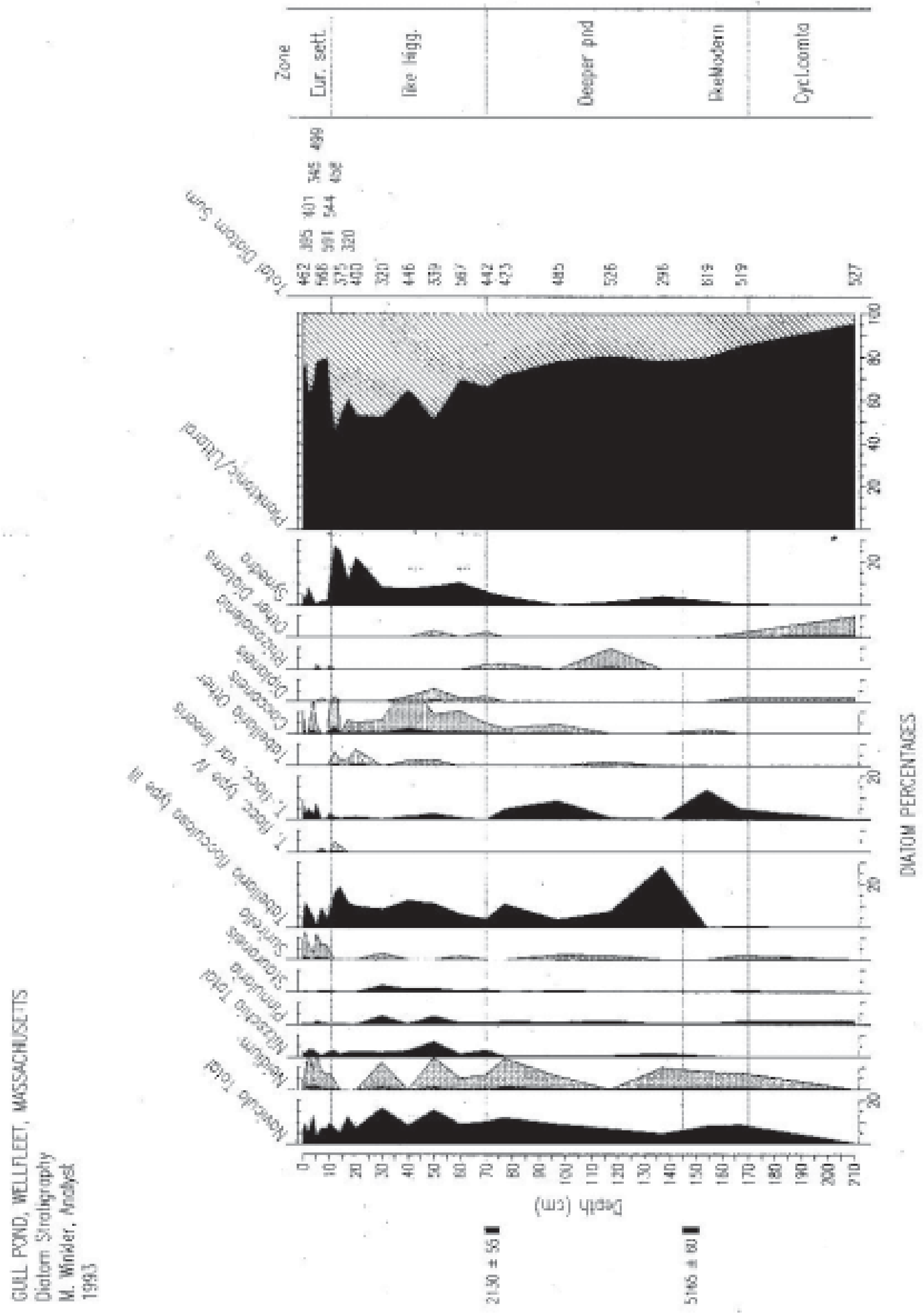

Figure 2-8 continued.

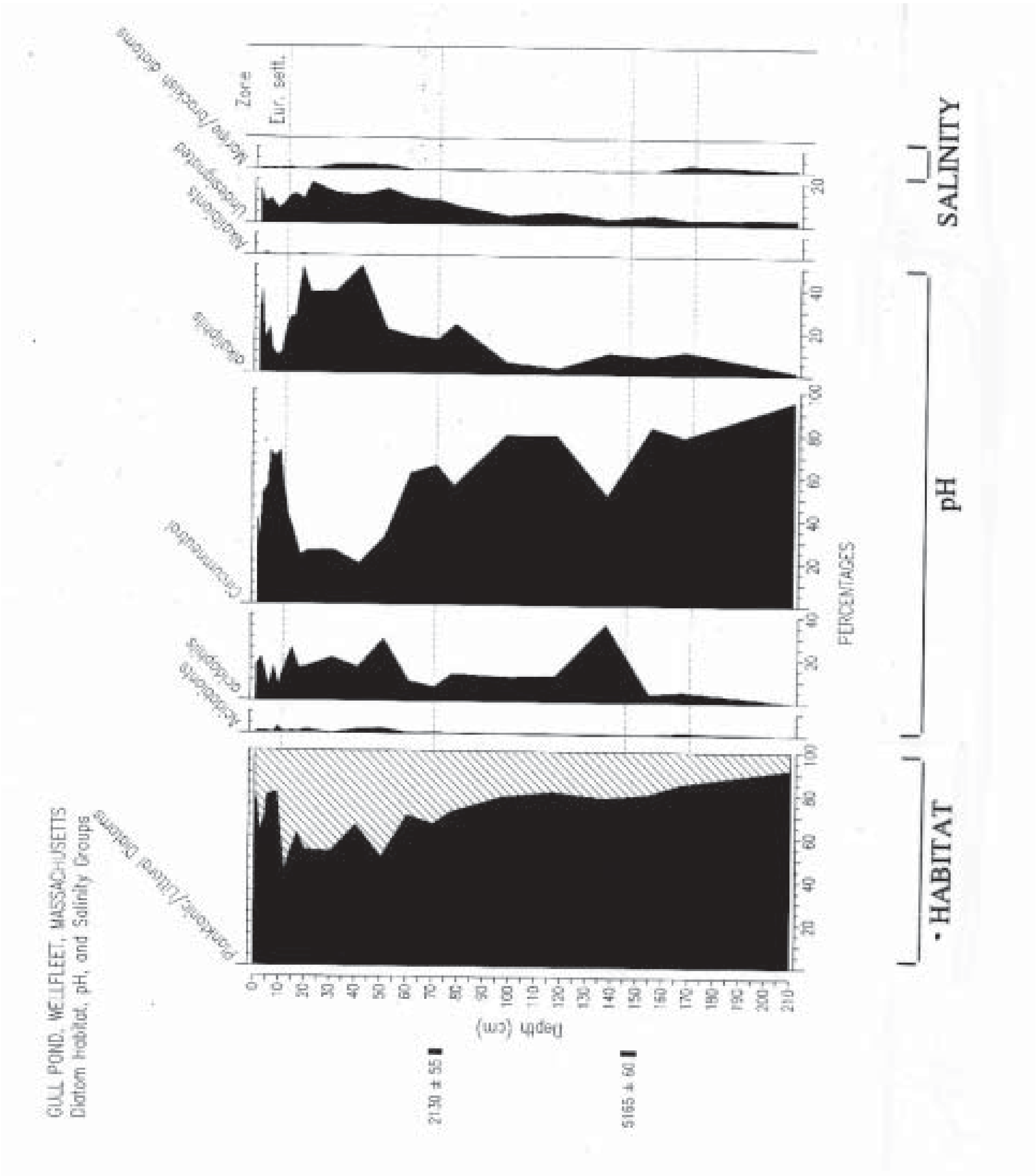

Figure 2.9. This figure presents the data from Figure 2-8 , from Gull Pond Wellfleet, divided into diatom habitat, pH, and salinity groups. The planktonic/littoral panel indicates the proportion of diatoms that float in the water column in deep water relative to diatoms that are attached to plants or the substrate in the shallow water at the edges of the pond. In the central 5 panels, Acidobionts through Alkalibionts, pH requirements increase (i.e. acidity declines) from left to right. The Undesignated panel represents species that were not assigned to a pH group. The Marine/brackish panel represents diatoms which have either been windborne into the pond from the Atlantic Ocean or Cape Cod Bay or brought into the pond by alewife migration up the Herring River from saltwater to freshwater.

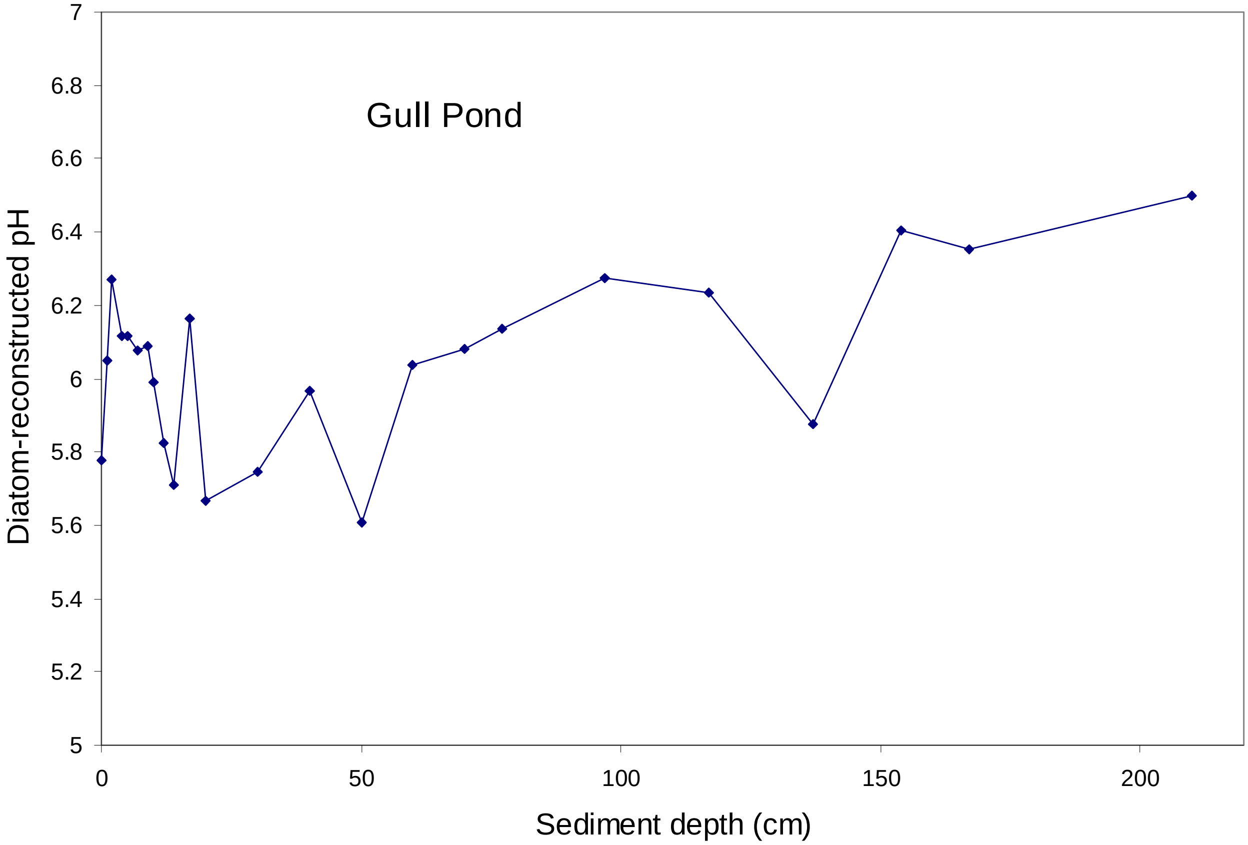

Figure 2-10. Diatom inferred (regression calculated) pH for Gull Pond throughout its history. Gull Pond's pH has been about 6 consistently over the length of record (mean = 6.0, standard deviation ± 0.2).

Outer Cape Ponds: Diatom pH Groups

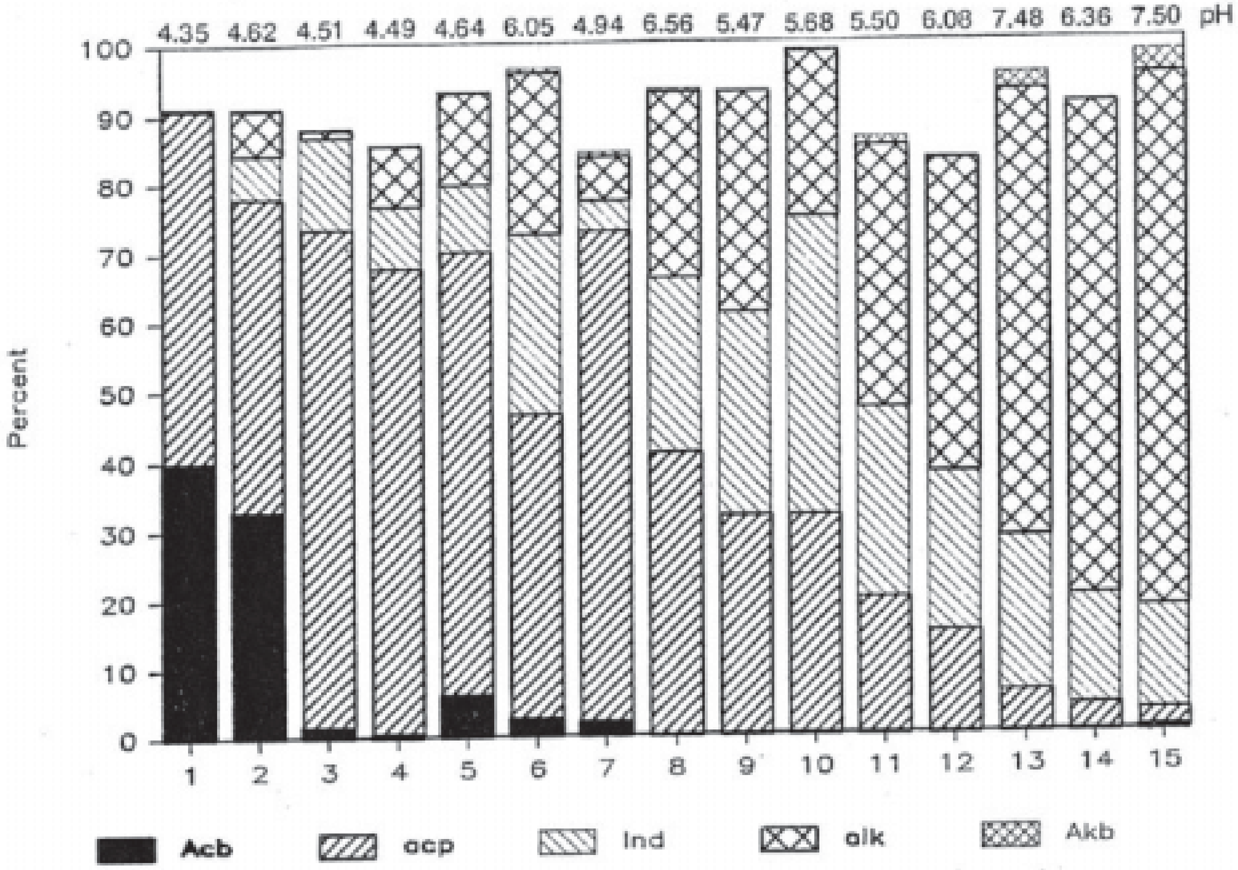

Figure 2-11. Data used to calculate regression equation for diatom-inferred pH for Cape Cod kettle pond sediment cores. Diatoms were analyzed from surface sediments collected in June, 1983 from the deepest part of 15 ponds in the Cape Cod National Seashore. Diatom taxa were assigned to Hustedt's (1939) pH groups and percentage composition by pH group was calculated for each pond. Acb = acidobionts, acp = acidophils, Ind = circumneutral, alk = alkaliphils, akb = alkalibionts. The pH value shown above each pond histogram is the mean pH of the pond calculated from all available measurements as of December 1985 (Winkler 1985c, 1988). The ponds are 1. KinnacumW, 2. LongW, 3. DyerW, 4. GreatW, 5. DuckW, 6. GreatT, 7. SpectacleW, 8. GullW, 9. HorseleechT, 10. RyderT, 11. WilliamsW, 12. HerringW, 13. HerringEastham, 14. HigginsW, 15. PilgrimT.

Limnetic cladocera in Seashore kettle ponds are represented by at least three species of *Daphnia* (*Daphnia cf. ambigua, D. catawba, and D. pulex*), three bosminids (*Neobosmina tubicen* [formerly *Eubosmina tubicen*], *Eubosmina longispina*, and *Bosmina longirostris* [*sensu latu*]), *Diaphanosoma* sp., and the large predator *Leptodora kindtii*. At least 4 littoral cladoceran species can be found in Seashore lakes (Table 2-2).

Results from cladoceran analysis of surface sediments from these 10 ponds taken from 1986-1997 were evaluated in terms of limnetic to littoral cladoceran community ratios (Table 2-3). The dominant limnetic and littoral cladocerans for each pond are shown in Table 2-4. The mean limnetic:littoral ratio for all 10 ponds was 63:37, close to 2:1. The landlocked, acidic, oligotrophic ponds and Snow Pond had fewer limnetic cladocera than littoral cladocera. Long Pond and the Gull Pond chain (Gull, Higgins, Herring, and Williams ponds) had more limnetic than littoral cladocera. The high limnetic percent for the Gull Pond chain is accounted for by the dominance of *Bosmina longirostris*, a small cladoceran (0.2-0.4 mm) that reproduces very rapidly (Table 2-4). *Bosmina* dominance in these lakes is the result of heavy predation on zooplankton by herring (*Alosa pseudoharengus, A. aestivalis*), which drives the limnetic zooplankton community to smaller, cryptic species. By contrast all landlocked ponds in this data set (which includes Snow and Long ponds) are dominated by either *Neobosmina tubicen* or *Eubosmina longispina*, both somewhat larger (0.3-0.6 mm) than *Bosmina*. This indicates that zooplanktivory is weaker in the landlocked ponds than in the Gull Pond chain.

The dominant littoral cladoceran species in these ponds (with the exception of Snow) is either *Rhynchotalona falcata* or *Chydorus brevilabris* (Table 2-4). *Rhynchotalona falcata* is an indicator of nutrient-poor, unvegetated, sandy substrates. *Chydorus brevilabris* flourishes at very low or very high pH or at high nutrient levels. It is frequently used as an indicator of eutrophication. Long, Gull and Ryder ponds are dominated *by R. falcata* indicating the presence of a sandy littoral zone with few macrophytes. Dyer and GreatT, which are considered oligotrophic ponds, are dominated by *C. brevilabris* probably because of the naturally low pH values of their waters. Duck Pond, naturally acidic and classed as mesotrophic, has a particularly depauperate modern littoral cladoceran assemblage of only 11 species, also dominated by *C. brevilabris*. This species also dominates the littoral assemblages of Higgins, Herring, and Willams ponds, but for these lakes it indicates nutrient enrichment to the point of eutrophication. Snow Pond's littoral community is dominated by the large-bodied sidid cladoceran, *Latona cf. setifera*. Snow Pond has one of the two highest color values for the Seashore kettle ponds (Table 1-1) and a large vegetated littoral zone. Both of these factors protect *Latona* from predation by visual predators such as fish.

Data on cladoceran assemblage changes over time are available for nine Seashore kettle ponds: Ryder and GreatT [Winkler, 1997b]; Gull, Higgins, Herring, and Williams [Winkler 1994]; Long, Snow, and DuckW. Tables 2-5 to 2-7 present summaries of these data for representative Seashore kettle ponds. *Neobosmina tubicen* has been the dominant limnetic species in Ryder Pond for the last 5000 years (Table 2-5), in DuckW for at least the last 2100 years (Table 2-6), and in Long Pond for at least the last 1700 years (Table 2-6). *N. tubicen* dominated GreatT immediately at or before European settlement, but was gradually replaced by *Eubosmina longispina* (Winkler 1997b). *E. longispina* also dominated Snow Pond sediments c. 3000 years ago (Table 2-6). There were times in the past when the Gull Pond chain was dominated by, or had substantial populations of *N. tubicen* (Table 2-7, and Winkler 1994). For Herring, Higgins, and Williams ponds periods of *N. tubicen* dominance alternated with periods of *Bosmina* dominance (Winkler 1994). The periods of *Bosmina* dominance in these ponds are interpreted as evidence of prehistoric herring migrations into these ponds indicating that this "unnatural disturbance" (see Chapter VII. Herring effects on

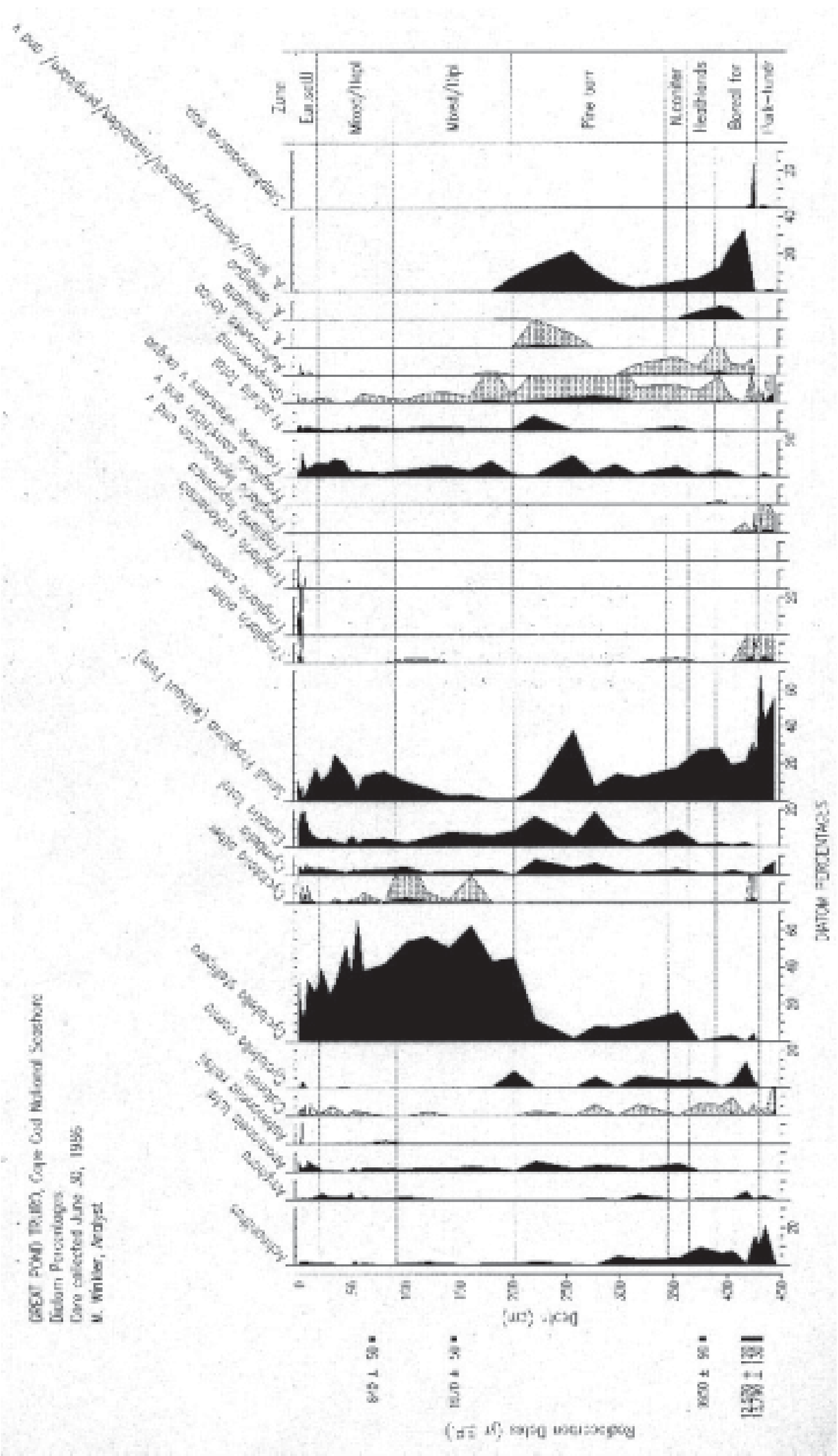

Figure 2-12a. Changes in diatom assemblages through time in Great Pond Truro. For definition of terms and a guide to reading the diagram see Figure 2-8 caption. The zones are those interpreted from pollen analysis (see Figure 3c). It is interesting to note that some of the diatom changes are concurrent with regional upland vegetation changes. Great Pond Truro is an example of the changes found in Group I ponds in the CCNS. However, major recent species changes have occurred due to liming (see text).

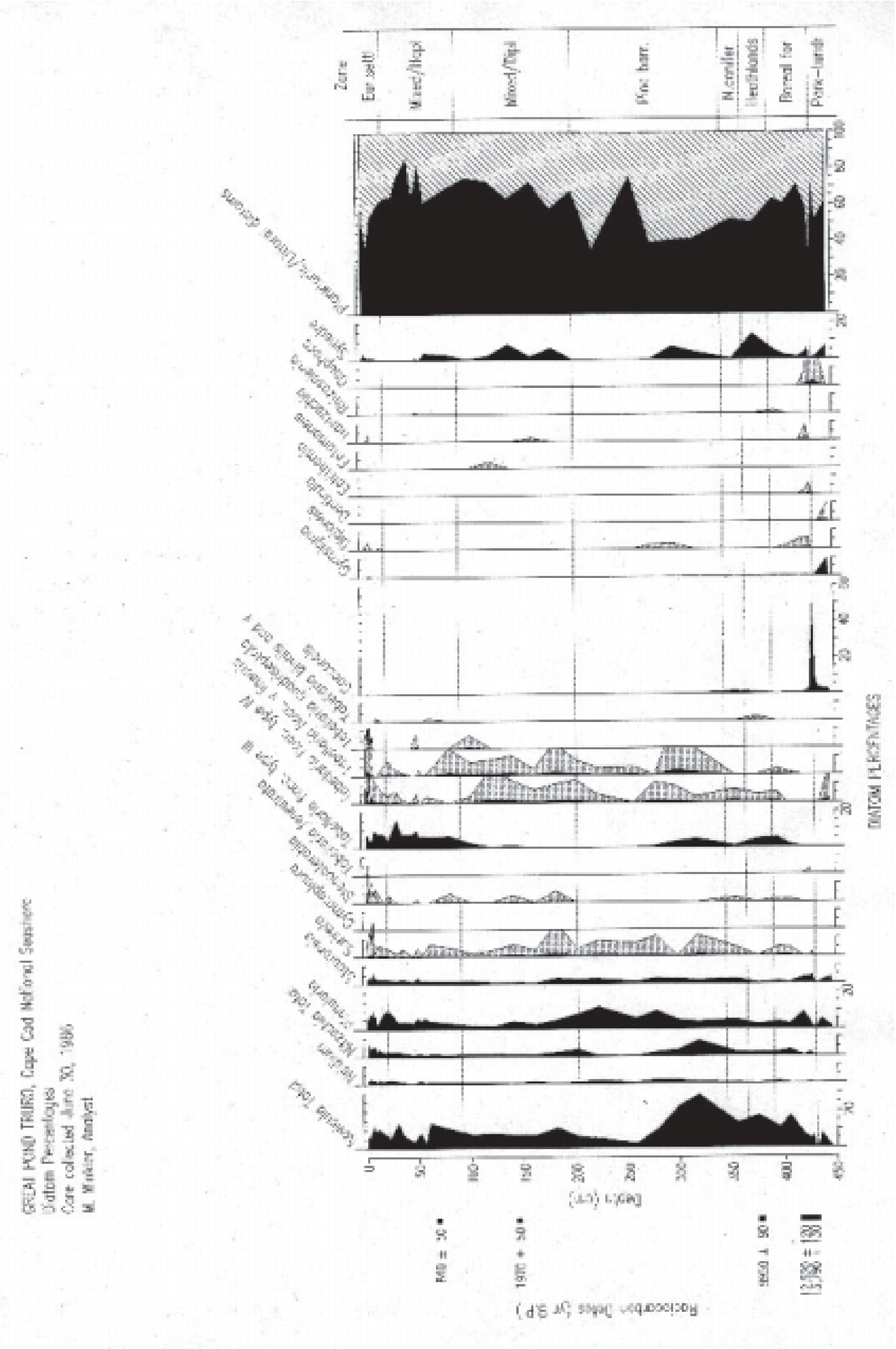

Figure 2-12b. Changes in diatom assemblages through time (continued).

Table 2-2. Littoral cladoceran species list for Cape Cod kettle ponds.

Chydoridae
Eurycercus glacialis
Eurycercus (Bullatifrons) sp.
Acroperus harpae
Alona (Biapertura) affinis
A. quadrangularis
A. rustica
A. bicolor
A. costata
A. guttata
A. intermedia
A. circumfimbriata
A. barbulata
A. setulosa
cf. Alonopsis americana
Camptocercus nec rectirostris
Graptoleberis testudinaria
Kurzia latissima
Leydigia leydigi
Monospilus dispar
Oxyurella cf. brevicaudis
Rhynchotalona falcata
Disparalona acutirostris
D. rostrata
Alonella excisa
Al. exigua
Al. nana
Al. pulchella
Anchistropus minor
Chydorus brevilabris/sphaericus
C. faviformis
C. linguilabris
Paralona pigra
Pleuroxus procurvus
P. denticulatus
P. straminius
P. spp.

Sididae
Sida crystallina
Latona sp.

Daphniidae
Scapholeberis sp.

Macrothricidae
Acantholeberis curvirostris
Ilyocryptus sp.
Ophryoxus gracilis
Parophryoxus cf. tubulatus
Macrothrix cf. laticornis

Table 2-3. A ranking of ponds by percent limnetic and littoral cladocerans in surface sediment.

Pond	% Limnetic	% Littoral
Dyer	42	58
Ryder	44	56
Great Truro	47	53
Duck	51	49
Snow	57	43
Long	69	31
Williams	73	27
Higgins	79	21
Gull	82	18
Herring	83	17
Mean	63	37

Table 2-4. Dominant limnetic and littoral cladoceran species identified in surface sediments.

Pond	Limnetic species	Littoral species
Deep, land-locked, acidic, oligotrophic		
Duck	*Neobosmina tubicen*	*Chydorus brevilabris*
Dyer	*Neobosmina tubicen*	*Chydorus brevilabris*
Long	*Neobosmina tubicen*	*Rhynchotalona falcata*
Great Truro	*Eubosmina longispina*	*Chydorus brevilabris*
Gull Pond chain		
Gull	*Bosmina longirostris*	*Rhynchotalona falcata*
Higgins	*Bosmina longirostris*	*Chydorus brevilabris*
Herring	*Bosmina longirostris*	*Chydorus brevilabris*
Williams	*Bosmina longirostris*	*Chydorus brevilabris*
Other ponds		
Snow	*Neobosmina tubicen*	*Latona cf. setifera*
Ryder	*Neobosmina tubicen*	*Rhynchotalona falcata*

Table 2-5. Ryder Pond (1991 core). Cladoceran summary.

Date (yr B.P.)	Depth cm	% Limnetic	%Littoral	Dominant limnetic species	Dominant littoral species
	9-10	32	68	*Neobosmina tubicen*	*Rhynchotalona falcata*
	60.8-62.5	80	20	*Neobosmina tubicen*	*Pleuroxus procurvus/* *Alona affinis*
Ambrosia rise					
	70-71	38	62	*Neobosmina tubicen*	*Rhynchotalona falcata*
	92-93	44	56	*Neobosmina tubicen*	*Rhynchotalona falcata*
	140-141	80	20	*Neobosmina tubicen*	*Rhynchotalona falcata*
	169-170	67	33	*Neobosmina tubicen*	*Rhynchotalona falcata*
3165	192-199				
	209-210	73	73	*Neobosmina tubicen*	*Alona affinis*
4930	219.5-231				
5145	217.5-234				
6390	253-255				
11,610	282-293				
	288-289	0	100		*cf*. small *Alona* spp.

Table 2-6. Cladoceran summaries for three Cape Cod kettle ponds from cores collected in 1997.

Long Pond (1997 core).

Date (yrs. B.P.)	**Depth cm**	**% Limnetic**	**% Littoral**	**Dominant limnetic species**	**Dominant littoral species**
12	0-1	69	31	*Neobosmina tubicen*	*Rhynchotalona falcata*
c. 375	19-20	60	40	*Neobosmina tubicen*	*Rhynchotalona falcata*
c. 1700	39-40	77	23	*Neobosmina tubicen*	*Rhynchotalona falcata*

Snow Pond (1997 core).

Date (yrs. B.P.)	**Depth cm**	**% Limnetic**	**% Littoral**	**Dominant limnetic species**	**Dominant littoral species**
4	0-1	57	43	*Neobosmina tubicen*	*Latona cf. setifera*
c. 3000	37-38	28	72	*Eubosmina longispina*	*Alona intermedia*
6000	67-68	0	100		*Alona rustica*

Duck Pond (1997 core)

Date (yrs. B.P.)	**Depth cm**	**% Limnetic**	**% Littoral**	**Dominant limnetic species**	**Dominant littoral species**
10	0-1	51	49	*Neobosmina tubicen*	*C. brevilabris*
c. 2100	30-31	47	52	*Neobosmina tubicen*	*C. brevilabris*

Table 2-7. Cladoceran summary for Gull Pond (1989 core).

Date (yrs. B.P)	Depth (cm)	% Limnetic	%Littoral	Dominant limnetic species	Dominant littoral species
	0.8-1.3	88	12	*Bosmina longirostris*	*Rhynchotalona falcata*
	4.7-5.6	72	28	*Neobosmina tubicen*	*Rhynchotalona falcata*
	8.1-9.2	69	31	*Neobosmina tubicen*	*Rhynchotalona falcata*
	9.2-9.9	63	37	*Neobosmina tubicen*	*Rhynchotalona falcata*
	25.7-26.6	79	21	*Daphnia cf. catawba*	*Chydorus brevilabris*
	49.9-50.7	65	35	*Neobosmina tubicen*	*Chydorus brevilabris*
2130	69.7-75				
	86-87	57	43	*Neobosmina tubicen*	*Rhynchotalona falcata*
	126-127	66	34	*Neobosmina tubicen*	*Rhynchotalona falcata*
5165	145-151				
	156-157	51	51	*Neobosmina tubicen*	*Rhynchotalona falcata*

Rhynchotalona falcata dominates the littoral cladoceran populations of Ryder Pond for most of the last 5000 years, Long Pond for the last 1700 years, and Gull Pond from 5000-1500 years ago and then from European settlement up to the present. It was found in eight of the nine ponds for which littoral cladocera were observed. This species is an indicator of nutrient-poor, unvegetated sandy littoral habitats. Because the outer Cape's kettle ponds are located in sandy outwash plains, this habitat type is common . The only pond in which *Rhynchotalona* was not observed is Williams Pond.

Chydorus brevilabris dominates the Williams Pond littoral assemblage throughout its 9500-year history. As mentioned above, *C. brevilabris* is frequently the dominant littoral cladoceran in nutrient-enriched waters. Williams Pond is surrounded by marsh and bog and may have received relatively high nutrient input throughout its history from organic material eroded into the pond by wave action (McLachlan et al. 1979). The Herring Pond littoral assemblage is also dominated by *C. brevilabris* throughout its 2900-year history. Herring Pond's position at the downstream end of a chain of lakes, and its shallow depth, may account for its high productivity (Frey 1980) and *C. brevilabris* dominance throughout its history. Both Williams and Herring ponds were found to be eutrophic when classified by Secchi depth observations of summer water clarity (see Table 4-4).

C. brevilabris also dominates the littoral populations represented in sediments attributed to the 1980's (A.D.) in Dyer Pond and in the 1990's (A.D.) and 2100 years ago in DuckW. *C. brevilabris* dominance in these two ponds is not the result of eutrophication, but probably reflects the low pH of these pond's waters and the presence of deep moss layers that may offer a littoral-type habitat for *C. brevilabris*.

How Geologic and Paleoecological Histories of the Seashore Ponds Differ

Group I ponds date from deglaciation of the Cape and were formed by ice block collapse in fairly impermeable clay-rich outwash sands; this fine-grained sediment slows water flow and thus holds seepage and precipitation water in the ponds. Thus, group I ponds are to some extent "perched", i.e. not directly connected with the groundwater. Because these perched conditions have kept them flooded continuously for over 10 millennia, they have experienced continuous sediment deposition since their formation. These ponds are DuckW, Dyer, GreatW, Williams, GreatT, and, possibly, Long Pond. Ryder Pond is a late-glacial kettle pond also, but its development was interrupted in the early Holocene.

The Group II ponds have truncated records which began in the middle Holocene. They were formed in clay-poor outwash sands and did not contain water until the rising sea level lifted the freshwater lens enough to intersect their basins. They are also in the Herring River drainage basin and were affected by barrier beach formation and salt marsh development (Roman 1987, Winkler and Sanford 1995). Snow Pond, although not in the Herring River drainage, may be a Group II pond. However, even within the pond groupings, there are unique attributes to each pond. Below we briefly discuss outstanding differences among the ponds and major results for each one.

Duck W

As presented above, DuckW has a very slow sedimentation rate (about 0.03 cm/yr), but one of the longest sediment records. The Duck Pond core contained a litter layer providing evidence for the ice-block origin of the kettle pond and a picture of the vegetation and the topography of the late-glacial uplands and the wetland biota of the developing pond. The radiocarbon date for the first lake sediments above the litter layer was 11,710 ± 120 years B.P. Today Duck Pond is relatively clear and deep (Table 1-1) and has mosses growing at a depth of 18 m (60 feet) in the deepest part of the pond (Winkler 1985a, Farmer 1988). The mosses were discovered by divers, among them Jean-Michel Cousteau, who had heard legends of the depth and clarity of Duck Pond (MacCoy 1958). The mosses have since been sampled repeatedly. The presence of mosses at depth attests to the clarity of the water at most times of the year in past decades. The recent decrease in Secchi depth records, especially at the end of summer (see Fig. 4-4 and Fig. 5-2) may have an effect on the continued growth of these plants under the water. Duck Pond has little aquatic vegetation growing around the shoreline (Roman et al., in press) and the bottom mosses may provide an unusual habitat for aquatic biota which usually live in the plant-filled shallow-water (littoral) parts of a pond. DuckW is also unique in that the dominant planktonic diatoms throughout the life of the pond have been acid *Aulacoseira distans* and varieties, *A. lirata* and varieties, and *A. perglabra* and varieties although circumneutral *Cyclotella stelligera* and varieties (which dominates all the other Seashore kettle ponds), *C. comta*, and *Tabellaria flocculosa* species are also present. MacCoy (1958) described Duck Pond limnetic zooplankton as a very simple system of two species of copepod; the calanoid *Diaptomus minutus* and an unidentified large cyclopoid copepod. Cladocera were not found by MacCoy in 1956 and 1957 water samples taken in July and August. However, Duck Pond sediments contain remains of *Neobosmina tubicen, Eubosmina longispina, Diaphanosoma,* and at least 15 littoral cladocera. Cladocera may be restricted to autumn, winter, and/or spring seasons in DuckW.

Dyer

Dyer Pond, like DuckW, has a kettle pond origin. We obtained 7 m (23 feet) of sediment that dated from 12,530 +/- 120 yr B. P. The overall sedimentation rate for this pond, 0.06 cm/yr, is almost twice that of DuckW. However the sedimentation rate in the first 7400 years of its development was as low as DuckW (0.03 cm/yr). After 4620 yr B. P. the sedimentation rate more than tripled to 0.11 cm/yr. At the same time the diatom species changes indicate that the pond deepened. There was a sharp increase in the planktonic diatoms *Cyclotella stelligera* and varieties and *Tabellaria flocculosa* that continued until the present. Dyer also has mosses similar to those at Duck Pond growing at depth.

GreatW

GreatW, as stated above, was an iron-rich bog before 11,700 yr B. P. Diatoms and other lake aquatics did not appear until after 11,000 yr B. P. when the bog became a lake. GreatW has a diatom shift roughly concurrent with the changes in Dyer. *Cyclotella stelligera* and varieties dominate after about 5000 yr B. P.

Great T

GreatT is similar to DuckW in two ways. It has a slow deposition rate, but a long sediment record (dating from 13,800 years), and it had a litter layer at the base of the sediments. The litter layer provided evidence of an ice-block origin for the pond and the twigs, leaves, seeds, and insects that were identified broadened the portrait of the late-glacial landscape of the outer Cape (see Vegetation Changes above). According to the diatoms (Fig. 2-12), GreatT was most alkaline shortly after deglaciation when there was a peak in alkaline *Stephanodiscus* taxa (the only time that members of this genus, primarily found in large alkaline lakes, appeared in any of the Seashore ponds). The most acid diatom taxa grew in the pond during the next 9000 years of development. The pond was dominated at that time by *Aulacoseira distans, A. lirata, and A. perglabra* diatoms and their varieties, and also by *Cyclotella comta*. At 4700 yr B. P. a shift to diatom dominance by *Cyclotella stelligera* and varieties occurs (Fig. 2-12). This is concurrent with what was happening to the diatoms in DuckW, Dyer, and GreatW and probably indicates a deepening of all of the ponds due to increased precipitation and possibly to the effects of sea level rise after 5000 yr B. P. GreatT has been limed several times in recent decades to maintain a fishery for stocked fish species. The liming has disturbed the water chemistry and the biota of the pond and has provided a time-line in the sediments.

In reaction to the liming events there was an increase in alkaline littoral diatoms such as *Gyrosigma, Diploneis*, *Cocconeis* and *Hantzschia* in the top few centimeters of the sediments. *Fragilaria construens* var *venter* and *Aulacoseira ambigua* also increased. More nutrient tolerant *Cyclotella* species appeared, as did *Asterionella formosa*. While some of the acid diatoms (*Fragilaria virescens v exigua, Eunotia* and *Pinnularia)* decreased, other acid taxa such as *Stenopterobia, Anomoneis serians v brachysira, Tabellaria quadriseptata*, and *T. binalis* increased probably responding to the regional increase in acid precipitation after the Industrial Revolution. The limnetic cladoceran *Neobosmina tubicen* decreased steadily after European settlement, but increased after liming.

Williams

Williams Pond, presently in the Herring River drainage because of a connection to Higgins Pond, is unusual in that it has a long history of uninterrupted sediment deposition dating from 9500 +/- 90 yr B. P. unlike the other three ponds in the Gull chain (Gull, Higgins, and Herring). Williams Pond is quite shallow today (about 2 m = 6 feet) and has unusual algal and bacterial blooms during the summer months. It is one of the more eutrophic Seashore ponds today (see Table 4-4 and Figs. 5-15 and 5-19). A large *Pediastrum* (a colonial green alga, see Fig. 2-3a) bloom is documented in the sediments before European settlement but is replaced by blue-green algae growth (Winkler 1994). Small *Fragilaria* dominate the diatom stratigraphy in the early Holocene. The diatom assemblages became more similar to the Group I ponds in the middle Holocene when *Cyclotella stelligera* and varieties dominated. *Cyclotella* was later replaced by more alkaline *Aulacoseira ambigua* and then by the continuous presence of benthic small *Fragilaria*. The diatoms document a habitat shift from a deeper to a shallower pond as the plankton percentages decrease from 90% to less than 40% in the top sediments. Definite post-European settlement changes are recorded by the change in diatom taxa in recent sediments. *Asterionella formosa, Fragilaria crotonensis, Cocconeis*, and *Gyrosigma* appear in the stratigraphy and other more alkaline *Aulacoseira* diatoms also appear. These changes now make Williams Pond diatoms more like those in the other Gull chain ponds and are a result of land use changes in the pond drainage basin and the digging of the connection between these ponds. The Williams Pond cladoceran assemblage was dominated by *Bosmina longirostris* 9500 years ago, but changed to *Neobosmina tubicen* dominance in the early Holocene when the diatom assemblage changed to resemble that of Group I ponds. About 5000 years ago *Bosmina* again became dominant. Dominance switched back to *N. tubicen* at c. 4000 years ago. From c. 3000 years ago up to the present *Bosmina* once more became dominant and the Williams Pond cladoceran assemblage resembled that of the Gull chain ponds.

Long

The 50 cm sediment core (P-core 2) that was obtained from Long Pond had an AMS-radiocarbon basal date of 2550 +/- 45 yr B. P. The core was also dated by ^{210}Pb to provide a chronology for the past 150 years. The sediment from 17 cm depth in the core was found to have a ^{210}Pb date of 1840 +/- 20 A. D. Long Pond, like the other kettle ponds, was dominated by the plankton diatom *Cyclotella stelligera* and varieties until European settlement. At that time the pond became more acid and there were increased littoral diatoms such as *Peronia fibula, Frustulia, Eunotia*, and *Pinnularia* and replacement of the *Cyclotella* plankton by acid *Aulacoseira perglabra* and *A. distans* and varieties, very acid *Asterionella ralfsii v americana*, and acid *Fragilaria virescens v exigua*. At the beginning of the 1950's there was a dramatic decrease in most of the above species and an increase in *Eunotia, Asterionella ralfsii*, and *Stenopterobia*. The percentage of littoral diatoms increases at that time from 50 to 75%. About 5% of the diatoms encountered were deformed—an unusual finding. Soot is plentiful in the sediments. The most recent diatom changes appear to date to the construction of the many cottages and septic systems that now line a portion of this pond and the increased use of the public beach during the summer. The construction of Route 6 in 1952 made access to the outer Cape in summer easier. Long Pond is increasing significantly in pH in recent decades (see Fig. 5-11).

Ryder

Ryder Pond is one of the most unusual of the kettle ponds. The Ryder Pond sediment core has a late-glacial date of origin of 11,610 +/- 110 yr B. P. on the basal sediments; pollen from boreal forest spruce, green alder, and jack pine dominated at that time. The diatoms in the basal sediments were similar to those in the late-glacial sediments of DuckW. They were primarily acid planktonic *Aulacoseira lirata/ distans/perglabra* and varieties. The sediment core, however, taken from the deepest part of the pond under 11 m of water, was interrupted by sands and gravels. Lake sediment deposition was then intermittent and continuous deposits did not start again until 5145 +/- 70 yr B. P. The core was further interrupted after European settlement with sandy deposits. Ryder Pond, therefore, is a kettle pond, but was affected by a storm event or prolonged drought, or series of events similar to those which mark the differences between Group I and Group II ponds. Indeed, the Ryder Pond truncated stratigraphy suggests that the Group II ponds (see below), or at least Gull Pond, may also have started development as kettle ponds but were similarly interrupted by the events or processes that deposited sands and gravels into Ryder Pond. After 5000 years B.P., the Ryder Pond diatom assemblage alternates dominance between *Cyclotella stelligera v tenuis* and small *Fragilaria*. There was increased presence of acid diatoms in the last few centuries after European settlement as well as diatoms indicative of increased nutrients such as *Asterionella formosa* and *Nitzschia* species. The diatom-reconstructed pH for the length of record for Ryder Pond is 5.6 +/- 0.5 (Table 2-1).

Ryder has had a unique recent chemical history (Winkler 1997b). During the period from 1986 to 1992, measured April pH data showed that Ryder Pond pH systematically declined from pH 5.3 to pH 4.3 (Fig. 2-13) while all other ponds monitored for pH at the time remained relatively stable with no systematic changes. In fact, a subset of pH data from lakes from the Acid Rain Monitoring program in Massachusetts for the same time period showed an increase in pH (Fig. 2-14). The diatom changes in Ryder Pond followed the pH changes very closely as acid littoral diatoms in the pond increased from 30% of the diatom sum to 90% during that time while planktonic diatoms disappeared. The diatom-inferred pH reconstruction closely reproduces the decline in pondwater pH (Fig. 2-15). These data demonstrate the power of diatom-inferred pH to provide reliable estimates of pH in recent decades and therefore gives us more confidence to use this technique to describe the past pH history of a lake. Other biotic changes in Ryder Pond during the pH decline included the appearance of the most sensitive acid-indicator species that were found during acidification experiments in lakes in Ontario and northern Wisconsin (Schindler, 1990; Carpenter et al., 1992).

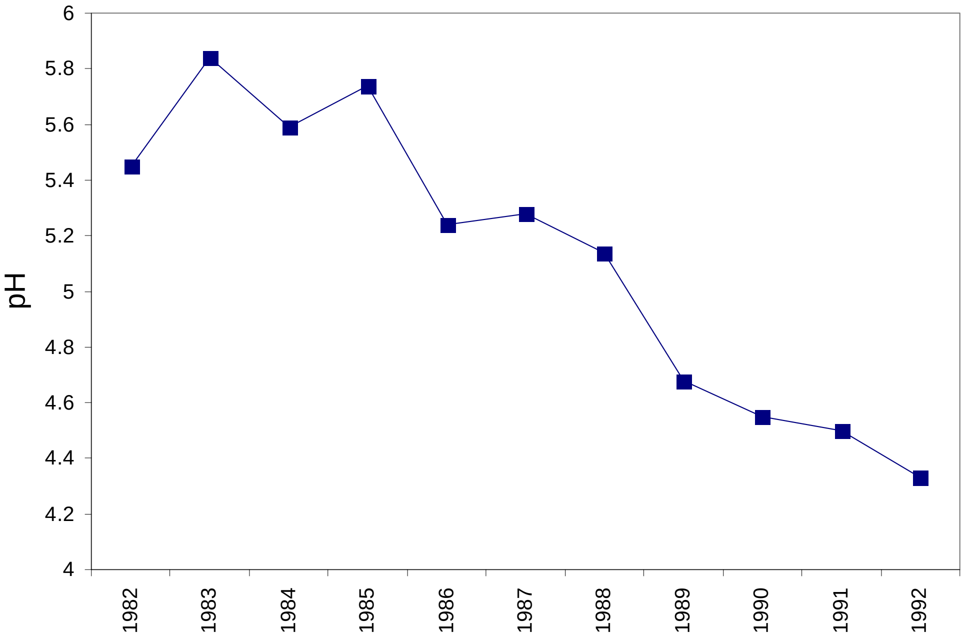

Figure 2-13. Ryder Pond April pH observations (1982-1992).

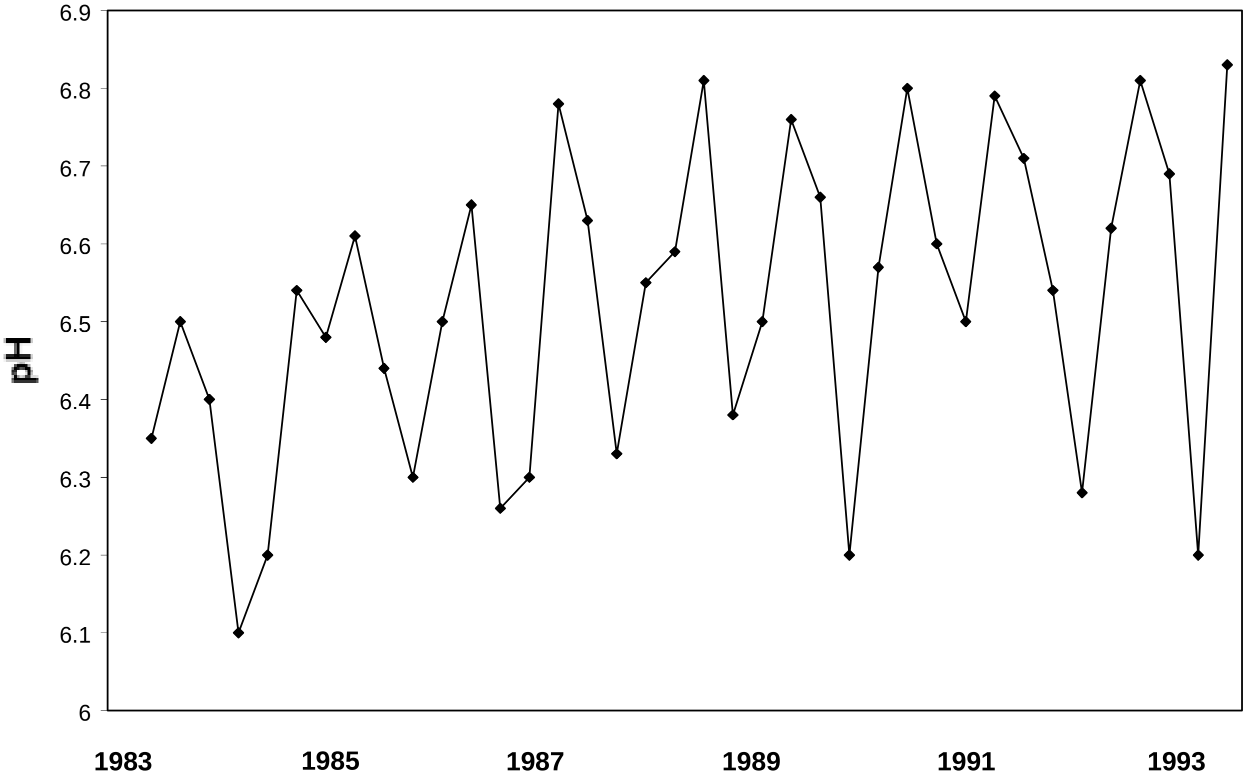

Figure 2-14. Median lake water pH vs. time for 719 freshwater sites sampled in Massachuetts by the Acid Rain Monitoring program (Godfrey et al. 1996).

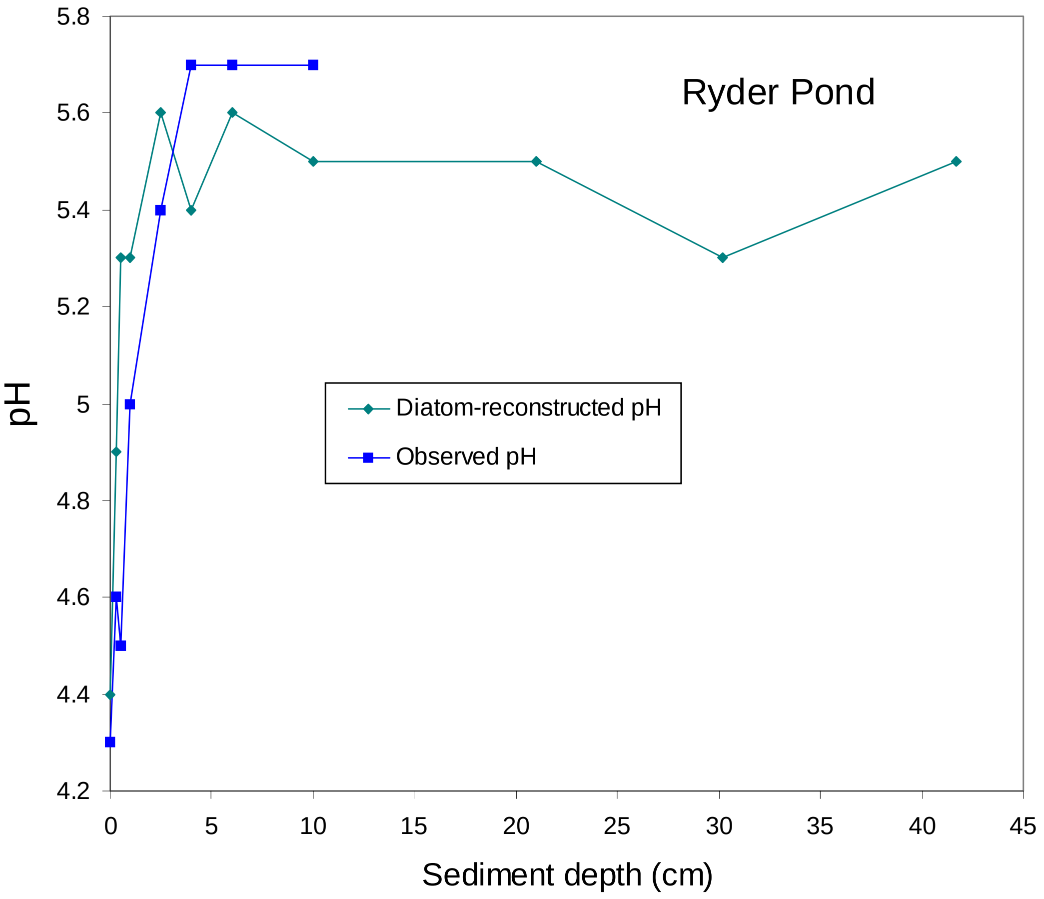

Figure 2-15. Ryder pond 1991 core. Diatom-pH reconstruction for recent decades.

In Ryder Pond there was an increase in filamentous green algae (for example, *Mougeotia*), the appearance of the acid diatom *Asterionella ralfsii v americana*, and the dinoflagellate cf. *Gymnodinium* species. As in the experimental lakes, fish in Ryder Pond were affected by the increased acidity. Examination of 1984 and 1986 fish survey data shows that young-of-the-year smallmouth bass present in 1984 were absent by 1986 (the beginning of the acidification), all minor species of fish declined in abundance by 1986, and pumpkinseed and yellow perch were the only fish reproducing in the pond by 1986. Residents in 1991 reported dead bass floating on the surface of the pond. The lake ecosystem change (a rapid decline in pH) was therefore expressed rapidly by species changes at a population level.

Total annual precipitation (TAP) records from a monitoring station (Truro National Atmospheric Deposition Program station) near the pond indicated that there was a systematic decrease in TAP from a high of 1600 mm in 1983 to less than 1000 mm in 1988 and 1990 (Fig. 2-16). TAP then began to increase again to more than 1200 mm by 1993. The relationship between the decrease in precipitation and the decrease in Ryder Pond pH was very significant. The Ryder Pond pH decline, however, lagged the precipitation decrease by two years (Fig. 2-16). We therefore know that the Ryder Pond pH decline was related to drought. We also know that it was caused by non-seasalt sulfate (NSS) in the drainage basin. The NSS sulfate increased from 20 to 105 μM concurrent with the pH decline from 5.4 to 4.3 (see Fig. 5-21). The NSS sulfate increase may be due to oxidation of reduced sulfur and runoff of sulfate from wetland deposits in the drainage basin which are aerated when the water table is low. Groundwater contribution to the pond decreases during drought resulting in further loss of base cations to the pond.

Although there is little clay in the basal late-glacial sediments, clay and silt in the sand and gravel layers which were laid down in the early Holocene may have formed a partially-perched aquifer for Ryder Pond further separating Ryder Pond from groundwater flow and its acid-neutralizing function. There is no apparent relationship between pH and pond elevation in this region of the Cape.

The exact relationaship between the hydrology of the pond (precipitate-groundwater-runoff-pondwater connection) and the chemistry of the pond has yet to be unraveled, but links among drought, high pondwater sulfate, and low pondwater pH are clear (see Chapter V, Ryder Pond, Figs. 5-20 and 5-21). A big question that has not been answered about the Ryder Pond pH decline is: why, among these 20 Cape Cod kettle ponds, was only Ryder Pond affected so dramatically? There is some indication of decreasing pH during the same period for Slough and Round (east) Ponds; however, the pH decline in these ponds is less severe. Slough declines about 0.5 pH units and Round (east) 0.3-0.4 units. Neither Slough nor Round (east) have a long enough monitoring record to assess whether these pH decreases are unusual.

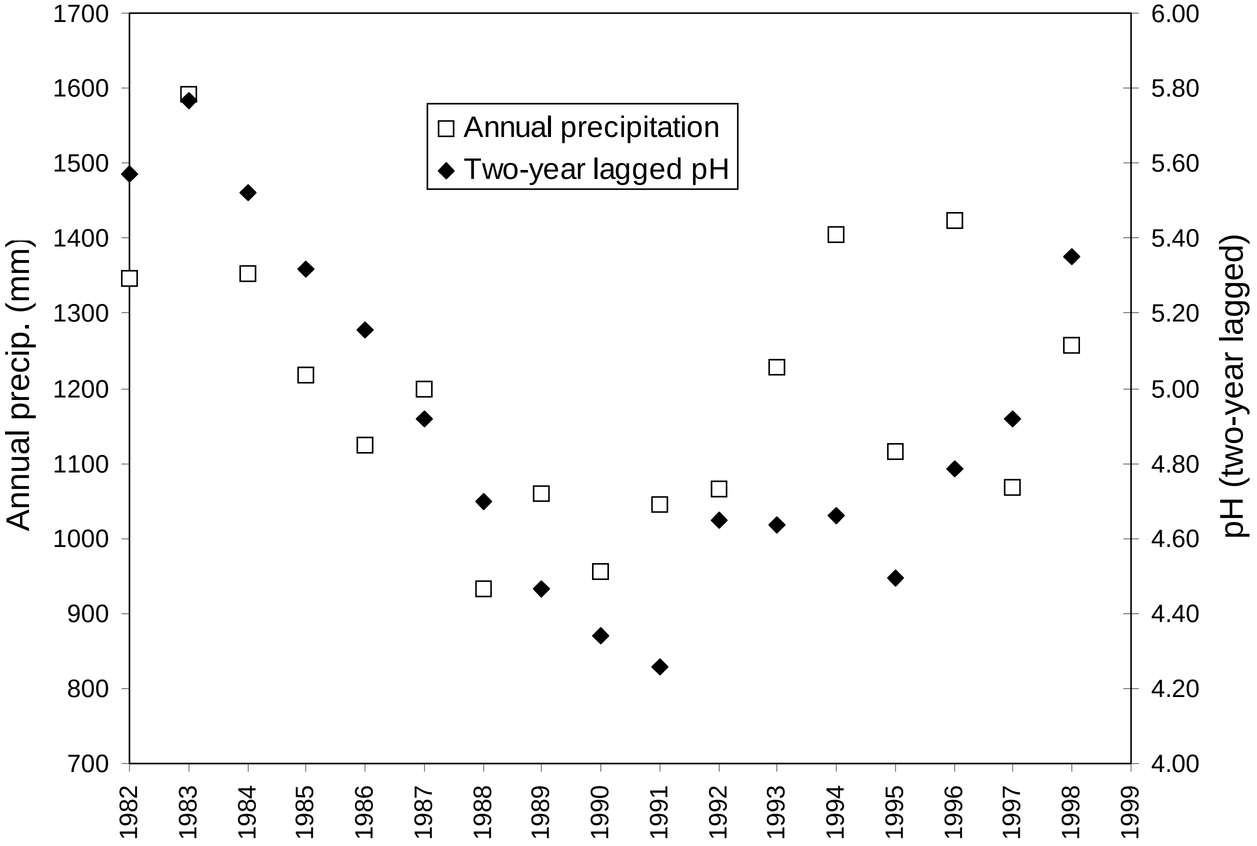

Figure 2-16. Ryder Pond pH lagged by two years against precipitation.

Gull, Higgins, and Herring - the Group II ponds

These ponds differ in major ways from the Group I kettle ponds. First, they are younger (Gull Pond basal organics dated to 5165 +/- 60 yr B. P., while Higgins and Herring ponds have basal dates of 2150 +/- 60 and 2885 +/- 60 yr B. P., respectively). Second, they are connected to the sea through the Herring River channel. Third, they have sand and gravel layers interspersed among their organic lake sediments (Fig. 2-2) similar to those in Ryder Pond. Throughout their length of record they also have a higher pH (Table 2-1), different biota, and different chemistry than the Group I kettle ponds. Interpretation of these data has led to several scenarios which may explain these findings and/or the origin and development of the Gull chain of ponds. They include: incomplete core retrieval; intense storm effects; geomorphic changes due to sea-level rise; barrier beach and salt marsh development; edaphic differences such as clay-rich and clay-poor outwash; their situation at lowest elevation of the ponds studied in relation to groundwater flow; and possible anthropogenic modification of the Herring River drainage basin before European settlement (Winkler 1994; Winkler and Sanford 1995). This region of the outer Cape, because of the direct connection with the sea, is more sensitive to geomorphic and sea-level changes than the region which includes the inland kettle ponds in South Wellfleet, Eastham, and Truro outwash plains (Fig. 2-1).

Gull Pond, the largest and deepest of the Seashore ponds, is at the head of the Herring River drainage. It is presently connected by a narrow channel with Higgins, Williams, and Herring ponds, but diatom (Fig. 2-8) and carbon isotope evidence suggests that this channel was first opened about 2000 years ago when tidal flats extended up the Herring River channel nearly to Herring Pond (Winkler 1994). While the two shallower ponds, Herring and Higgins, have been dominated by similar diatom assemblages throughout their existence, assemblages have become even more similar in the recent sediments due to the modern channels connecting the ponds. Gull Pond stands apart for the first three millennia of its observed sediment record when it was dominated by the circumneutral, planktonic diatoms *Cyclotella stelligera* and varieties (the same taxa that dominate all the Group I ponds) indicating deeper and clearer water. After 2130 +/- 55 yr B. P. (almost the exact time, 2150 +/- 60 yr B. P., that organic deposition began in Higgins Pond) the diatom assemblage in Gull Pond (Fig. 2-8) became more like the assemblages in the other ponds in the system (Fig. 2-1). Gull Pond was dominated at that time by small *Fragilaria* and *Fragilaria crotonensis* and *Asterionella formosa,* indicative of increased nutrients and the higher alkalinity that would be brought in by exchange of water with Higgins and Herring Ponds and the Herring River. Alewives (*Alosa* spp.) also came up the Herring River to spawn in the ponds in the spring (as they do today) contributing to the increase in alkaline and saline conditions in Gull Pond. The similar diatom assemblages in Gull and Higgins Ponds for that interval indicate a connection between the ponds in place for more than a millennium. Explanations for this connection include geomorphic changes in the Herring River basin, increased storminess, increased precipitation, and opening and closing of the channel by Native Americans living near or using the Herring River Basin. Such modifications would not require a high level of technology and Champlain's 1605 map of Nauset Marsh in Eastham shows native fishery structures (Ganong 1922) from which we infer a long-standing Native American fishery. However, the cladoceran assemblages of Gull Pond for the period 2130 yr B. P. to just before European settlement do not show an alewife effect, i.e. no replacement of *Neobosmina tubicen* by *Bosmina longirostris*. Before European settlement the Gull diatom assemblage was again dominated by circumneutral *Cyclotella* species indicating separation between Higgins and Gull ponds. The diatoms in the most recent sediments of Gull Pond (Fig. 2-8 and 2-9) have changed again to an assemblage indicative of nutrient enrichment, a result of the opening of the modern channel between the two ponds and other anthropogenic impacts in the Gull Pond drainage basin. Replacement of *N. tubicen* and *Daphnia catawba* by *Bosmina* occurs after European settlement consistent with Gull Pond being open to alewife migration.

A white precipitate (gull feces?) was found at 40 cm depth in the Higgins Pond core. Chemical analysis of the precipitate recorded high concentrations of phosphorus, sulfur, zinc, and copper.

The addition of nutrients from gull feces in recent years has been quantified for Gull Pond (Portnoy and Soukup 1990). The Higgins Pond core suggests that this mode of nutrient import may also have occurred prehistorically.

Snow

A 75-cm (29-inch) sediment core from Snow Pond (Fig. 2-2) was analyzed for diatoms, pollen, charcoal, and cladocera. Snow Pond sediment from 27 cm depth was dated by ^{210}Pb to have been deposited in about 1869 A. D. AMS-radiocarbon dating yielded a basal date of 6000 +/- 50 yr B. P. and a date of 3470 +/- 35 yr B. P. on sediment from 40-41 cm depth. Basal Snow Pond sediments consisted of fibrous peaty organic deposits (70.6% organic content) that contained abundant charcoal particles and sponge spicules, but no diatoms. Pollen and spore analysis of the bottom sediments record abundant aquatic macrophytes, sedges, grasses and ferns. Upcore sand and sandy gyttja were laid down before 3500 years and the few diatoms found were all small *Fragilaria*. Absence of diatoms and scarcity of cladocera, all of which were littoral species, suggests Snow Pond was a seasonally inundated bog from 6000 years ago to about 3500 yr B. P. when water depth increased. Continuous deposition of gyttja began at about 3500 years ago and abundant limnetic diatoms and limnetic cladocera appeared at this time. There was a *Pediastrum* algae bloom in the early days of European settlement. Small *Fragilaria* and *F. virescens v. exigua* dominated the remainder of the sediments with *Cyclotella stelligera* and varieties until the middle of the 1940s (A.D.) when dramatic changes occurred in the diatom assemblages. Route 6 was built in 1952 and Snow Pond is adjacent to this road. Although Snow Pond has no houses nearby, the building of the major road through the Outer Cape probably encouraged increased use of the pond. Also dust from road building reached the pond and soot increased in the sediments. By 1952 +/- 2.1 A.D. the number of littoral diatoms increased from 25% to more than 60%. Acid *Eunotia* diatoms and other littoral diatoms became abundant and *Cyclotella* and small *Fragilaria* diatoms decreased. Diatoms indicating both increased acidity and increased nutrients appeared. Dinoflagellates became abundant. Limnetic cladocera increased to more than 50% of total cladocera comprising 7 taxa including large-bodied *Daphnia*. Ragweed, plantain, and dock pollen increased and the pollen of oak, other hardwoods, white pine and hemlock decreased. Pitch pine increased in the area around Snow Pond as it did in the region.

How Seashore Ponds Are Similar

The sediment records of all of the ponds contain evidence of land clearance by the European colonists (see Vegetation Changes above). Besides these anthropogenic indicators, increased nutrients to the pond since European settlement and especially in recent decades are evident. These minerals stimulate the growth and decay of algae, dinoflagellates, and other organisms and add to the organic enrichment and eutrophication of the pondwater. Nutrients come to the ponds most directly from local sources such as road runoff, septic system leachate, fertilizer runoff, and recreational use of the ponds, but they may also come from seasalt in marine breezes and fogs and from afar via atmospheric deposition.

Heavy metals including lead (Pb), arsenic (As), selenium (Se), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), nickel (Ni), zinc (Zn), lithium (Li), and mercury (Hg)—as analyzed by ICP-OES and ICP-MS—have also increased in the more recent sediments of all of the outer Cape ponds (Fig. 2-17). Impacts of these toxic pollutants on pond biota are largely unknown, but bioaccumulation and toxicity to zooplankton, fish, and humans have been documented elsewhere (Winkler 1994; Colborn et al. 1996). Changes in diatom morphology to bizarre forms have been interpreted as resulting from increased trace metal loading in freshwaters (Yang and Duthie 1993). In the Seashore ponds, deformed diatoms were found in Long Pond, and worn frustules were found in Higgins and Herring Ponds. However, the worn diatoms may be the result of fish changes and/or zooplankton predation.

A pilot study of element concentrations in cladoceran ephippia (the resting eggs of cladoceran zooplankton) found in the Gull Pond sediments (Winkler 1994) indicates that modern ephippia contain higher concentrations of lead, chromium, arsenic, selenium, barium, and phosphorus than ephippia from lower levels of the core. These results suggest concentration of toxic metals by the biota. They also suggest that the mechanics of bioaccumulation factor into the transfer of some elements through the food web in the pond. Biotic uptake may occur in the water column before chemicals are sequestered in the sediments or during active uptake or passive redeposition from the sediments. The ephippia results are in accord with elevated metal levels found in the modern sediments of Gull Pond. For example, lead (Pb) concentrations are about 136 ppm in the Gull Pond top sediments while lead is less than 7.5 ppm in sediments that date below European settlement. Williams Pond had 99.7 ppm Pb in the top sediments and less than 5.4 ppm Pb in pre-European settlement sediments. Similar elevated values for Pb are found in top sediments of Snow (> 123 ppm) and DuckW (> 255 ppm) and can be compared with much lower Pb values (< 20 ppm in Snow and < 9 ppm in DuckW) in pre-European settlement sediments (M.G. Winkler, unpubl. data). High Pb and other element concentrations were also found in modern sediment samples from ponds in the Provincelands area of the Cape (Winkler 1994). Pb from fuel is disseminated as an aerosol and in runoff from highways. It also comes from decaying lead water pipes and from uses in an array of manufacturing processes.

The natural acidity of these ponds exacerbates the problem of accumulation of heavy metals in the pond sediments. Low pondwater pH changes the solubility of some compounds, increases precipitation of others from the water into the sediments, and changes the solubility of naturally occurring but potentially toxic metals such as aluminum and manganese making them more available to the biota (Hem, 1992). Most of the heavy metals

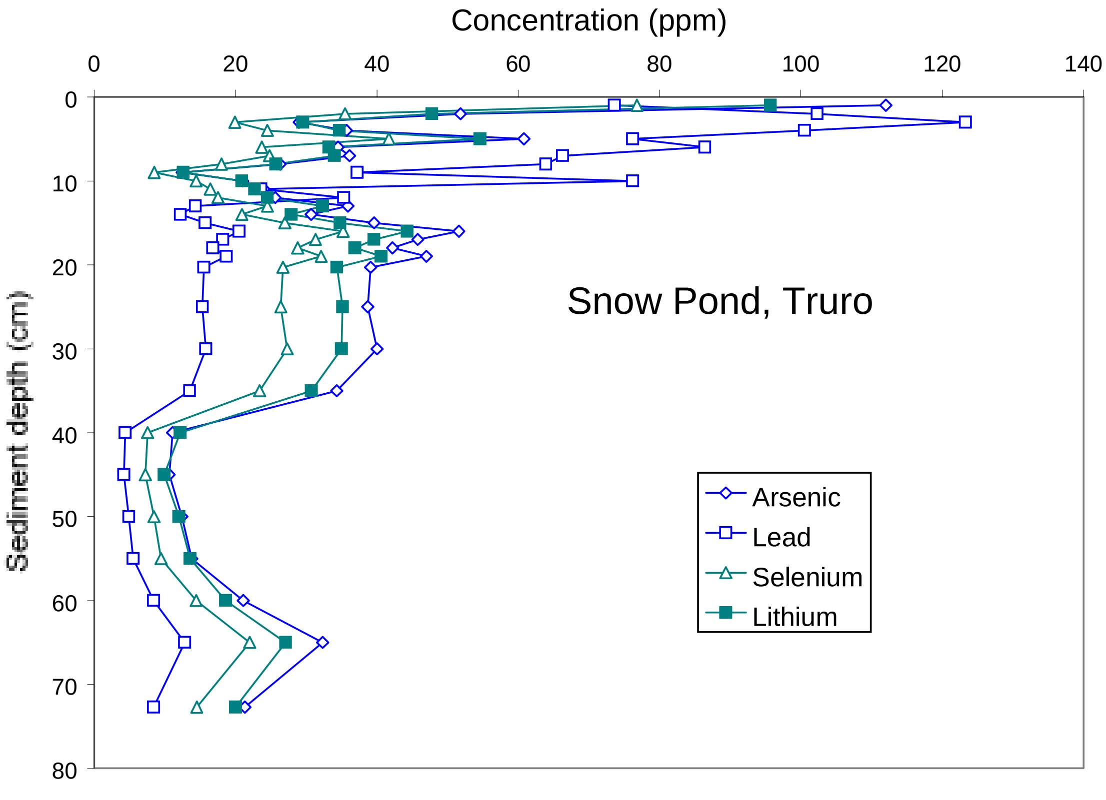

Figure 2-17. Selected metals from inductively coupled plasma-optical emissions spectrometry (ICP-OES) analysis of Snow Pond sediments.

found in the Seashore ponds arrive via atmospheric deposition. For example, mercury (Hg) values in the top sediments of Ryder Pond have increased about 7.5 times since European settlement (Winkler, 1997b). The recent Hg values in Ryder Pond sediments of 0.23 µg/g dry wt. are close to the post-Industrial Revolution mean value of 0.24 µg/g found during a survey of trace metals in lake sediment cores in northern Wisconsin (Rada et al. 1989). The pre-European-settlement value of Hg from Ryder Pond of 0.03 µg/g is in line with pre-Industrial background levels of Hg in Wisconsin lakes of 0.04 to 0.12 µg/g . The similarity in mercury concentrations from kettle lakes half a continent away from each other suggests that the source for Hg in these lakes and ponds is atmospheric and is probably global in extent. Higher levels of these toxic metals come from local point sources.

It is hard to separate which of the above factors dominate the limnology of the ponds today. Most probably all processes (natural and anthropogenic) affecting the ponds since European settlement and the Industrial Revolution are working in concert to change the biota of the ponds.   Shoreline erosion, land use changes and direct recreational use of the ponds are contributing to nutrient increases that, if intense enough, will lead to eutrophication and more rapid filling of the ponds (high sedimentation rates and abundant algal blooms).   Increased heavy metal deposition and storage of these toxic metals in sediments and increased UV-β radiation will change the biota of the ponds. Human use decreases water clarity, while increased UV-β radiation and higher acidity clarify water but change species assemblages and habitat use. The water chemistry changes affect both the exchange of elements at the sediment/water interface and the availability of elements to organisms. We are just beginning to understand the interactions between components of aquatic environments and have found that although some conclusions can be generally applied to groups of lakes, most lakes have attributes that make them unique. There are still many connections and mysteries to be unraveled by continued monitoring and study.

Chapter III. Brief history of monitoring and research

Limnological surveys of the Seashore's kettle ponds began in the mid-1970s with occasional surveys of all the ponds in 1975 and 1976 (Soukup 1977). Pond chemistry and trophic status were characterized with measurements of Secchi depth, chlorophyll α and total phosphorus, and profiles of light, temperature, conductivity and dissolved oxygen. Acid-base balance was poorly documented, however, because: 1) currently available pH electrodes were unreliable in the dilute (low-ionic-strength) pond waters, and 2) no alkalinity data were taken.

The first reliable pond pH data were collected in 1982 using electrodes and quality assurance acquired with CCNS's admission into the National Atmospheric Deposition Program network.

In 1984, CCNS volunteered to serve as the regional field laboratory for the Acid Rain Monitoring project (ARM) funded by the Massachusetts Division of Fisheries and Wildlife (MDFW) and coordinated by the University of Massachusetts Water Resources Research Center (Godfrey et al. 1996). The ARM program provided quality assurance and began an agenda of quarterly measurements of surface water pH and alkalinity for nearly all outer Cape freshwater bodies. Although the ARM program terminated in 1994, Seashore staff has continued the quarterly observations to the present; thus, a continuous 14-year record of pH and alkalinity, and nearly continuous ionic data, now exists.

Systematic pond profiling has been conducted during summer by Park natural resource staff since 1986. Eleven ponds were monitored in 1986 and 1987. Sampled ponds were reduced to seven from 1988 through 1991. The convening of a panel of experts to review the program in 1992 led to an intensified program consisting of spring sampling of all 20 ponds, plus biweekly summer sampling of a representative group, i.e.Gull, Duck, Ryder, Spectacle and Great Truro (Martin et al. 1993). This group of "primary ponds" was expanded to include five more (Great Wellfleet, Dyer, Herring, Long and Snow) in 1996. In addition, sampling of all 20 ponds in August began in that year. The present monitoring schedule and monitoring variables are summarized below (Table 3-1); see the full protocol for monitoring approach and detailed methods (Portnoy et al. 1999). See Appendix A for an explanation of monitoring variables. Note that EPA trend detection research for lake water quality monitoring prescribes at least annual sampling for physical, practical, hydrological and statistical reasons (Loftis et al. 1989).

Besides the general surveys, specific aspects of lake limnology, paleoecology and biogeochemical cycling have been investigated at specific CCNS ponds; each of these studies has produced water quality information. The extensive and comprehensive paleoecological work by M.G. Winkler and P.R. Sanford is summarized in Chapter II. In 1956 and 1957, MacCoy studied light, phytoplankton and especially zooplankton in Duck Pond, Wellfleet, and may have been the first of the scientific community to document its outstanding transparency (MacCoy 1958). An assessment of waterbird contributions to the nutrient budget of Gull Pond produced monthly limnological profiles at both Gull and Duck Ponds in 1979 and 1980 (Portnoy & Soukup 1990). Massachusetts Audubon Society and MDFW monitored the effects of the addition of agricultural limestone to Great Pond Truro, using Ryder Pond as a control; monthly limnological monitoring continued at both ponds from January 1984 to October 1986 (Shortelle & Colburn 1987).

Studies intended to evaluate aquatic plants as indicators of kettle pond water quality include metals analyses of submersed mosses (Farmer 1988), qualitative macrophyte mapping of 17 ponds by Coe and Soukup (1978) and more quantitative sampling by Roman and others (in press) of macrophytes in five ponds in 1995. The latter team used multivariate analyses to relate aquatic macrophyte species composition, cover and associated environmental variables to pond trophic status as described by concurrent monitoring of Gull, Duck, Great-Wellfleet, Great-

Truro and Ryder Ponds. Based on a variety of multivariate methods, it was determined that eutrophic Herring Pond was dominated by floating aquatic vegetation (*Brasenia scheberi*, *Nymphoides cordata*, *Nymphaea odorata*), and the algal stonewort *Nitella*, a community that was probably strongly influenced by high porewater PO_4-P concentrations and fine-grained sediments. In contrast, vegetation of oligotrophic to mesotrophic Duck Pond was sparse, containing no floating aquatics, and was dominated by emergent plants. Low porewater nutrients, low sediment organic content, high water clarity, and low pH best defined Duck Pond's environment. The species composition and relative abundance of aquatic macrophytes provided good indicators of the trophic status of these five ponds.

Table 3-1. Summary of water quality variables by sampling period for the current CCNS Kettle Pond Monitoring Program.

	Quarterly	*Spring*	*Summer*	*August*
Ponds included	All	All	Primary set[c]	All
Profiles[a]	-	+	+	+
Secchi depth	-	+	+	+
Surface water				
pH/Alkalinity	+	-	-	-
NH_4 / NO_3	-	+	-	+
TP	-	+	-	+
Chlorophyll α	-	+	-	+
Major ions[b]	-	+	-	-

[a] Temperature, conductivity, pH, Eh and dissolved oxygen.
[b] SO4, Cl, Ca, Mg, K, Na.
[c] Primary set of ponds includes Duck, Dyer, Great (Truro), Great (Wellfleet), Herring, Gull, Long, Snow, Spectacle and Ryder.

Chapter IV. Water Quality

General limnology and regional context

To understand the special nature of the outer Cape Cod kettle ponds, their physical and chemical characteristics are compared to freshwater ponds and lakes all over Cape Cod, throughout the Commonwealth of Massachusetts, and throughout the northeast U.S. (Table 4-1).

From Table 4-1, it is evident that Seashore pond chemistry reflects a much greater marine influence than that of ponds elsewhere in the Northeast, in Massachusetts and even elsewhere on Cape Cod. Seashore ponds are relatively high in sodium and chloride, the principal dissolved constituents of seawater, and low in calcium and magnesium. The ratios between the various major ionic constituents and chloride, a conservative ion, show Seashore pondwater to approximate dilute seawater much more closely than do the populations of Cape or Massachusetts ponds taken as a whole (Fig. 4-1). The preponderance of marine salts also results in a conductivity nearly three times the northeast US median value (Table 4-1).

Seashore ponds are about one pH unit, or about 10 times, more acidic than the median for all Cape Cod ponds; most CCNS ponds have no bicarbonate buffering capacity (alkalinity < 0 µEq/L). The low pH causes high aluminum dissolution, with concentrations about twice the State median, and very low silica which, though abundant in native sands, requires much higher pHs (>8) for significant dissolution. The sedimentary record (see Chapter II) indicates that most ponds have been acidic for thousands of years, well before the advent of acid precipitation and expected from local soils and acid-

Table 4-1. Median values of physical and chemical variables for Cape Cod National Seashore ponds compared to samples of lakes from the Northeast US (Lindthurst et al. 1986), and from Massachusetts and Cape Cod (Godfrey et al. 1996). CCNS data are from April 1999 except for Mn, Fe, Al and Si from April 1993.

	Northeast US	Mass.	Cape Cod	**CCNS**
Depth (m)	4.2			**8**
Area (ha)	16.7	4.1	3.2	**5.0**
pH	6.8	6.62	6.00	**5.1**
Alkalinity (µEq/L)	137	201	36	**4.4**
Conductivity (µS/cm)	43			**114**
Total phosphorus (µg/L)	9	8		**8.7**
Chlorophyll α (µg/L)				**1.45**
Secchi depth (m)	2.3			**5.4**
Cl^{-1} (µEq/L)	60	423	423	**791**
SO$_4^{-2}$ (µEq/L)	115	167	123	**64**
Na^{+1} (µEq/L)	83	430	446	**583**
Ca^{+2} (µEq/L)	177	273	73	**44**
Mg^{+2} (µEq/L)	70	136	119	**162**
K^{+1} (µEq/L)	12	36	23	**21**
Mn (µg/L)	12	30	10	**50**
Fe (µg/L)	50	230	100	**30**
Al (µg/L)	50	20	20	**45**
Si (mg/L)	1.9	2.5	0.6	**0.06**

forming vegetation. Interestingly, the atmospheric deposition of sulfate, the primary acidifying anion in Cape precipitation, appears to have declined since the mid-1980s (Fig. 4-2).

Fortunately, high marine salt deposition is not accompanied by substantial dissolved nutrients, which if abundant would cause algal blooms. Low productivity is expected with the ponds’ low total phosphorus (TP) concentrations, and evidenced by a median Secchi depth over twice the northeast states median.

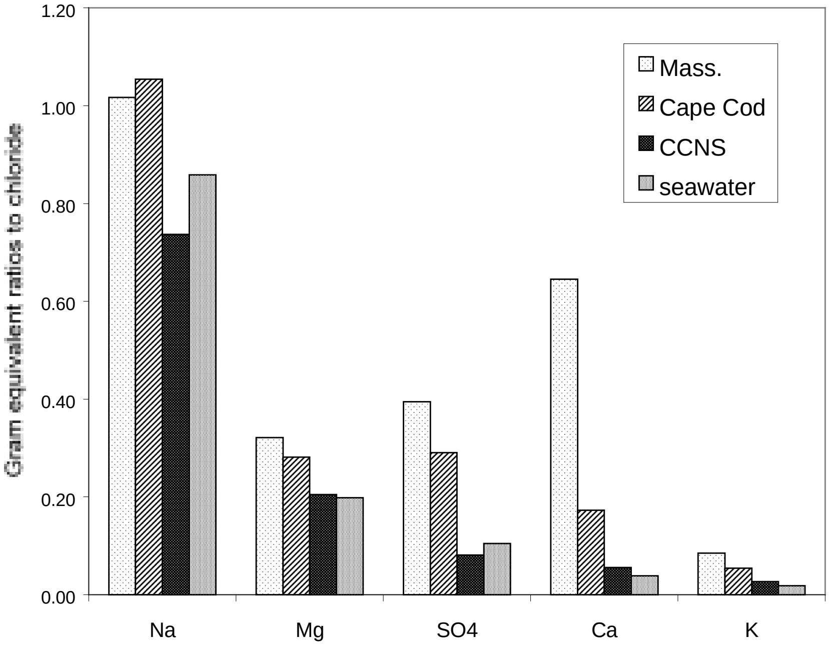

Figure 4-1. Comparison of the major-ions-to-chloride ratios in ponds statewide, in ponds Cape-wide, in Seashore ponds and in seawater.

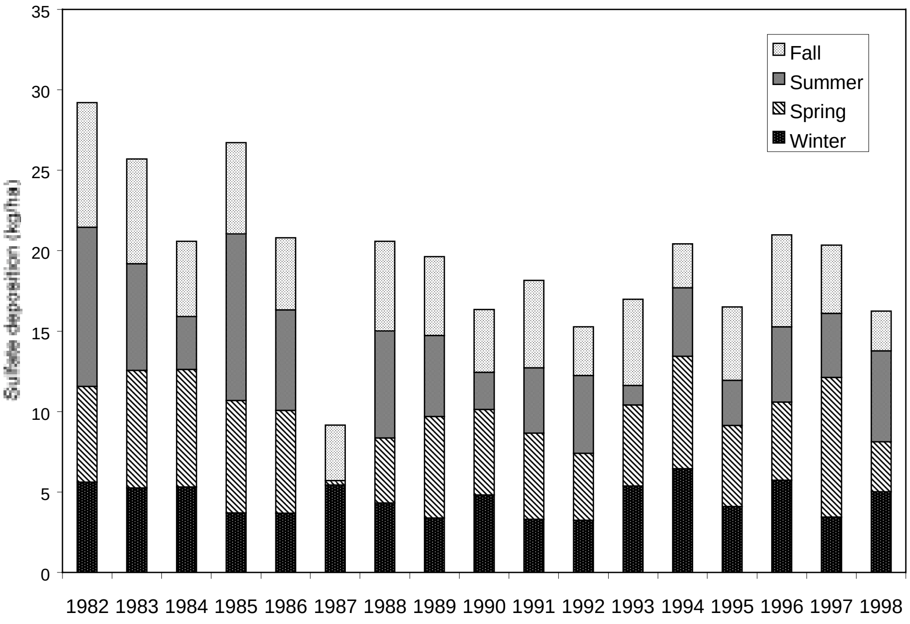

Figure 4-2. Seasonal and annual sulfate deposition on outer Cape Cod. Data are from the National Atmospheric Deposition Program. Summer data are missing for 1987.

Cultural eutrophication

The primary management issue for CCNS kettle ponds is *cultural eutrophication*, defined as an increase in organic loading of an aquatic system by human activities. The addition of nutrients, especially phosphorus, stimulates algal and/or aquatic plant growth. Increased production of drifting algae (phytoplankton) reduces water clarity and loads the water column and sediment with organic matter. Organic loading in turn reduces the concentration of dissolved oxygen, a constituent that is essential for most aquatic animals. In addition, low bottom-water oxygen causes additional phosphorus to be released from the sediment to the water column, further stimulating algal growth and organic loading in a positive feedback loop.

Pond trophic classification

Pond trophic status is commonly assessed by measuring clarity (Secchi transparency), chlorophyll α (an algal pigment that serves as a surrogate for algal biomass), total phosphorus and nitrogen (principal plant nutrients) and the depth and duration of deep-water oxygen depletion (anoxia) during the summer months. A system of classifying lakes as oligotrophic, mesotrophic, eutrophic and hypereutrophic, in increasing order of nutrient enrichment, uses all of these variables excepting total nitrogen and summer anoxia (Heiskary & Walker 1988, Table 4-2).

Total phosphorus and chlorophyll α data are fragmentary before 1997 for the Seashore ponds (see data appendices) and no reliable total nitrogen data have yet been collected. Chlorophyll α has been measured twice annually, in April and August, since 1997 (Table 4-3). [See Appendix 7 for raw data.]

Secchi transparency has been the most frequently measured variable for the Seashore ponds since the mid-1970s; data are reported by pond and year in Chapter V and Appendix 5. Currently Secchi depth is measured biweekly from May through October for the ten most intensively monitored ponds (indicated in Table 4-3), and once in April and August for the remainder. Using Secchi transparency to classify the ponds according to the Carlson index produces the following results (Table 4-4).

Table 4-2. General trophic classification of lakes using the Carlson trophic state index (Heiskary & Walker 1988). Values are annual averages.

Parameter	Oligotrophic	Mesotrophic	Eutrophic
Total phosphorus (µg/L)	4.0	15	40
Chlorophyll α (µg/L)	0.7	3.5	12
Secchi transparency (m)	10	3	1.3

Table 4-3. Chlorophyll α concentrations (ug/L) in surface waters of the 20 Seashore kettle ponds listed in order of increasing chlorophyll α concentration for August 1999, i.e. clearest ponds are at the top. All values are means of triplicate samples. See Appendix 7 for the complete data set. Ponds in bold letters are monitored biweekly during the annual stratification period.

	1997		1998		1999	
	April	August	April	August	April	August
Horseleech	0.25	0.34	1.02	0.62	0.52	0.11
Higgins	0.73	0.55	1.69	1.92	1.46	0.84
Great T		0.37	0.18	0.93	1.50	0.92
Spectacle	0.36	0.26	0.71	1.87	0.79	0.99
Snow		0.11	1.68	0.67	1.77	1.05
Dyer		1.72	0.17	0.80	0.85	1.14
Long	0.59	2.98	0.54	1.11	1.35	1.29
Gull	0.53	0.39	1.94	0.31	2.72	1.37
Round East	0.50	0.97	0.45	0.80	2.36	1.47
Duck		0.79	0.82	1.16	1.22	1.50
Slough	0.58	1.03	5.96	2.76	0.46	1.83
Northeast				1.07	1.15	2.33
Round West	0.14	1.37	0.53	1.14	0.42	2.48
Southeast	1.11		0.58	14.46	2.62	3.14
Great W		1.05	0.52	1.87	0.92	3.47
Kinnacum	1.95	1.19	10.06	8.28	10.55	7.97
Ryder		0.51	2.17	8.19	0.74	8.63
Williams	1.25	7.59	2.09	12.46	2.49	12.61
Herring	0.74	1.39	1.25	6.65	2.24	15.51
Turtle	3.06	3.06	1.43	10.46	1.89	16.15

Table 4-4. Pond trophic status in 1999 based on summer biweekly Secchi depth observations of clarity.

	Mean summer Secchi (m)	Trophic class
GREAT(W)	8.1	oligotrophic
GULL	7.5	“
LONG	6.9	“
GREAT(T)	6.6	“
DYER	6.1	“
SPECTACLE	6.1	“
ROUND EAST	5.8	“
SNOW	5.7	“
DUCK	5.1	mesotrophic
HIGGINS	5.1	“
ROUND WEST	4.6	“
HORSELEECH	4.0	“
RYDER	3.9	“
SLOUGH	3.8	“
SOUTHEAST	3.4	“
NORTHEAST	2.9	“
HERRING PD.	2.2	“
KINNACUM	1.6	eutrophic
WILLIAMS	1.5	“
TURTLE	1.3	“

Oxygen profiles as a monitoring tool

To better characterize trends in water column productivity and possible eutrophication, the CACO program recently extended biweekly sampling of oxygen profiles to completely bracket the spring-summer-fall period of water column stratification and deep-water oxygen depletion (hypolimnetic anoxia). Quantifying the intensity (depth and duration) of anoxia requires frequent (e.g. biweekly) depth profiles of dissolved oxygen throughout the typical May through October period of water column stratification. Monitoring data of this intensity have only been collected from a group of ten “primary” Seashore ponds in 1999: Duck, Dyer, Great-Wellfleet, Great-Truro, Gull, Herring, Long, Ryder, Snow and Spectacle. In the future these data will be used with pond bathymetry to compute a summary statistic (e.g. “anoxic factor”, Nurnberg 1995) to represent the depth and duration of hypolimnetic anoxia, and potential phosphorus release from the sediments. Results to date are interesting in showing how different the ten ponds are in the depth and timing of hypolimnetic anoxia, as well as the necessity of sampling throughout stratification to adequately represent and quantify this important symptom of eutrophication (Fig. 4-3).

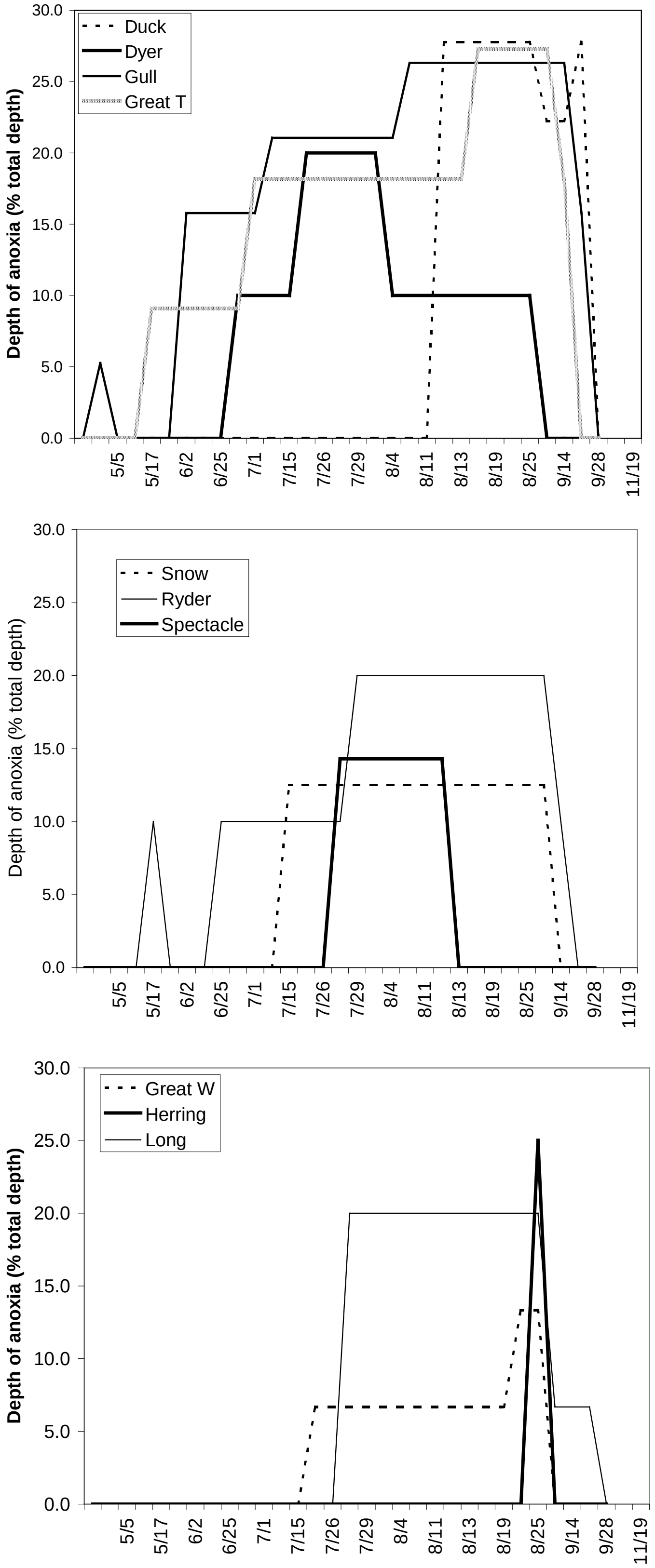

Figure 4-3. Duration and depth (as percent of total depth) of hypolimnetic anoxia in 10 ponds monitored biweekly in 1999.

Phosphorus sources contributing to cultural eutrophication

The element phosphorus, which limits algal growth in the freshwater kettle ponds, can arrive in the water column from in-flowing groundwater, atmospheric deposition, waterbird feces, soil erosion, human swimmers, and human waste from shoreline septic systems. Research has shown that phosphorus influx to the ponds from unpolluted groundwater, the atmosphere, and, except for Gull Pond, waterbirds is minor (Portnoy & Soukup 1990). Nutrient input from soil erosion has not been assessed but may be important along steep pond shores with increased human traffic. Urine from swimmers may be a substantial source of phosphorus in small, heavily used ponds (John Colman, USGS, personal communication) as humans excrete 2-2.5 grams of phosphorus in urine each day (Harper 1969).

In addition, all ponds have a large sedimentary reserve of phosphorus that can be released by sediment disturbance (re-suspension) or oxygen depletion (Mortimer 1942). The phosphorus-rich organic sediments of all but the shallowest ponds, e.g. Herring, Williams or Kinnacum, are protected from mechanical disturbance by the ponds' great depths. On the other hand, deepwater oxygen depletion is common at the kettle ponds in summer. Sedimentary phosphorus release due to oxygen depletion requires that a pond first stratify into warm-surface and cold-bottom waters that do not mix. Once isolated from atmospheric oxygen, bottom waters become oxygen-depleted (anoxic) by microbial respiration. Anoxic conditions cause the chemical release of phosphorus otherwise bound to minerals at the sediment surface.

The capture of solar energy as heat in surface waters causes thermal stratification. Particles in the pondwater, e.g. algal cells, increase the absorption of heat to warm the surface waters. Thus, the availability of phosphorus for algal growth in spring and early summer enhances the thermal stratification that leads to deepwater oxygen depletion and consequent "internal loading" of phosphorus from the sedimentary reserve. If the surface water is isolated from the sedimentary phosphorus supply during summer stratification, increases in algal growth during this period must be fueled by pollution from the shallow littoral zone and watershed, and not from internal loading.

Trends in pond water clarity through spring and summer may provide insight into the relative importance of internal loading versus on-going watershed pollution at each pond. As mentioned, during summer stratification most phosphorus released from the sediment is trapped in stagnant bottom waters and cannot fertilize phytoplankton growth in the well-lit surface waters; therefore, ponds receiving significant non-sedimentary phosphorus loading, i.e. from watershed pollution or littoral sediments, should show decreasing clarity as the summer progresses. In contrast, ponds where ongoing watershed pollution is less important in their annual nutrient budgets than the background supply of phosphorus should show little change in clarity throughout the summer stratified period.

For example, Secchi depth data for Duck Pond suggest a continual supply of "new" phosphorus from watershed pollution; clarity declines throughout the summer (Fig. 4-4). Gull Pond's Secchi depths are much more stable, suggesting that algal production is principally controlled by the recycling of phosphorus supplied initially to surface waters prior to stratification. Thus, ponds like Duck may be much more sensitive to present and future watershed loading of phosphorus than Gull; however, this relationship needs more study.

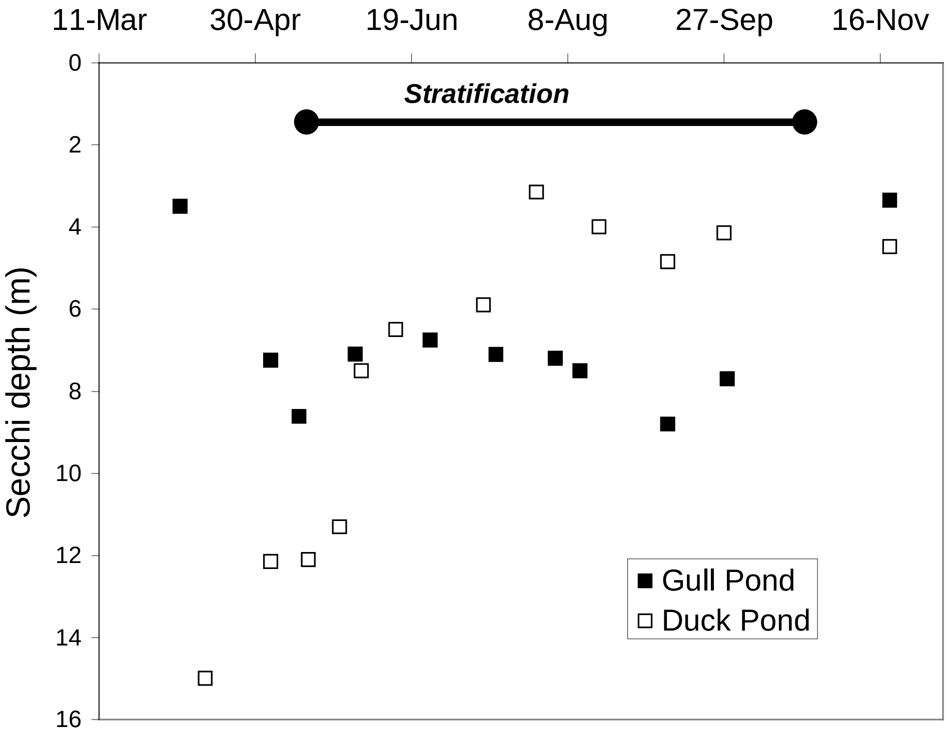

Figure 4-4. Biweekly (1999) Secchi transparency data for two Seashore kettle ponds.

The question of nitrogen saturation

With increased atmospheric deposition of nitrate (NO_3) in acid rain, watersheds and ponds can become "nitrogen saturated" (Kelly et al. 1990). Nitrogen saturation occurs when the nitrogen-removal capacity of the ecosystem, through algal assimilation and denitrification, is exceeded with the excess nitrogen accumulating as dissolved NO_3. With increased use of shoreline dwellings, shoreline septic systems can also represent a source of nitrate to downgradient pondwaters. Nitrate, unlike phosphate, is highly mobile in Cape Cod soils. Nitrate-rich wastewater plumes may discharge into downstream pondwaters with little attenuation of their nitrate load. Nitrate concentrations over 1 micromolar may indicate nitrate saturation of the pond system (Kelly et al. 1990).

According to the above definition, all of the Cape ponds appear to be nitrate-saturated based on the Park's April 2000 survey of this constituent in pond surface water (Fig. 4-5). Because they are all within 6 km of one another, atmospheric nitrate loading per unit surface area should be similar. Also, pondwater nitrate does not appear to correlate with the size of the area contributing water to each pond. Nitrate from upgradient septic systems is therefore implicated as the source of high nitrate. However, statistical analysis (regression) shows no significant relationship between the number of shoreline homes and pondwater nitrate, even when the former was made proportional to pond area or volume. The question of nitrate (as well as phosphorus) transport from shoreline septic systems to the ponds is the subject of newly funded research (Colman et al. 2000).

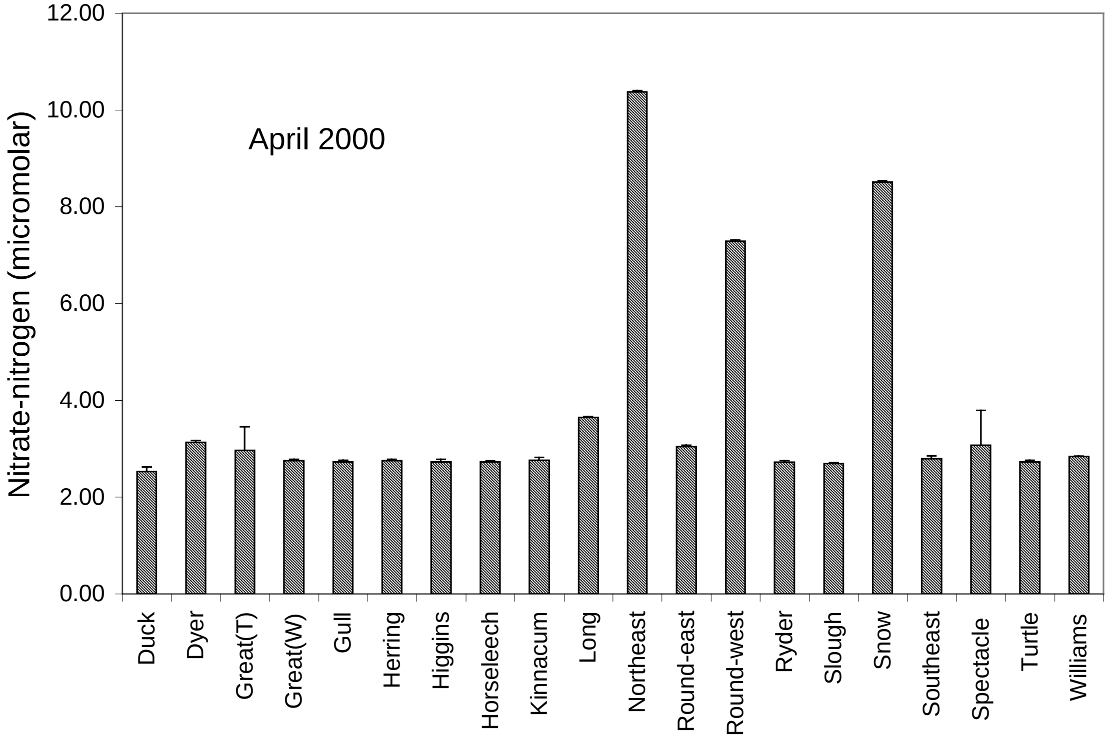

Figure 4-5. Nitrate-nitrogen in pond surface water in April 2000. Mean ± SE; N = 3.

Chapter V. Pond-specific characteristics and trends

Duck Pond, Wellfleet

Site-specific studies

Because of this pond's extreme clarity and isolation from most development, it has been a favorite for study since at least the 1950's. MacCoy (1958) studied transparency, phytoplankton and especially zooplankton vertical migrations at Duck Pond in the summers of 1956 and 1957, with anecdotal accounts of larger biota and limited water quality data.

Duck Pond's largely undisturbed watershed has made it attractive as a focus for intensive paleoecological and paleolimnological research since 1980 (Patterson et al. 1984, Winkler 1982, 1985, 1988). The thick (4-m deep) organic sediments in the pond's deepest basin have been cored and interpreted to reconstruct a 12,000-yr post-glacial history of regional climate, fire frequency, and vegetation as well as local water quality and the effects of nearby land use.

Two studies of the hydrologic relationship between Seashore ponds and the surrounding aquifer have utilized Duck as representative of the land-locked kettle ponds (Horsley & Witten 1996, Sobczak et al., in review). Duck Pond is positioned at the very top of the fresh groundwater lens which forms a mound toward the center of the outer Cape peninsula. Water table mapping and modeling showed that groundwater flows into the pond from all around its perimeter; pondwater discharges back into the aquifer through deep pond sediments. This system limits the size of the "watershed", or area contributing water to the pond, and therefore limits the amount of dissolved substances, including nutrients and base cations, that leach into the pond.

Modern limnology and trends

This 5.1-ha (12.6 -acre) 18-m (60-ft) deep kettle is located at the top of the fresh Chequesset groundwater lens in South Wellfleet. Pondwater is acidic and very clear. The apparent slight increase in pH since the early 1980s, may be a sign of increased nutrient loading (Fig. 5-1); however, the change is not statistically significant.

Transparency data dating back to the mid-1950s show substantial decreases in clarity between 1958 and 1975, and between 1975 and the early 1980s (Fig. 5-2). A possible source of added nutrients is the evident, but unquantified, swimmer use of the pond over the past two decades. Swimmers cause shoreline soil erosion and, with no nearby restroom, likely urinate in or near pondwaters.

Another potential indicator of increased pond productivity due to nutrient loading is the pondwater sulfate to chloride ratio. As for many of the Seashore ponds, there has been a decline in the April (mixed water column) sulfate:chloride ratio since the mid-1980s despite fairly constant sulfate deposition from rain and snowfall (Fig. 5-3). [Sulfate is the primary acidifying anion in Cape Cod precipitation.] A decrease in pondwater sulfate, relative to the conservative ion chloride, suggests increased removal of sulfate by anaerobic bacteria. These microbes thrive in oxygen-free environments that are supplied with copious organic matter; they respire sulfate instead of oxygen as they break down the organic matter to obtain energy for growth. Increased water column production would theoretically increase organic loading and decrease dissolved oxygen concentrations in bottom waters, leading to increased sulfate respiration and decreasing the sulfate:chloride ratio.

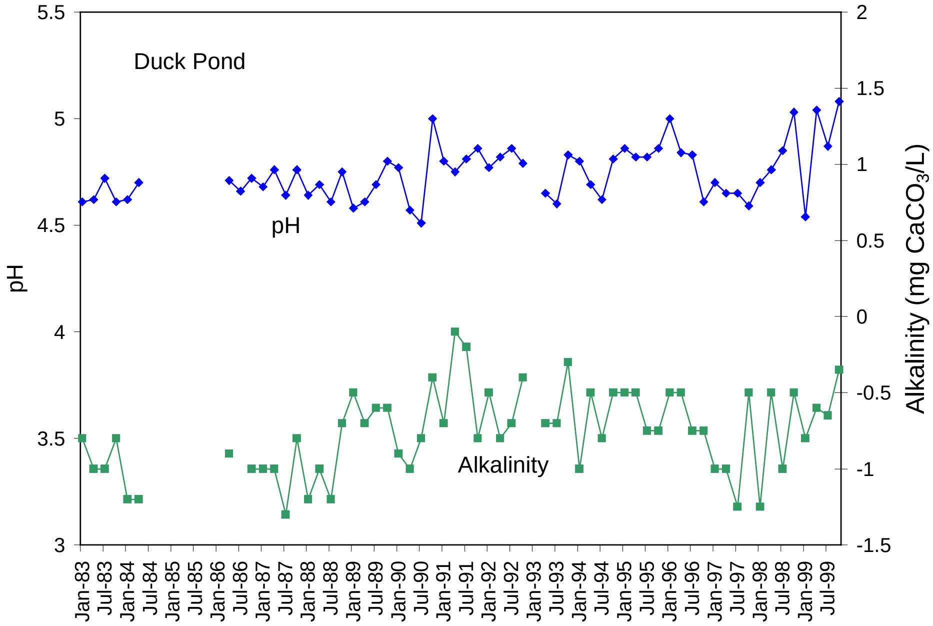

Figure 5-1. Duck Pond pH and alkalinity trends.

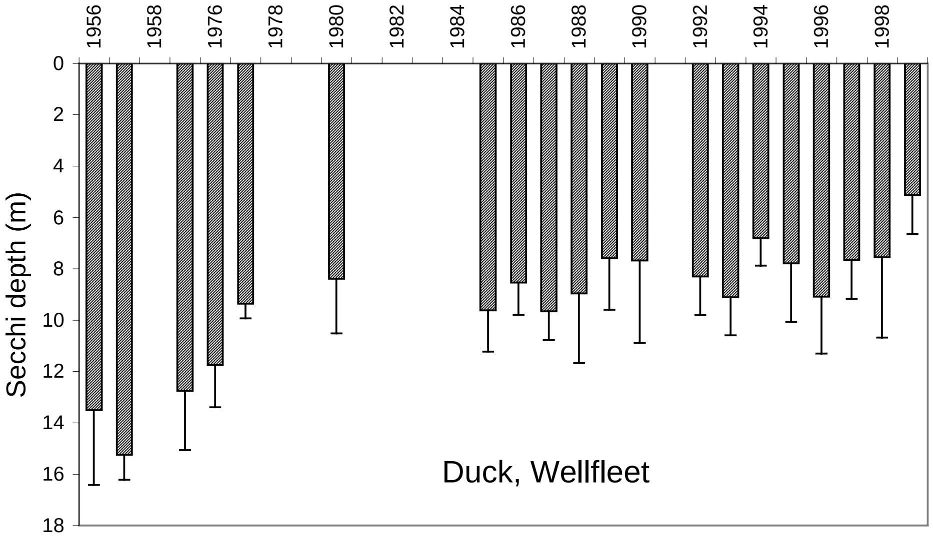

Figure 5-2. Trends in Secchi transparency at Duck Pond. Data are means of April through September observations (± SD).

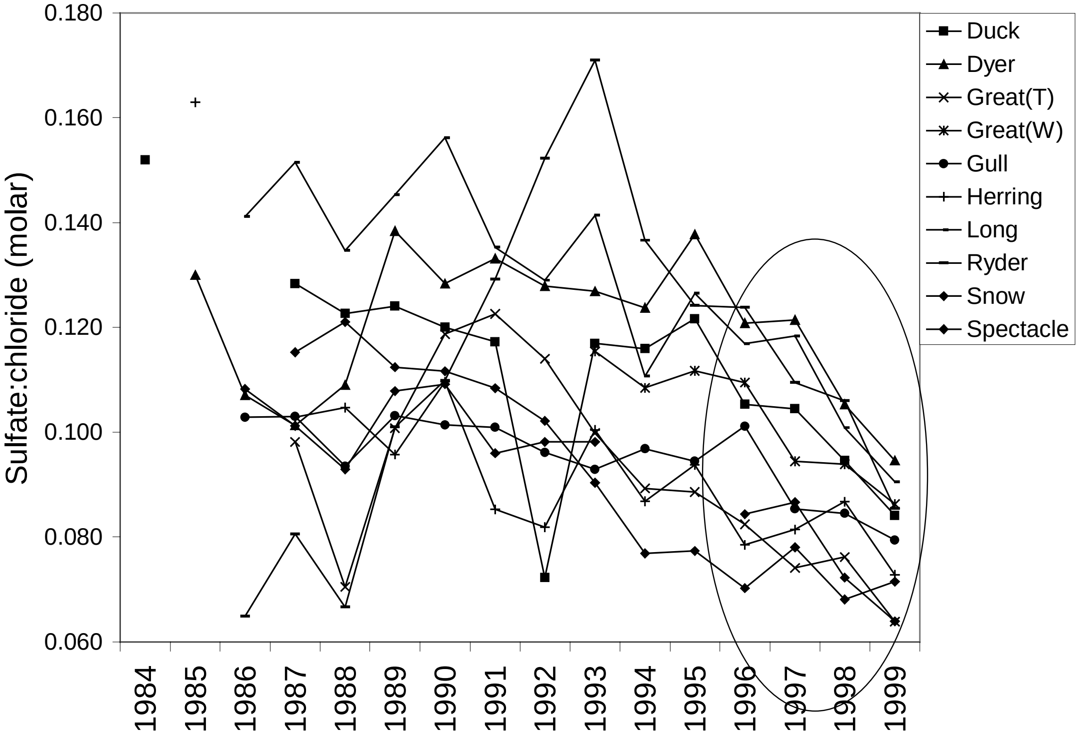

Figure 5-3. Trends in April sulfate:chloride ratios in ten Seashore ponds. Note declining ratios since about 1995.

Dyer Pond

Although more shallow than some of the other landlocked kettle ponds, Dyer shows high clarity with Secchi depths almost always over 5 meters (Fig. 5-4). A major hiatus in the monitoring record occurred between 1991 and 1996 because Dyer was initially excluded from the set of "primary ponds" sampled on a biweekly basis through the summer. With the limited data, trends are not apparent, except to say that this remote pond remains very clear. Thermal stratification of the water column and oxygen depletion at depth begins fairly early, i.e. late June, and lasts until late August, probably because Dyer is relatively sheltered from winds that would otherwise promote mixing. Anoxic bottom water accumulates through the summer months, until cooler air temperatures in late August cause surface waters to cool and the pondwaters to completely mix. This pond is a bit more remote than Duck Pond and has no formal parking, perhaps explaining its relatively higher clarity (Fig. 5-4).

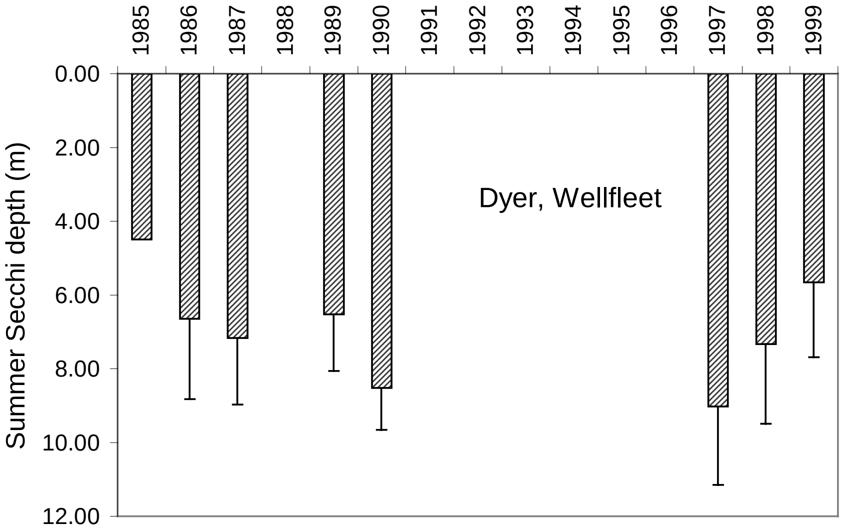

Figure 5-4. Trends in Secchi transparency at Dyer Pond. Data are means of April through September observations (± SD).

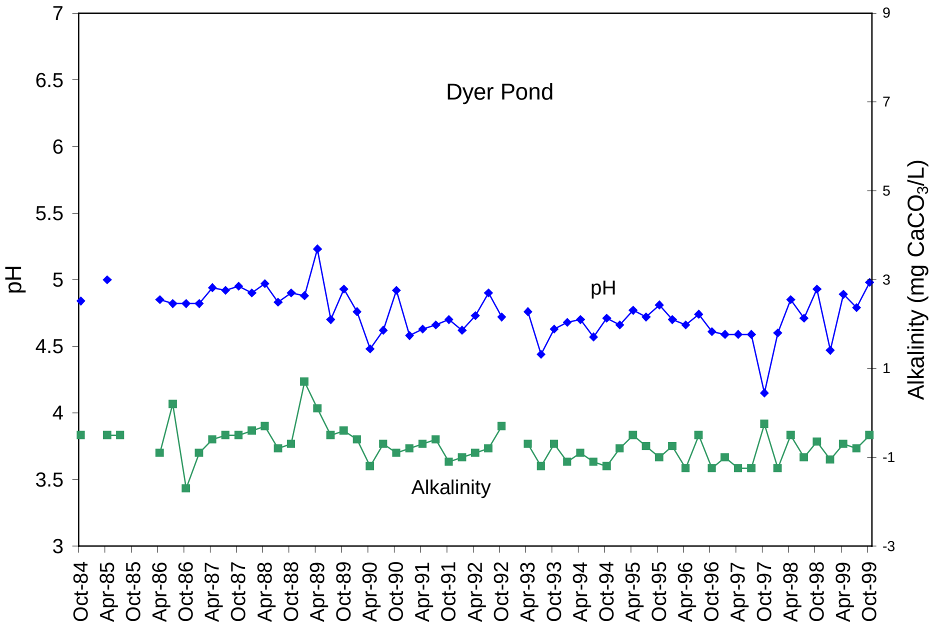

Figure 5-5. Dyer Pond pH and alkalinity trends.

Quarterly sampling for pH and alkalinity has continued uninterrupted since the mid-1980's. There has been little change in acid balance at Dyer pond over that period (Fig. 5-5).

The Great Pond (Wellfleet) Complex – including Southeast, Northeast

Great Pond and its satellites are similar in pH and alkalinity, with the exception of shallow and muddy Turtle Pond, presently more an emergent wetland than a kettle pond. Great, Southeast and Northeast appear acidic and oligotrophic, i.e. generally poor in acid neutralizing capacity (alkalinity), nutrients and the algae and plants that depend upon the latter for growth. Great Pond transparencies are extremely high (Fig. 5-6), particularly in spring when a Secchi disk is often visible at a depth of 15 meters on the pond bottom. Data are insufficient at present to indicate significant changes in water clarity. Quarterly monitoring shows that alkalinity and pH have changed little since the mid-1980’s (Fig. 5-7).

Southeast Pond shows a recent increase in pH with fairly stable alkalinity. Although the pH change is not statistically significant, this pond may be suffering increased nutrient loading (Fig. 5-8). A summer home with on-site septic system occupies the sand spit separating Great and Southeast Ponds. Given its proximity and low elevation (and nearness to the water table) this wastewater system likely contributes nutrients to both ponds, with expectedly greatest impact to the much smaller water body.

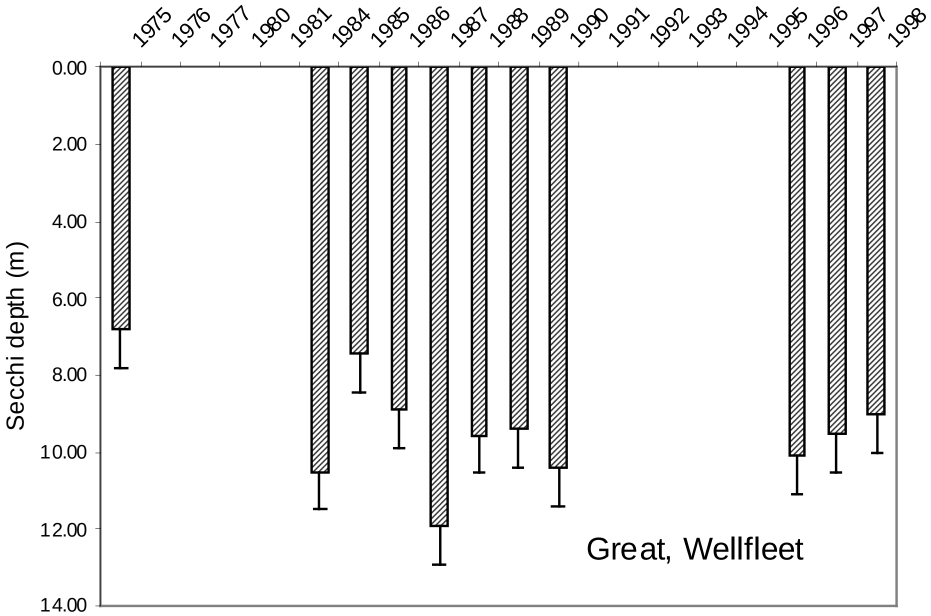

Figure 5-6. Trends in Secchi transparency at Great Pond (W). Data are means of April through September observations (± SD).

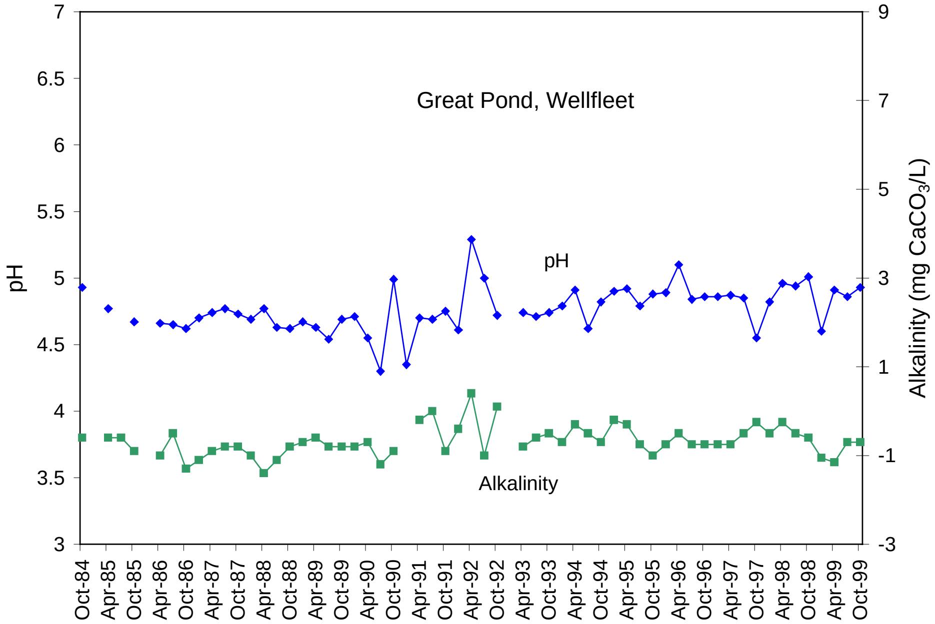

Figure 5-7. Great Pond (W) pH and alkalinity trends.

Northeast Pond was among the ten ponds with nitrate concentration well over 1 micromolar in August 1999; in fact, nitrate-nitrogen was twice that of Great Pond (Fig. 4-5). Nitrate is a highly conservative constituent of wastewater in the Cape Cod aquifer; its abundance in Northeast Pond suggests an upgradient source of pollution. However, an anthropogenic source of nutrients to Northeast Pond is unclear because adjacent dwellings are set back from the shore. pH and alkalinity have changed little since the early 1980's (Fig. 5-9).

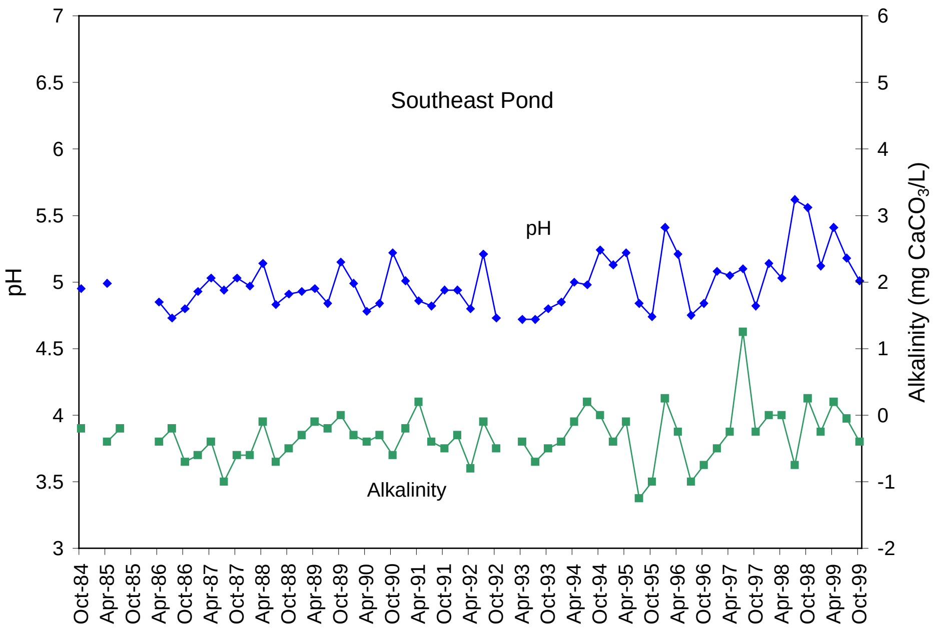

Figure 5-8. Southeast Pond pH and alkalinity trends.

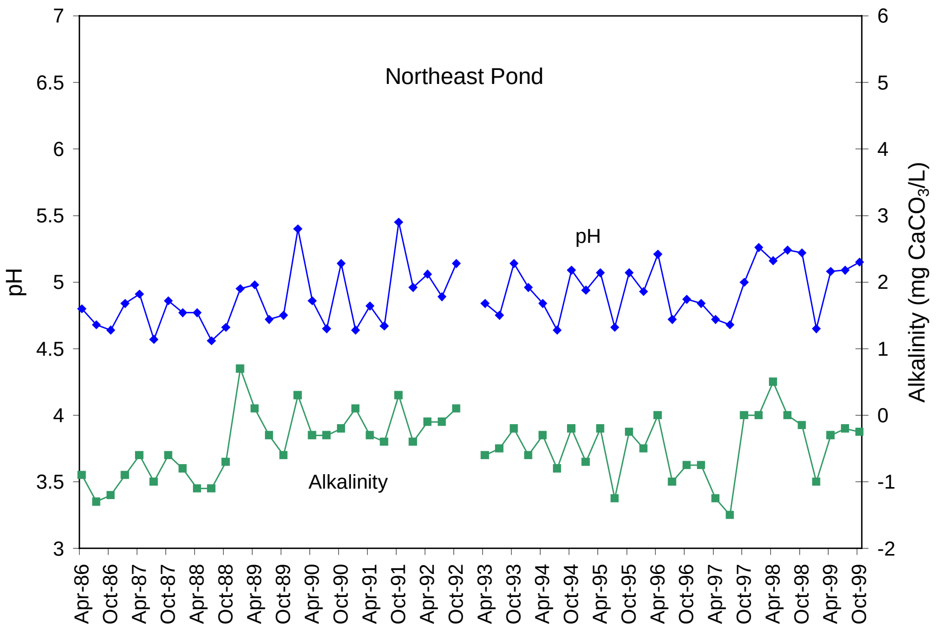

Figure 5-9. Northeast Pond pH and alkalinity trends.

Long Pond

Long Pond has two distinct east and west basins; however, monitoring has focused on the latter because of the presence of the Town landing and beach area which funnel most human use to the west end. Long is a very deep (15 meter), clear and acidic kettle pond with Secchi transparencies ranging from six to ten meters (Fig. 5-10). Biweekly monitoring of water quality was conducted by Seashore staff during summer from 1985 to 1991, and from 1996 to the present. The apparent decline in transparency since the late 1980's is not statistically significant.

The Long Pond pH record shows a slightly increasing trend over the past 10 years suggesting increasing productivity (Fig. 5-11). Increased pH can signal higher algal production as the phytoplankton consume CO_2 (carbon dioxide) and thereby reduce the water-column concentration of carbonic acid. Increased sulfate and nitrate removal, e.g. by algae or sulfate reducing or denitrifying bacteria, can also cause pH to increase, but this, unlike CO_2 uptake, would be accompanied by increased alkalinity which is not evident in the record.

Although naturally nutrient poor, Long has the highest density of shoreline homes within its watershed (Table 1-1). The public beach is very heavily used during summer, with only portable toilets for restrooms. It is likely that the pond is receiving nutrients both indirectly from surrounding on-site wastewater leachate and directly from human excretion. Shoreline soil erosion is another nutrient source, and the intensity of summer activity around the Town beach disturbs forest soils which may contain substantial phosphorus. Fortunately, recent revegetation of the old Town parking area has greatly reduced soil disturbance and erosion.

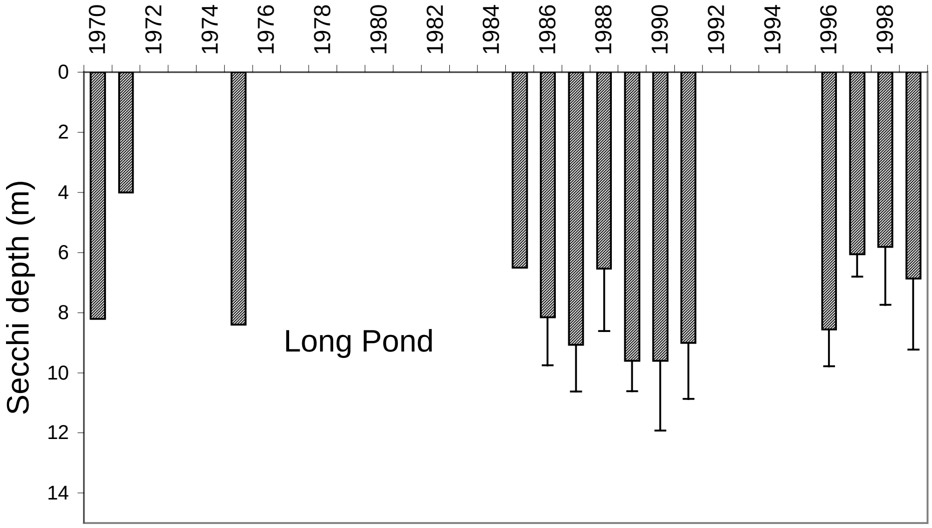

Figure 5-10. Trends in Secchi transparency at Long Pond. Data are means of April through September observations (± SD).

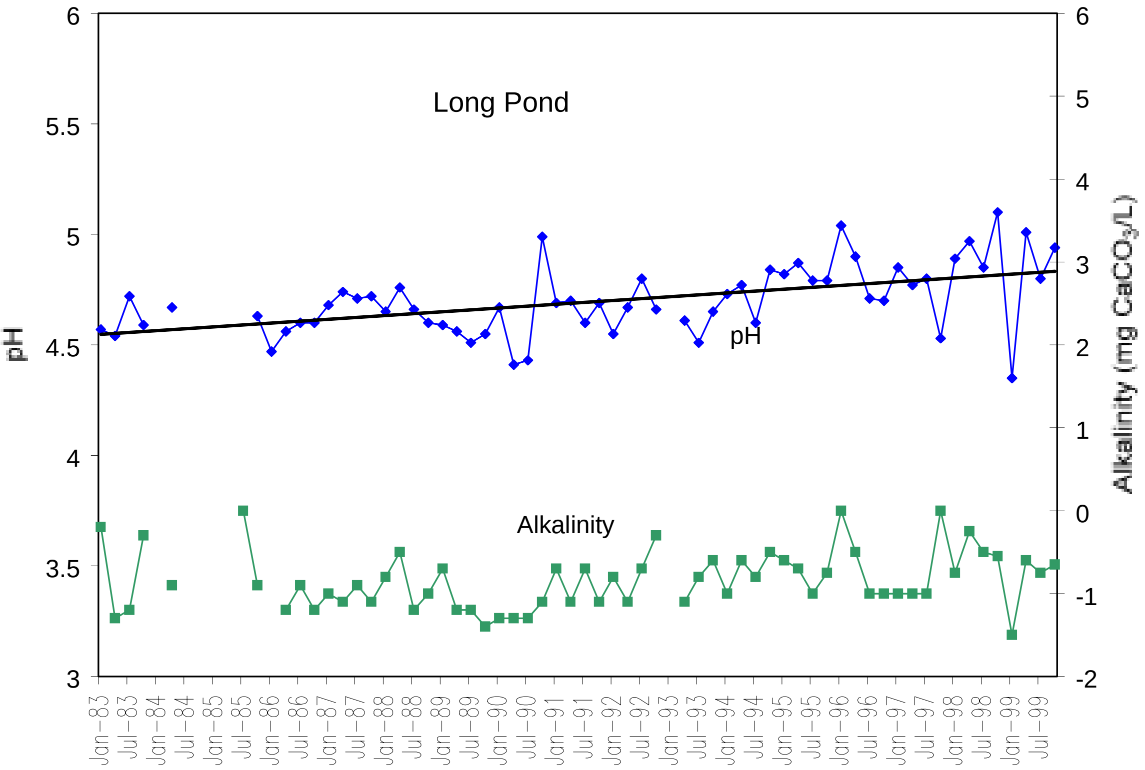

Figure 5-11. Long Pond pH and alkalinity trends. A significant increase in pHis shown by the regression line.

Great Pond - Truro

The Commonwealth has treated land-locked Great Pond with agricultural limestone at least twice, in 1975 and 1985, to raise pH and enhance stocked trout survival. These liming events increased modern pH and alkalinity above natural conditions. Unfortunately, pH measurements of these low-ionic-strength kettle pond waters require special electrodes that were generally unavailable until the 1980's; therefore, pH observations made before the 1975 liming are unreliable. However, pH reconstructions from diatom assemblages in the sediment core from Great Pond document past changes in pH (see Chapter 2 and Table 2-1). The addition of ground limestone, and the stocking of non-native fish, may have also affected the pond's trophic structure, i.e. the density, size and species composition of predators and their prey, and therefore affected phytoplankton and water clarity (Shortelle & Colburn 1986, 1987).

With summer Secchi transparencies of 4-6 meters, Great Pond is moderately productive for a landlocked kettle pond, despite the low density of shoreline homes and near absence of swimmers (Fig. 5-12). Soil erosion is confined to one informal beach on the pond's eastern shore.

The liming event in March 1985 is evident in the pH and alkalinity data (Fig. 5-13). In general, it appears that Great Pond returned to its pre-liming pH and alkalinity by the early 1990's.

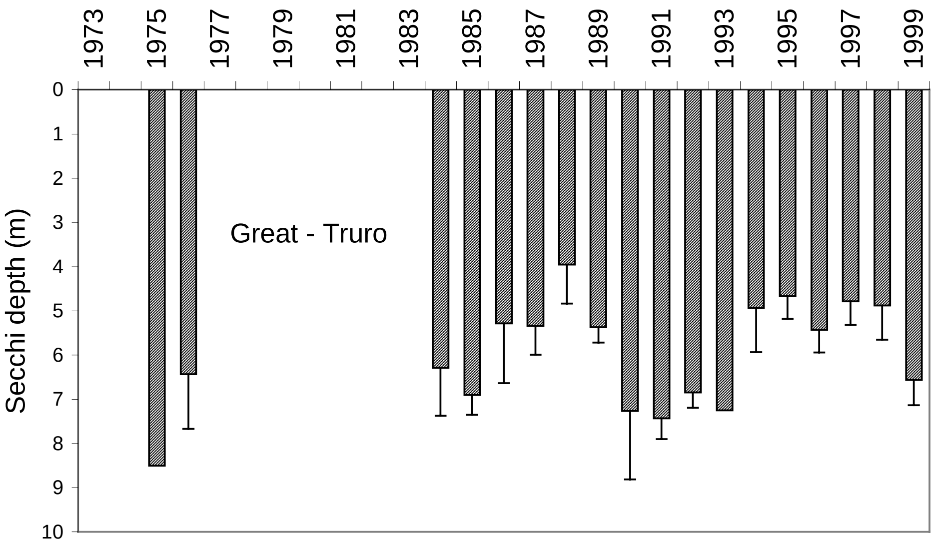

Figure 5-12. Trends in Secchi transparency at Great Pond (T). Data are means of April through September observations (± SD).

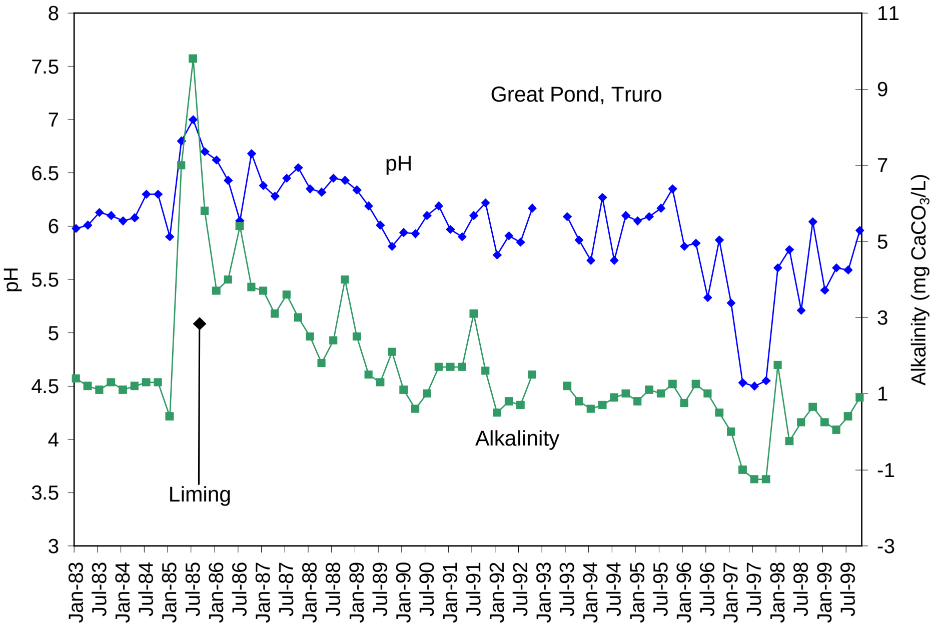

Figure 5-13. Great Pond (T) pH and alkalinity trends.

The Gull Pond Chain

This group includes Gull, Higgins, Williams and Herring Ponds, which are connected to each other via manmade sluiceways and to Cape Cod Bay via the Herring River estuary. Besides (and because of) the marine surface water connection, this pond group is distinctive in supporting a run of river herring (*Alosa aestivalis* and *A. pseudoharengus*) and in providing herring spawning habitat in the shallow littoral zones of all four ponds.

Site-specific studies

Gull Pond in particular has been the subject of several studies, mainly because of its large size, easy access and concerns about heavy summer use. Rich (1980) studied hypolimnetic respiration in Gull and two other Cape lakes outside the National Seashore, finding Gull Pond oligotrophic at the time of observation (1976). Portnoy and Soukup (1990) estimated phosphorus loading from the thousands of gulls that traditionally rested on Gull Pond, especially before landfill closure. This source of phosphorus was substantial - 52 kg/yr or about 78% of the load from surrounding septic systems, assuming no soil removal of the nutrient. Kling and others (1991) compared the relative roles of nitrogen and sulfur cycling in alkalinity generation in Gull and an upper Cape pond (Mares Pond), finding that nitrogen, rather than sulfur, dominated in Gull. Winkler (1994) examined sedimentary diatoms, cladocerans, stable carbon isotopes and chemical properties to reconstruct the post-glacial evolution of the Gull Pond chain of lakes (see Chapter II, *Geologic Origins and Paleo-ecology*). Roman and others (in press) have analyzed relationships between water quality, sediment type and aquatic plants.

Groundwater flow into and out of Gull Pond has been investigated at least four times since the late 1970's (Ryan 1980, Dowd 1984, Horsley & Witten 1996, Sobczak et al. in review.). Consistent findings were that groundwater enters the pond from the south and southeast and exits the pond towards the north, as well as through the sluiceway during high-water periods. Pondwater residence time has been estimated at 10-15 years (Dowd 1984).

Modern limnology and trends

Summer Secchi depths of 2-6 meters indicate mesotrophic conditions in Gull and Higgins Ponds (Fig. 5-14). Gull shows little recent change, except for an apparent decline in clarity since the mid-1970's; data for Higgins are too few to suggest a trend.

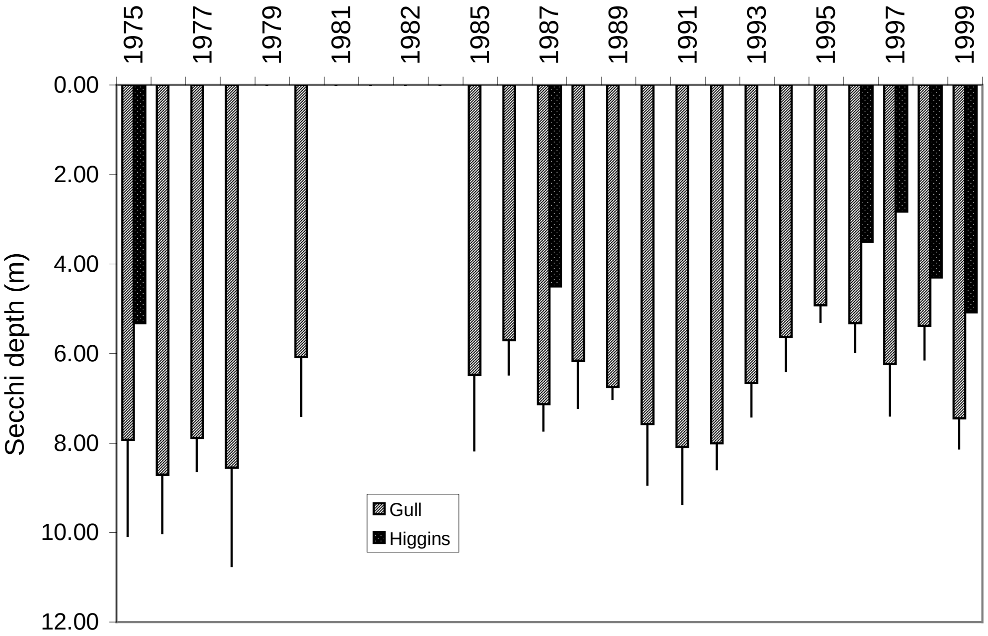

Figure 5-14. Secchi transparencies at Gull and Higgins Ponds. Data are means of April through September observations (± SD).

In contrast, clarity is often under 2-3 meters at Herring Pond, and always less than 2 meters at Williams putting them in the “late eutrophic” and “eutrophic” classifications (Fig. 5-15), respectively, of Canavan and Siver (1995). The principal physical difference between Gull and Higgins, and Herring and Williams is depth (Table 1-1). Phytoplankton production in the latter two shallow ponds is promoted by the proximity of nutrient-rich sediments to well-lit surface water. In shallow ponds summer winds readily bring nutrient-rich bottom waters to the surface where they are available to algae, whereas wind-induced currents cannot overcome the density stratification that develops during the summer in deeper Higgins and Gull Ponds.

Ponds in the Gull Pond chain have a significantly higher pH than the land-locked ponds (average 6.45 versus 4.88). This is likely due to local hydrogeology, specifically the relatively large land area contributing water to the former group. The source of groundwater flowing into Gull Pond is an extensive area to the south and east. Long groundwater flow paths lead to high concentrations of dissolved constituents derived from the soil matrix. In contrast, groundwater flow paths are very short around the small ponds at the top of the groundwater lens like Duck; solute flux from soil to pondwater is correspondingly low. These solutes include both nutrients and base cations, in part explaining the relatively high productivity and alkalinity of the Gull Pond chain.

Acid-base balance has changed little over the period of record within the Gull Pond chain except for regular seasonal oscillations and an apparent increase in alkalinity at Higgins Pond since about 1986 (Fig. 5-16 & 5-17). Increased alkalinity and pH in the warmer months is due to the biological removal of acid anions (nitrate and sulfate) from the water column. Bacteria are important in pond nitrogen and sulfur cycling and can both assimilate nitrate and sulfate and use them as alternate electron acceptors in the absence of oxygen for the decomposition of organic matter. During winter, biological activity slows and acidifying anions are released to again lower pH and alkalinity. As expected, greater seasonal fluctuations occur in the the more productive and biologically active ponds, Herring and Williams (Fig. 5-18 & 5-19).

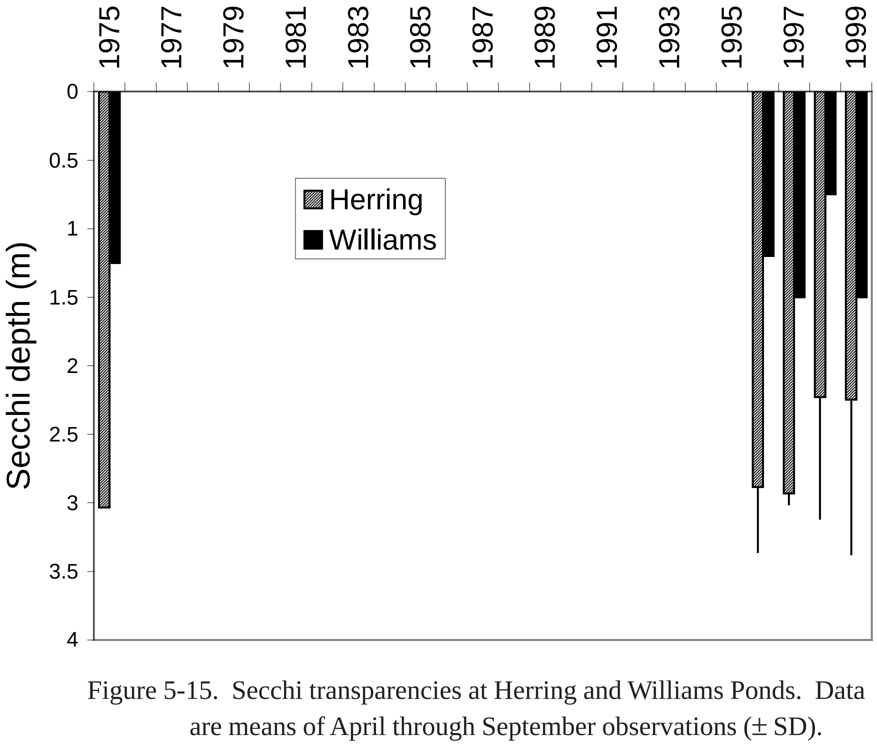

Figure 5-15. Secchi transparencies at Herring and Williams Ponds. Data are means of April through September observations (± SD).

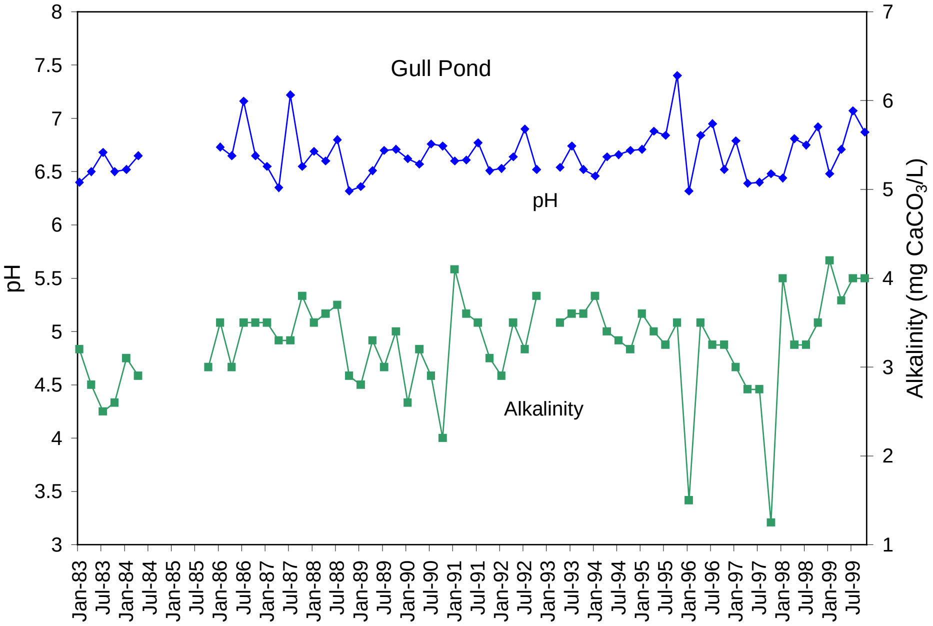

Figure 5-16. Gull Pond pH and alkalinity trends.

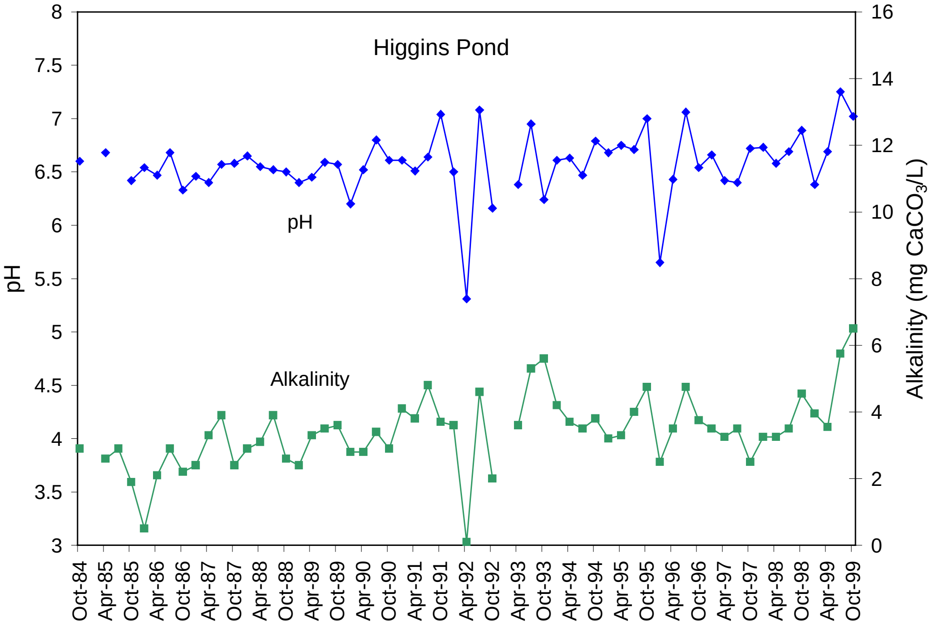

Figure 5-17. Higgins Pond pH and alkalinity trends.

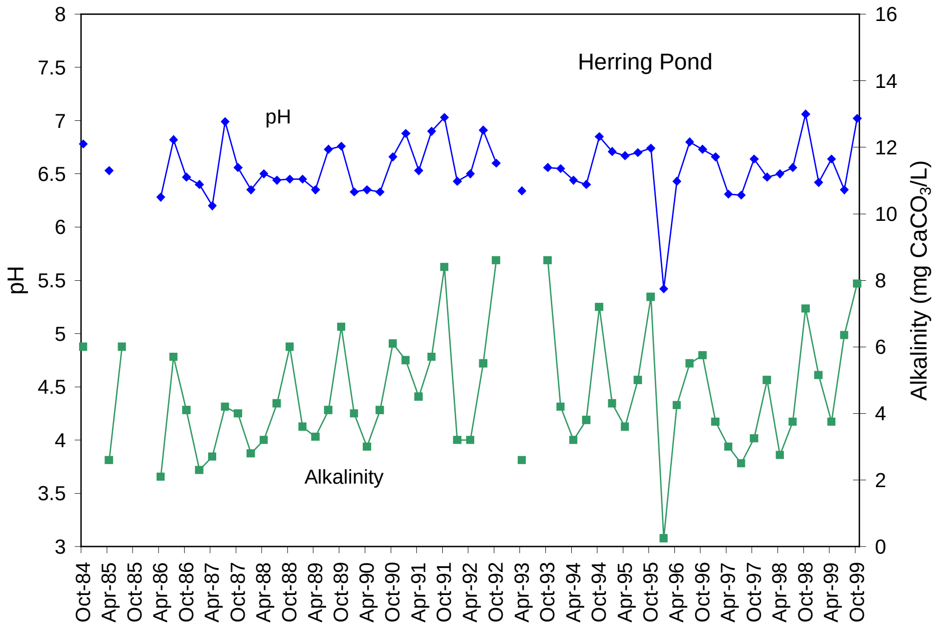

Figure 5-18. Herring Pond pH and alkalinity.

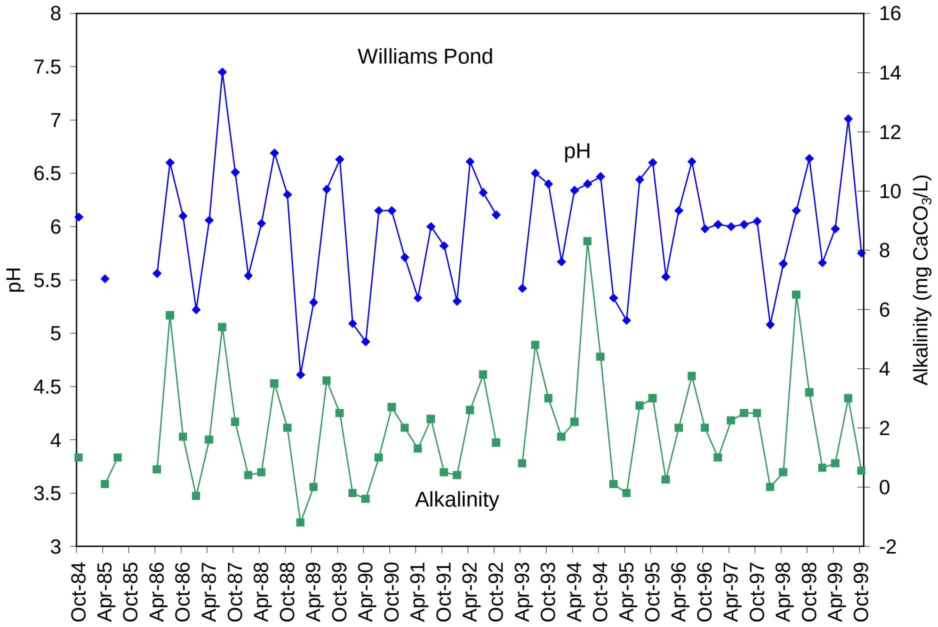

Figure 5-19. Williams Pond pH and alkalinity trends.

Ryder Pond

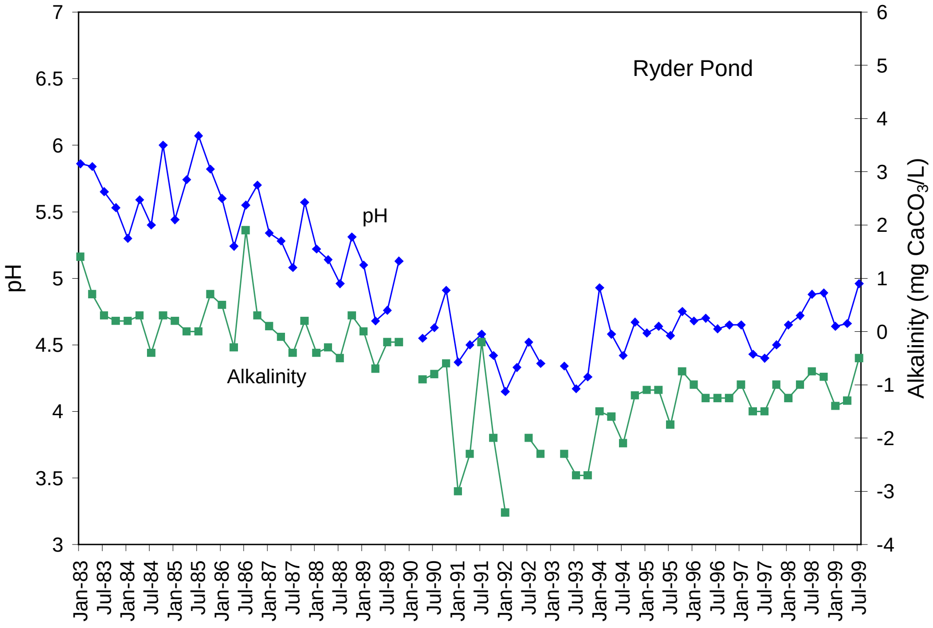

Figure 5-20. Ryder Pond pH and alkalinity trends.

This pond is exceptional in showing major changes in productivity and especially pH, alkalinity and ionic composition (Appendix 4) over the past two decades. pH declined 1.5 units (Fig. 5-20) while sulfate increased from 7 to 14 mg/L between 1986 and 1993. Sulfate is the principal acidifying anion in Cape Cod precipitation; however, analysis of the atmospheric deposition record of sulfate from the National Atmospheric Deposition Program collection site in Truro showed that sulfate deposited in rain and snow was insufficient to account for the increase in pondwater sulfate over this period. Sulfate is also abundant in sea salt, which is deposited all across the Cape peninsula especially during strong easterly gales, but pond sulfate concentrations greatly exceed that expected from sea salt, given the concentration of chloride, a conservative seawater ion (Fig. 5-21). Thus, the excess sulfate causing the pH decline must have come from within the watershed.

A potential source of sulfate is the wetland sediment around the pond. Analysis of sediment cores collected at two locations in Ryder Pond's fringing wetlands (Portnoy, unpublished data) revealed that the top meter of wetland sediment contains 100 times the

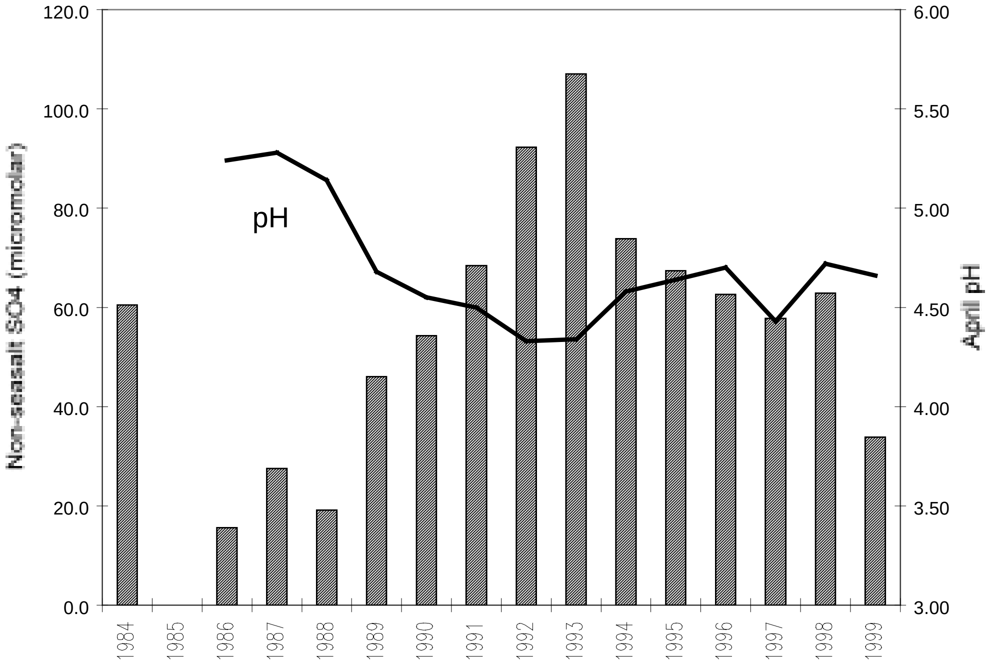

Figure 5-21. Non-seasalt sulfate concentration (bars) and pH trends at Ryder Pond.

sulfur needed to explain the sulfate increase in pondwater from 1986 to 1993.

Under waterlogged conditions, sulfur is stored in organic matter and in insoluble iron minerals. These minerals are stable so long as the peaty sediment remains wet and free of oxygen. If aerated, e.g. by low water during a drought period, the sulfur would oxidize to soluble sulfate, leaching sulfuric acid into poorly buffered pondwater.

Water table and pond levels can fluctuate annually as much as a meter (Cape Cod Commission, unpublished data), the depth of our sediment analysis; however, water table measured in the nearest Cape Cod Commission index well correlates poorly with Ryder pond sulfate and pH. Also, the question remains why Ryder Pond would behave differently from other land-locked kettle ponds with fringing wetlands. Cores from Great Pond (Truro) fringing wetlands contained comparable stores of sulfur. Perhaps less iron is available in the Ryder pond basin to bind with sulfides and keep acidifying sulfate from the water column. More research is needed, but for now the mechanism causing sulfur oxidation, sulfate increase and consequent acidification of Ryder Pond remains unknown.

Since 1993 Ryder has additionally shown a significant decrease in summertime transparency (Fig. 5-22), and increase in the productivity of the water column ($r^2 = .90$, $P<.01$). Lowered pH and transparency may be linked through the sulfur cycle. Lake sulfate concentration has proved to be a good predictor of water column productivity of lakes world-wide (Caraco et al. 1990). Sulfate is reduced microbially to free sulfides during summer hypolimnetic anoxia; the sulfides bind to iron in the pond bottom. Sulfate reduction, and consequent sulfide production, is often limited by sulfate supply in freshwaters (Giblin & Wieder 1992). Increased water column sulfate leads to increased hypolimnetic sulfides which compete with phosphate for the available iron. With less iron available for phosphate precipitation, more phosphorus is released into the water column to fuel phytoplankton production and reduce water clarity. If, as hypothesized above, Ryder Pond were unusually low in available iron, both acid balance and phosphorus mobility would be especially sensitive to additional sulfate.

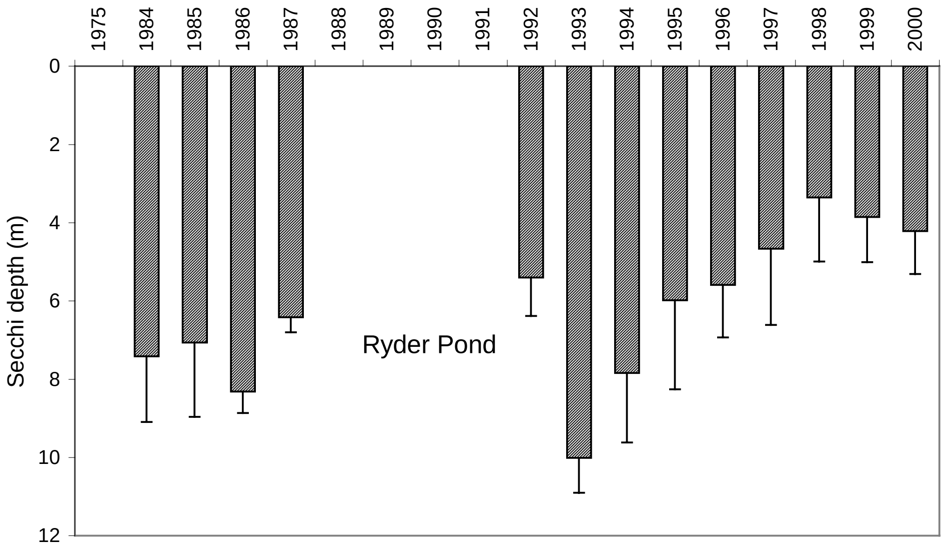

Figure 5-22. Trends in Secchi transparency at Ryder Pond. Data are means of April through September observations (± SD).

Slough Pond

This pond has moderate clarity and is in the mesotrophic class with Secchi depths generally 4-6 meters in summer. We found only one observation of Secchi depth prior to 1986 (August 1952) and no trends are obvious over the past 15 years (Fig. 5-23).

pH and alkalinity have been stable except for a roughly 0.5 unit dip in pH from 1986 to 1993, a period when, interestingly, Ryder Pond pH declined about 1.5 units (Fig. 5-24). The mechanism in either case has not been determined (see Ryder Pond discussion).

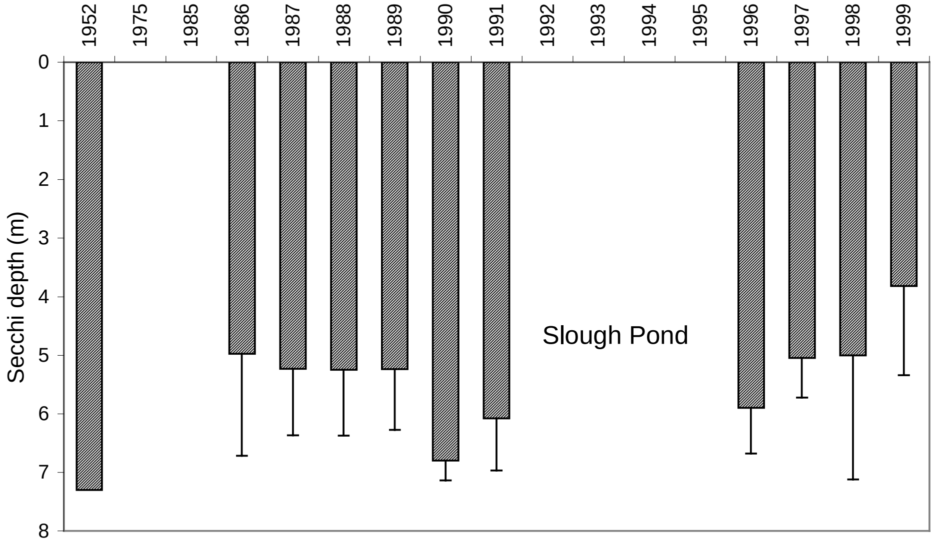

Figure 5-23. Trends in Secchi transparency at Slough Pond. Data are means of April through September observations (± SD).

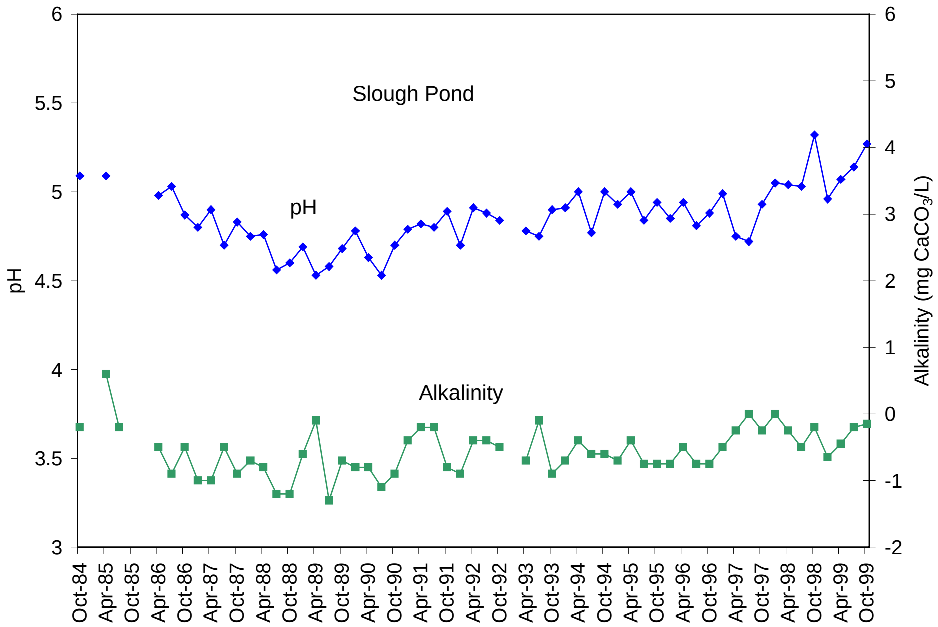

Figure 5-24. Slough Pond pH and alkalinity.

Snow Pond

Located just beside Highway 6 with easy access for swimming, Snow Pond receives intensive swimmer use and a long history of shoreline soil erosion during July and August. Nevertheless Secchi depths indicate a mesotrophic, or moderately productive water column (Fig. 5-25). pH and alkalinity (Fig.5-26) are also intermediate among land-locked Seashore ponds and have been stable since the unexplained high values of 1986.

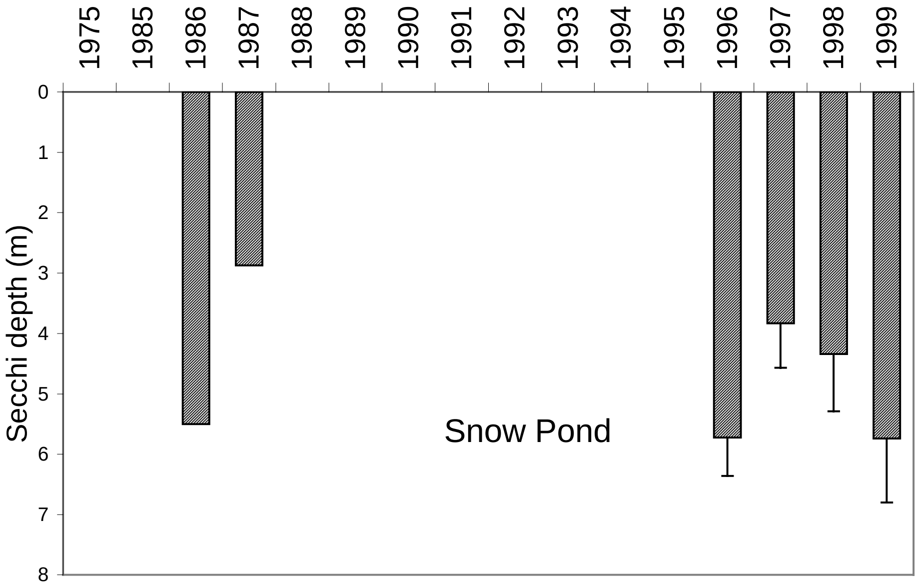

Figure 5-25. Trends in Secchi transparency at Snow Pond. Data are means of April through September observations (± SD).

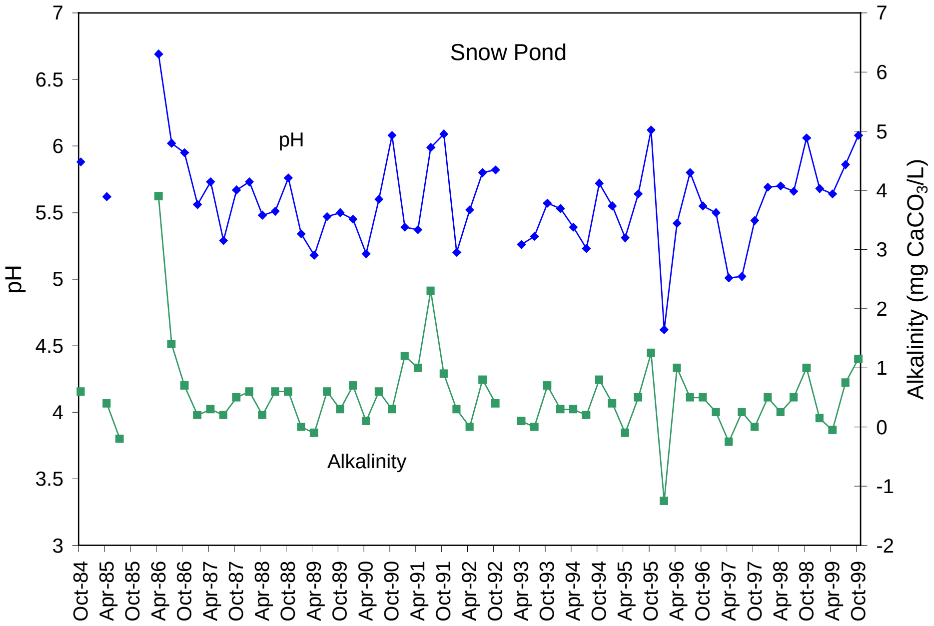

Figure 5-26. Snow Pond pH and alkalinity.

Spectacle Pond

Despite its small size, Spectacle has been included among the Seashore's "primary" ponds for monitoring every two weeks because of concerns for increased swimmer use. Although visitation data are lacking, it is apparent that an increasing number of people have used this remote pond over the past decade. Human activity along the shoreline disturbs vegetative cover causing soil erosion which will likely reduce water clarity over the long term.

Spectacle is presently mesotrophic, with evidently little change in transparency since the early 1990's (Fig. 5-27); prior observations are too few to assess more historic trends. pH and alkalinity have been stable since 1985 (Fig. 5-28).

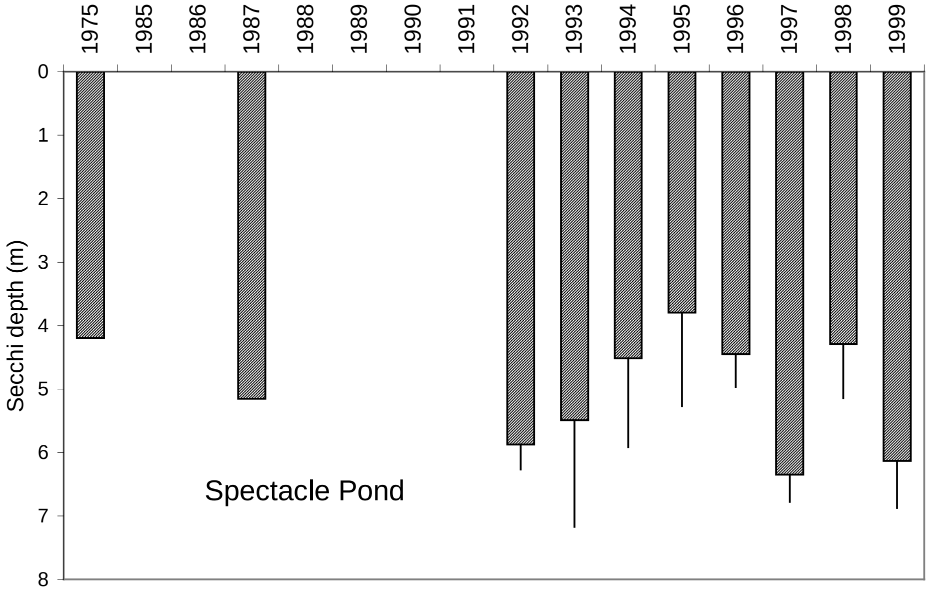

Figure 5-27. Trends in Secchi transparency at Spectacle Pond. Data are means of April through September observations (± SD).

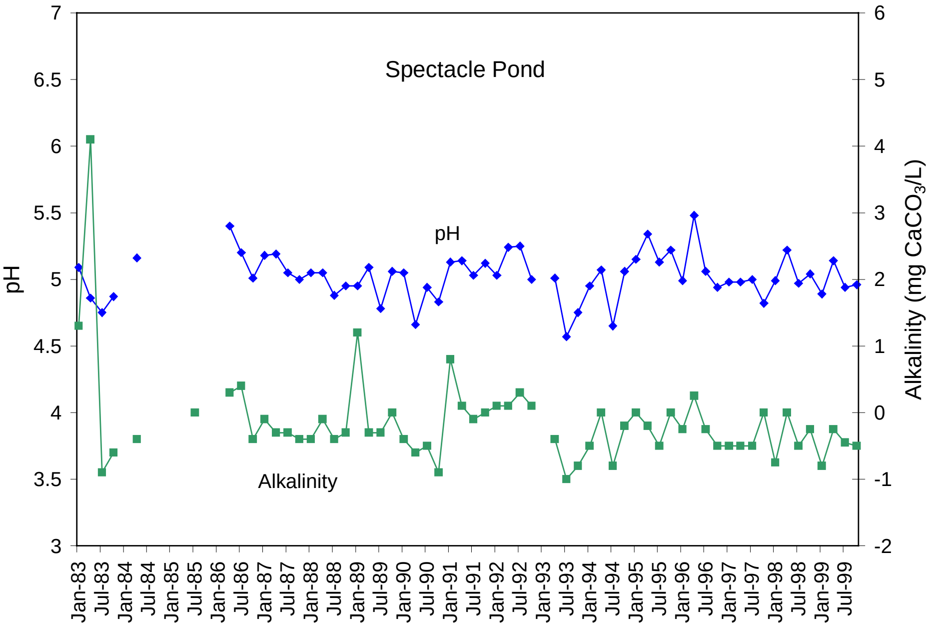

Figure 5-28. Spectacle Pond pH and alkalinity trends.

Horseleech, Kinnacum, and Turtle Ponds

Few water quality observations are available for these three ponds. They have been included in quarterly sampling of pH and alkalinity since 1984. Beginning in 1996 they have been sampled each year in both April and August for indicators of eutrophication as part of the Park's 20-pond survey. See Appendices for raw data.

Horseleech is the closest of the Truro-Wellfeet kettle ponds to the ocean. Relatively high salt deposition, especially from easterly winds, is reflected in elevated electrical conductivity (Table 1-1), about 44% higher than the average for all 20 ponds. The pond is mesotrophic with Secchi transparencies of about four meters, although in April water is so clear that the bottom is visible at five meters depth. The pH record (Fig. 5-29) does show large seasonal fluctuations due to a fairly productive water column during the summer.

Kinnacum and Turtle Ponds are shallow and expectedly highly productive with high chlorophyll concentrations and low Secchi depths. Their sediments are rich in organic matter, which decomposes to release plant nutrients. In such shallow ponds, these abundant nutrients can readily diffuse or be carried by currents from the pond bottom to well-lit surface waters. At the pond surface, they fertilize phytoplankton causing algae blooms. These ponds are among the most eutrophic, i.e. nutrient enriched, of the Seashore kettle ponds (Table 5-4) albeit due more to their depth than to any human disturbance or pollution.

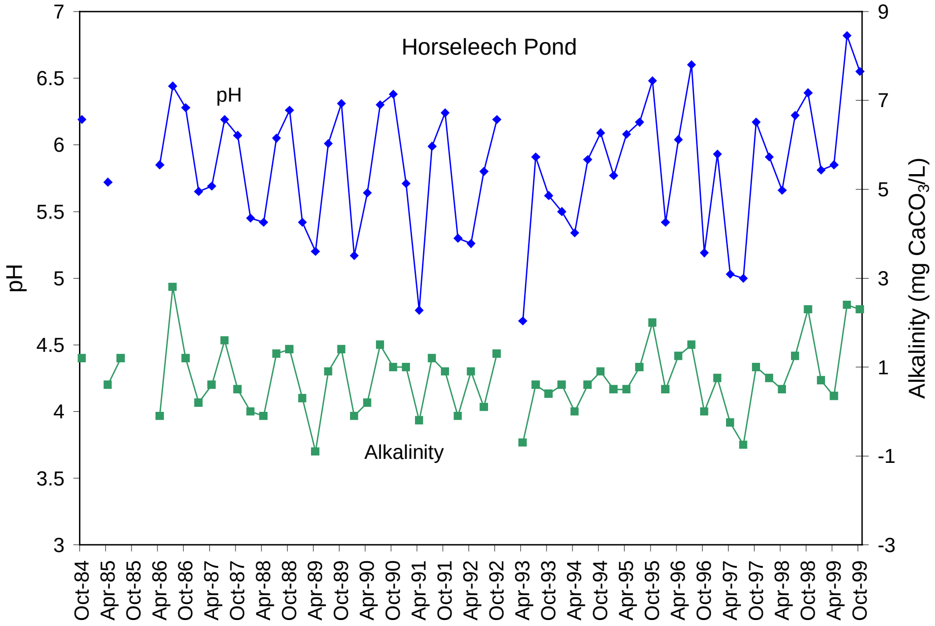

Figure 5-29. Horseleech Pond pH and alkalinity.

Chapter VI. Summary and Management Implications

The Wellfleet and Truro kettle ponds are especially sensitive to changes in acid balance and nutrient inputs because of their low acid-neutralizing capacity and phosphorus concentrations. Despite the proximity of the ocean, most ponds remain highly dilute. This low ionic strength confers a sensitivity to the addition by human activities of acidity or nutrients, potentially causing acidification or eutrophication.

Despite large increases in atmospheric loading of sulfuric and nitric acid since 19th century industrialization, pond pH has remained remarkably stable (Winkler 1988). Apparently, the kettle ponds are able to buffer acid inputs through biogeochemical processes, e.g. sedimentary sulfate reduction and denitrification. With regional reductions in the atmospheric deposition of sulfate (Fig. 4-2), there is little reason to expect decreasing pH at least over the short term (decades).

On the other hand, cultural nutrient loading and consequent eutrophication continue to be the principal management concerns for kettle ponds. However, conclusions regarding trends in water quality are tentative because data before 1996 are disappointingly fragmentary; our most complete data set is for pH and alkalinity collected quarterly since 1985. Cultural eutrophication, through increasing swimmer use and/or pond shoreline residency, is expected to increase pH and alkalinity through increased algal and microbial removal of acidifying anions (e.g. nitrate and sulfate, Stumm & Morgan 1981). When subjected to statistical analyses (Appendix 8), Long and Great (Truro) Ponds show significant changes (increases) in pH. Major water quality changes at Great Pond in Truro since 1975 are clearly the result of liming.

A more direct measure of water column nutrient enrichment is Secchi transparency, the depth to which one can see a Secchi disk lowered into the water column. Of all the variables commonly used to monitor pond trophic state, Secchi transparency is the most simple and repeatable integrator of water column production, i.e. phytoplankton density, in the well-lit surface. Substantial declines in mean summer Secchi transparency are evident for Duck Pond since the 1970s and Ryder Pond since 1993. This is further evidence of increasing nutrients, phytoplankton production and organic loading.

Thus, increased water column productivity of Long, Duck and Ryder suggests on-going cultural eutrophication; however, identification of the major source or sources of nutrients, and most importantly phosphorus, has yet to be accomplished. Possible nutrient sources include atmospheric deposition, soil erosion, swimmer excretions (urine), wildlife usage (primarily gulls) and shoreline septic systems. Atmospheric loading is small, only 2.2 kg/yr into 44 ha Gull Pond, for example. Excreta from resting waterbirds are likely only important in the largest ponds (again Gull Pond, Portnoy & Soukup 1990) and bird use of these ponds has decreased with closure of town landfills.

A potentially major source of phosphorus are the many on-site wastewater treatment systems along pond shorelines. Although phosphate, unlike nitrate, is readily sorbed to minerals in typically aerobic groundwater, this ion could be passing from septic leach fields to ponds where: 1) the intervening distances and travel times are short, 2) the subsurface chemical environment remains anaerobic inhibiting mineral oxidation and phosphate sorption, or 3) where phosphate sorption sites have become saturated. An investigation of nutrient transport along these shoreline flow paths should begin at Gull Pond in 2001 (Colman et al 2000).

Many other ponds are showing cumulative alkalinity and pH increases, albeit as yet statistically insignificant. In this regard it is important to realize that the non-parametric tests used for trend analyses are very sensitive to short (i.e. small sample sizes) and interrupted (i.e. missing data) periods of record. Therefore, successful trend detection in these kettle ponds will require extensive and uninterrupted records over 25-30 years (Appendix 8).

Collection of high-quality and consistent data sets requires the maintenance of a team of well-trained and dedicated staff. With the inception of the CCNS Prototype Inventory and Monitoring Program, the outlook for long-term program maintenance, quality assurance and consistency is much improved.

Chapter VII. Recommended Research and Monitoring

Besides the incipient nutrient transport study (Colman et al. 2000), several additions are recommended to the Seashore's kettle pond research and monitoring program to improve our understanding of each pond ecosystem and to address water quality concerns.

Hydrogeologic characterizations

Pond-specific discussions (Chapter V) highlight the potential importance of local hydrogeology on pondwater levels, residence times and water quality for the more intensively studied Gull, Duck and Ryder Ponds. Hydrologic characterization of Gull and Duck Ponds (Horsley & Witten 1996, Sobczak et al., in review) has done much to explain their very different water chemistries. Radical recent changes in acidity and productivity of Ryder Pond may be explained with a better understanding of local hydrology. In fact, local hydrology affects water quality in all of the ponds with its influence becoming even more important as surrounding land use changes.

A first step would be to establish measuring points and to institutionalize at least quarterly measurements of the level of all twenty ponds. A start in this direction has been made by the Seashore's Inventory and Monitoring Program with the installation of siphon wells (McCobb et al. 1999) at Gull, Duck, Great-Wellfleet, Great-Truro, Ryder, Dyer, Long, Snow and Herring Ponds. Local bench marks and staff gauges are needed at the remaining 11 ponds.

The U.S. Geological Survey has begun research to produce an integrated groundwater model for the entire outer Cape (Masterson and Barlow 2000). This study will for the first time delineate groundwater flow paths so that contributing areas can be mapped upgradient of each pond basin. This information can be combined with land use data and coupled to empirical and geochemical modeling results of the nutrient transport study (Colman et al. 2000) to estimate the influx of nutrients and other solutes via groundwater flow. This work should produce a major contribution to our understanding of the differences in water quality among the 20 pond systems.

Phosphorus budgets

Besides the above-mentioned study of nutrient transport from shoreline septic systems, other sources of phosphorus (P) loading need estimation, especially for those ponds like Gull, Duck, Long, Snow and Great-Wellfleet subject to increased recreational use and shoreline disturbance. Efforts to quantify "internal loading", i.e. regeneration of P from the sediment during summer stratification, are warranted, but should relate measured mass flux of P from the sediment to seasonal pond circulation and light profiles. For example, seasonally high sediment regeneration of P has no impact on primary production in the water column if light is the limiting factor on phytoplankton growth. Also, too much emphasis on internal loading, which can be admittedly large, ignores ongoing "external" loading of new phosphorus added to the ponds by swimmers, bank erosion and septic systems.

Post-glacial development

To explore questions raised in the paleoecology studies, research should be undertaken to determine the origin and basal ages of kettle ponds that have not previously been cored. This would help define the post-glacial landscape and time frame within which the kettle ponds developed, and would help interpret the interruption of pond sediments by massive deposition of sands and gravels in the early to mid-Holocene. The cause of such depositional hiatuses may become clearer when additional ages and sediment stratigraphies are known. These data would also contribute to knowledge of: 1) changes in topography on the Outer Cape since deglaciation; 2) the building of barrier beaches, bays, and salt marshes; and 3) the effects of these physiographic changes on the development of the kettle ponds and on the changes in the flow of water across the narrow outer Cape peninsula.

Changing diatom assemblages

Research to date has shown that specific diatom assemblages indicate a pond's contemporary acid balance or nutrient status; however, the species composition of these water-quality-sensitive assemblages has changed since the time of European settlement. Diatoms indicating acid conditions before settlement are different from those indicating recent acid conditions. Similarly, diatoms indicating nutrient increases today are different from those species that showed similar trophic changes in the past. These species replacements document that within-lake changes since settlement are different in some way from past water quality changes. Further study of this phenomenon, perhaps as a component of studies to quantify phosphorus and other nutrient and metal loading sources, should be initiated.

Phytoplankton monitoring

Periodic monitoring of phytoplankton species composition and abundance should be intiated. Planktonic algae are the basis of most kettle pond food chains. The diatom changes presented in Chapter II (and references therein) provide evidence of water quality changes in the past and, even more dramatically, in recent decades. Environmental fluctuations may go unnoticed for years, but may be expressed almost within the season by changes in pond algae. These organisms have very short generation times and populations respond quickly and detectably to environmental change. In addition, pond sediments hold the equivalent of "seed banks" of a wide variety of algal species waiting for the right conditions to bloom; many species, therefore, are always present in small quantities. As an example, the recent pH decline in Ryder Pond (see Chapters II and V, above), was followed closely by diatom changes from which the pH could be inferred (Fig. 2-15). Total phosphorus and other nutrient changes in the recent past have also been inferred from modern diatom response to measured nutrient concentrations. Thus, phytoplankton associations may provide early warnings of changing environmental conditions.

Macrophyte monitoring

Changes in water quality can also cause and be reflected in changes in aquatic macrophytes (Roman et al., in press). Macrophyte species composition and distribution should be part of trophic dynamics research. The kind and abundance of aquatic plants in the ponds today may also provide analogs for water quality and watershed physiography in the past. For example, abundant oospores of the alga *Nitella* (Fig. 2-4) were found in the oldest sediments of Great Pond, Truro dating from c. 12,000 yr B. P.; during modern surveys (Roman et al., in press) *Nitella* was present in Herring and Gull Ponds. Macrophyte and other biological data can contribute to and help refine indices of pond trophic status currently limited to Secchi transparency, chlorophyll α, and phosphorus concentrations, and should probably be conducted every five years.

Duck Pond zooplankton

Further research on the zooplankton community of Duck Pond (Wellfleet) should be pursued. Summer zooplankton hauls (MacCoy 1958) evidently yield only 1 or 2 copepod species, yet the sediment record shows that *Neobosmina tubicen*, *Diaphanosoma* sp. and at least 15 littoral cladocera species live in the pond. Limnetic cladocera may be seasonally restricted in Duck Pond, much like littoral cladocera are in other systems. Seasonality may be constrained by nutrient pulses at overturn or by fish planktivory.

Ryder Pond research

This pond's dramatic changes in acidity and sulfur cycling since 1984, and in productivity since 1993, need further study. The doubling of sulfate concentration between 1986 and 1993, and consequent pH decline, suggests a major oxidation of reduced sulfur within the watershed. There appears to be no direct anthropogenic cause for the sulfate increase. The fact that no other pond showed a similar change may indicate that Ryder has a peculiar geochemistry or local hydrology that results in massive sulfate mobilization during meteorological anomalies, such as drought. High sulfate and low pH did correlate with a period of low annual rainfall.

Perhaps Ryder has more reduced sulfur within a depth range that can be oxidized and released into the pondwater during low-water years, or the local hydrogeology results in extreme water table depression during periods of no or low recharge. Perhaps this pond has low sedimentary iron (Fe) for sulfide precipitation and long-term sequestration as pyrite in shoreline littoral or bordering wetland sediments. A scarcity of sedimentary Fe would also explain the productivity increase since 1993 because 1) this element is responsible for the sorption of phosphorus at the sediment surface and 2) the high sulfate, reduced to sulfide during summer hypolimnetic anoxia, might exhaust the Fe available for phosphate immobilization. All of these hypotheses need careful field and laboratory testing.

Herring effects on the trophic dynamics of the Gull Pond chain

Studies elsewhere have shown that fry can decrease water clarity by preying upon and reducing zooplankton grazers of algae (Shapiro 1990, also Chapter II of this report on cladocera analyses). Because the present run has been maintained since at least 1893 (Belding 1921) by periodic dredging of sluiceways between the ponds and between Herring Pond and Herring River, the river herring's effects on pond trophic structure and water clarity, if any, could be considered an unnatural disturbance. An ongoing survey of freshwater fishes within the Seashore is only a first step in assessing the abundance and ecological role of river herring on the Gull Pond chain. Further work on the ponds' trophic structure and modeling of the effects of herring removal are needed (Godfrey et al. 1999) before any change in sluiceway management is considered.

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Appendices

1. Explanation of selected monitoring variables
2. Water quality profiles
3. pH
4. Alkalinity
5. Major cations and anions
6. Secchi transparency
7. Total phosphorus
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Appendix 1

Explanation of selected monitoring variables

Temperature is measured along with electrical conductivity (specific conductance) to follow thermal stratification of the water column. Water masses of different temperature and, thus, density can stratify with little mixing between layers during summer months leading to stagnant, and often oxygen-poor, conditions in bottom waters. Temperature profiling describes the relative thermal resistance to mixing. Anoxia induces the chemical reduction of iron and the release of sedimentary phosphorus and sulfides into the water column. Phosphorus release can trigger algal blooms, if transported to well-lit depths, and sulfides are toxic to aquatic life. Temperature profiles can also be useful for evaluating groundwater inputs and outputs and for computing heat budgets.

Electrical conductivity is a measure of the amount of dissolved constituents in water. It is temperature-dependent (and readings must be temperature-compensated) and thus aids in identifying thermal stratification. More importantly, the loss of oxygen from deep pondwater in summer causes the dissolution of limnologically important substances (iron, phosphorus, and sulfides) that show up as increased conductivity.

***Dissolved oxygen*.** Besides being essential for aerobic respiration (and therefore critical for the survival of aquatic animals), oxygen concentrations influence all major nutrient cycles, including the storage of phosphorus in lake sediments. Lakes undergoing eutrophication typically show increases in the duration of deep-water anoxia and the thickness (i.e. vertical extent) of anoxic bottom waters.

***Light penetration*.** A light meter is used to measure incident light (visible range) above the lake surface and at specific depths, preferably simultaneously, to calculate the percent transmission through the intervening water column. Photosynthesis and aquatic plant production are dependent upon available light; thus, photosynthetic oxygen production is often limited by light transmission to the bottom waters of turbid lakes. This phenomenon can exacerbate deep-water oxygen depletions. Light profiles can also show where plankton organisms are concentrated and thereby explain subsurface peaks in the oxygen profile.

***Secchi depth*.** A single measurement of the maximum depth at which the black and white 30-cm disk can be seen is widely used as an index of clarity.

Hydrogen ion concentration is represented by **pH**, the negative logarithm of $[H^+]$, and measures the acid-base balance of water. Pondwater pH is determined by the combination of ions in solution. The pondwater's ionic composition is affected by surrounding soils, atmospheric inputs and in-pond chemical and biological processes. Conversely, pH affects both chemical reactions and the aquatic biotic community.

Alkalinity measures the acid-neutralizing (i.e. buffering) capacity of pondwater, and is therefore a measure of the ability to resist pH change while receiving acidic inputs, as from acid deposition.

Total nitrogen and total phosphorus (TN and TP) are measures of the total concentration of these elements in the water column, including dissolved species, which are scarce in nutrient-limited kettle ponds, and the more abundant N and P contained in organic particles including plankton. To measure TN and TP colorimetrically, water samples must be digested to convert all N and P to inorganic forms. Since P is rapidly cycled by water column biota in P-limited pond systems, soluble reactive P is often undetectable in the water column and total P is a better measure of this element's availability. Total P is measured by digestion of unfiltered samples.

Nitrate and ammonium are included as potentially sensitive indicators of septic leachate loading. Because most ponds are likely P- rather than N-limited, dissolved inorganic N should persist in the water column to provide a tracer of contamination from shoreline wastewater disposal systems.

Chlorophyll α is measured as a surrogate for algal biomass. Particulate matter, including plankton, is collected on filters that are ground and the chlorophyll extracted in acetone for spectrophotometric determination of the pigment concentration.

Appendix 2: Water Quality Profiles.

The following profiles are examples only. For the full data set, see Cape Cod National Seashore website at : www.nps.gov/caco/resources

Duck Pond, Wellfleet

Date	Depth(m)	Temp(C)	Conductivity	DO%	DO(ppm)	pH	Eh	Light (% incident)
5/17/99	Air							119.9
	Surface	16.87	107	104.8	10.15	4.67	298.9	75.7
	0.5	16.86	107	104.5	10.12	4.67	302.9	60.2
	1	16.85	106	104.2	10.09	4.66	305.4	43.4
	2	16.82	106	103.8	10.06	4.66	309	44.9
	3	16.78	106	103.5	10.03	4.66	312.1	37.2
	4	16.7	106	103.1	10.02	4.65	313.8	31.5
	5	16.43	107	104.6	10.24	4.66	319.2	27.2
	6	15.78	106	107.5	10.65	4.66	323.2	24.1
	7	15.27	106	108	10.82	4.67	325.1	20
	8	14.19	107	108.8	11.17	4.66	329.3	16.3
	9	12.78	106	117.5	12.45	4.66	335.5	13.6
	10	11.57	106	120.1	13.07	4.66	342.3	10.7
	11	10.72	105	120.2	13.33	4.63	350.5	7.82
	12	10.06	106	117.9	13.25	4.63	356	5.1
	13	9.6	107	109.2	12.41	4.61	362.5	3.2
	14	9.23	107	97.5	11.22	4.57	374.1	2.2
	15	8.97	108	93.7	10.83	4.55	382.2	1.5
	16	8.92	108	91.1	10.52	4.54	387.9	1.02
	17	8.9	108	89.1	10.32	4.54	368.4	0.71
	17.4	8.89	108	62.8	7.14	5.86	218.2	0.41

Date	Depth(m)	Temp(C)	Conductivity	DO%	DO(ppm)	pH	Eh	Light (% incident)
5/27/99	Air							116.5
	Surface	19.94	105	103.7	9.42	4.79	292.9	10.06
	0.5	20	105	103.2	9.38	4.77	303.8	73.4
	1	19.87	105	102.9	9.36	4.77	308.2	59
	2	19.12	104	101.3	9.37	4.75	316.6	52.1
	3	19.05	104	101.7	9.43	4.76	317.7	38.9
	4	18.85	105	102	9.48	4.75	320.9	24.7
	5	18.69	104	101.9	9.51	4.75	323.9	23
	6	18.12	104	105.2	9.92	4.75	326.5	16.3
	7	16.67	104	109.4	10.64	4.75	330.2	18.2
	8	15.53	104	110.5	10.98	4.75	333.1	11.4
	9	13.77	104	120.8	12.54	4.73	339.9	10.3
	10	12.37	105	121.5	12.89	4.71	348.6	8.3
	11	11.63	104	119.8	13.02	4.71	354.4	6.4
	12	10.73	104	113.5	12.56	4.69	361.6	4.3
	13	10.1	106	101.2	11.39	4.67	368.7	3.5
	14	9.62	106	90.6	10.31	4.63	376.8	1.7
	15	9.34	107	79.5	9.1	4.6	386.4	1.1
	16	9.21	107	76.5	8.79	4.59	394.6	0.7
	16.5	9.18	106	69	8	4.6	318.5	0

Date	Depth(m)	Temp(C)	Conductivity	DO%	DO(ppm)	pH	Eh	Light (% incident)
6/14/99	Air							124
	Surface	23.3	113	100.7	8.6	4.91	492	82
	0.5	23.3	113	100.5	8.6	4.91	492	72
	1	23.17	113	100.5	8.62	4.92	494	55
	2	23.08	113	100.1	8.59	4.93	496	36.6
	3	22.99	113	100.6	8.67	4.94	498	29.7
	4	22.92	113	101.7	8.76	4.95	501	24
	5	22.74	113	100.8	8.72	4.96	502	18.1
	6	22.2	113	102.1	8.9	4.95	505	15.8
	7	20.04	111	116.9	10.68	4.96	510	12.2
	8	18.09	111	116.3	11	4.91	516	9
	9	16.31	111	122.6	12.06	4.84	524	7.4
	10	14.66	110	123.8	12.59	4.8	528	5.5
	11	13.13	110	122.4	12.91	4.77	533	4.6
	12	12.14	110	116.6	12.57	4.73	537	3
	13	10.97	111	95.3	10.55	4.68	542	1.7
	14	10.42	111	79.9	8.95	4.63	548	1.2
	15	9.99	111	67.3	7.59	4.61	554	0.79
	16	9.81	112	60.3	6.86	4.59	559	0.53
	17	9.78	112	57.8	6.59	4.59	565	0.32
	17.3	9.78	112	57.1	6.49	4.6	567	0.27

Date	Depth(m)	Temp(C)	Conductivity	DO%	DO(ppm)	pH	Eh	Light (% incident)
6/30/99	Air							129
	Surface	25.25	107	97.9	8.02	4.35	339	102.5
	0.5	25.29	106	97.8	8.02	4.36	339	75.1
	1	25.29	106	98	8.02	4.37	339	82.3
	2	25.27	107	98	8.03	4.38	339	44.6
	3	25.23	106	98.1	8.05	4.4	339	32.6
	4	25.18	107	98	8.04	4.39	340	27.5
	5	24.83	106	101.4	8.4	4.4	341	17.3
	6	23.71	105	102.1	8.64	4.41	341	11.4
	7	21.53	103	117.9	10.38	4.41	342	10.1
	8	18.92	103	116.4	10.78	4.39	344	6.9
	9	16.73	103	118.3	11.44	4.34	348	5.4
	10	14.92	102	119.3	12.01	4.39	345	4.2
	11	13.44	102	116	12.07	4.38	346	3.1
	12	12.37	102	100.6	10.66	4.39	347	2.4
	13	11.11	103	79.4	8.68	4.35	349	1.6
	14	10.61	104	62.8	6.93	4.32	351	1
	15	10.34	103	57.7	6.36	4.31	352	0.64
	16	10.17	104	48.4	5.41	4.3	352	0.38
	17	10.17	104	42.7	4.78	4.35	352	0.22

Appendix 3: pH

Month-year	DUCK(W)	DYER	GREAT(T)	GREAT(W)	GULL	HERRING PD.	HIGGINS	HORSELEECH	KINNACUM	LONG	NORTHEAST	ROUND EAST	ROUND WEST	RYDER	SLOUGH	SNOW	SOUTHEAST	SPECTACLE	TURTLE	WILLIAMS
2-83	4.61		5.98		6.40	7.06			4.51	4.57			4.79	5.86				5.09		
4-83	4.62		6.01		6.50	7.45				4.54				5.84				4.86		
7-83	4.72		6.13		6.68	7.55				4.72				5.65				4.75		
10-83	4.61		6.10		6.50	7.30				4.59				5.53				4.87		
1-84	4.62		6.05		6.52	7.28								5.30						
4-84	4.70		6.08		6.65	7.26				4.67				5.59				5.16		
7-84																				
10-84		4.84		4.93		6.78	6.60	6.19				5.24	4.75		5.09	5.88	4.95		5.04	6.09
1-85																				
4-85		5.00		4.77		6.53	6.68	5.72				5.42	4.75		5.09	5.62	4.99		4.93	5.51
7-85																				
10-85				4.67			6.42			4.63				5.82						
1-86			6.62		6.73		6.54			4.47				5.60						
4-86	4.71	4.85	6.43	4.66	6.65	6.28	6.47	5.85	4.60	4.56	4.80	5.56	4.90	5.24	4.98	6.69	4.85	5.40		5.56
7-86	4.66	4.82	6.05	4.65	7.16	6.82	6.68	6.44	4.52	4.60	4.68	4.18	4.79	5.55	5.03	6.02	4.73	5.20		6.60
10-86	4.72	4.82	6.68	4.62	6.65	6.47	6.33	6.28	4.40	4.60	4.64	5.76	4.94	5.70	4.87	5.95	4.80	5.01		6.10
1-87	4.68	4.82	6.38	4.70	6.55	6.40	6.46	5.65	4.64	4.68	4.84	5.77	5.03	5.34	4.80	5.56	4.93	5.18		5.22
4-87	4.76	4.94	6.28	4.74	6.35	6.20	6.40	5.69	4.65	4.74	4.91	5.54	5.00	5.28	4.90	5.73	5.03	5.19		6.06
7-87	4.64	4.92	6.45	4.77	7.22	6.99	6.57	6.19	4.52	4.71	4.57	5.52	4.48	5.08	4.70	5.29	4.94	5.05		7.45
10-87	4.76	4.95	6.55	4.73	6.55	6.56	6.58	6.07	4.52	4.72	4.86	5.65	4.80	5.57	4.83	5.67	5.03	5.00		6.51
1-88	4.64	4.90	6.35	4.69	6.69	6.35	6.65	5.45	4.60	4.65	4.77	5.43	4.96	5.22	4.75	5.73	4.97	5.05		5.54
4-88	4.69	4.97	6.32	4.77	6.60	6.50	6.55	5.42	4.62	4.76	4.77	4.77	4.93	5.14	4.76	5.48	5.14	5.05		6.03
7-88	4.61	4.83	6.45	4.63	6.80	6.44	6.52	6.05	4.40	4.66	4.56	5.34	4.72	4.96	4.56	5.51	4.83	4.88		6.69
10-88	4.75	4.90	6.43	4.62	6.32	6.45	6.50	6.26	4.38	4.60	4.66	5.46		5.31	4.60	5.76	4.91	4.95		6.30
1-89	4.58	4.88	6.34	4.67	6.36	6.45	6.40	5.42	4.50	4.59	4.95	5.36	4.72	5.10	4.69	5.34	4.93	4.95		4.61
4-89	4.61	5.23	6.19	4.63	6.51	6.35	6.45	5.20	4.43	4.56	4.98	5.25	4.62	4.68	4.53	5.18	4.95	5.09		5.29
7-89	4.69	4.70	6.01	4.54	6.70	6.73	6.59	6.01	4.31	4.51	4.72	5.06	4.65	4.76	4.58	5.47	4.84	4.78		6.35
10-89	4.80	4.93	5.81	4.69	6.71	6.76	6.57	6.31	4.40	4.55	4.75	5.17	4.65	5.13	4.68	5.50	5.15	5.06		6.63
1-90	4.77	4.76	5.94	4.71	6.62	6.33	6.20	5.17	4.61	4.67	5.40	5.17	4.78		4.78	5.45	4.99	5.05		5.09
4-90	4.57	4.48	5.93	4.55	6.57	6.35	6.52	5.64	4.25	4.41	4.86	5.05	4.55	4.55	4.63	5.19	4.78	4.66		4.92
7-90	4.51	4.62	6.10	4.30	6.76	6.33	6.80	6.30	3.98	4.43	4.65	4.93	4.68	4.63	4.53	5.60	4.84	4.94		6.15
10-90	5.00	4.92	6.19	4.99	6.74	6.66	6.61	6.38	4.74	4.99	5.14	5.10	5.08	4.91	4.70	6.08	5.22	4.83		6.15
1-91	4.80	4.58	5.97	4.35	6.60	6.88	6.61	5.71	4.62	4.69	4.64	4.79	4.70	4.37	4.79	5.39	5.01	5.13		5.71
4-91	4.75	4.63	5.90	4.70	6.61	6.53	6.51	4.76	4.45	4.70	4.82	4.95	4.70	4.50	4.82	5.37	4.86	5.14		5.33
7-91	4.81	4.66	6.10	4.69	6.77	6.90	6.64	5.99	4.31	4.60	4.67	5.00	4.74	4.58	4.80	5.99	4.82	5.03		6.00
10-91	4.86	4.70	6.22	4.75	6.51	7.03	7.04	6.24	4.39	4.69	5.45	4.98	4.88	4.42	4.89	6.09	4.94	5.12		5.82
1-92	4.77	4.62	5.73	4.61	6.53	6.43	6.50	5.30	4.41	4.55	4.96	4.78	4.81	4.15	4.70	5.20	4.94	5.03		5.30
4-92	4.82	4.73	5.91	5.29	6.64	6.50	5.31	5.26	4.53	4.67	5.06	5.20	5.14	4.33	4.91	5.52	4.80	5.24	4.54	6.61
7-92	4.86	4.90	5.85	5.00	6.90	6.91	7.08	5.80	4.49	4.80	4.89	5.00	5.12	4.52	4.88	5.80	5.21	5.25		6.32
10-92	4.79	4.72	6.17	4.72	6.52	6.60	6.16	6.19	4.34	4.66	5.14	4.96	4.82	4.36	4.84	5.82	4.73	5.00		6.11
1-93																				
4-93	4.65	4.76	4.58	4.74	6.54	6.34	6.38	4.68	4.45	4.61	4.84	4.80	4.84	4.34	4.78	5.26	4.72	5.01		5.42
7-93	4.60	4.44	6.09	4.71	6.74		6.95	5.91	4.33	4.51	4.75	4.90	4.52	4.17	4.75	5.32	4.72	4.57		6.50
10-93	4.83	4.63	5.87	4.74	6.52	6.56	6.24	5.62	4.27	4.65	5.14	4.80	4.68	4.26	4.90	5.57	4.80	4.75		6.40
1-94	4.80	4.68	5.68	4.79	6.46	6.55	6.61	5.50	4.53	4.73	4.96	5.00	4.64	4.93	4.91	5.53	4.85	4.95		5.67
4-94	4.69	4.70	6.27	4.91	6.64	6.44	6.63	5.34	4.56	4.77	4.84	5.18	4.65	4.58	5.00	5.39	5.00	5.07	5.00	6.34
7-94	4.62	4.57	5.68	4.62	6.66	6.40	6.47	5.89	4.60	4.60	4.64	4.92	4.50	4.42	4.77	5.23	4.98	4.65	5.08	6.40
10-94	4.81	4.71	6.10	4.82	6.70	6.85	6.79	6.09	4.67	4.84	5.09	5.17	4.80	4.67	5.00	5.72	5.24	5.06	5.35	6.47
1-95	4.86	4.66	6.05	4.90	6.71	6.71	6.68	5.77	4.81	4.82	4.94	5.12	4.77	4.59	4.93	5.55	5.13	5.15	5.08	5.33
4-95	4.82	4.77	6.09	4.92	6.88	6.67	6.75	6.08	4.72	4.87	5.07	5.26	4.90	4.64	5.00	5.31	5.22	5.34	4.66	5.12
7-95	4.82	4.72	6.17	4.79	6.84	6.70	6.71	6.17	4.59	4.79	4.66	5.07	4.79	4.57	4.84	5.64	4.84	5.13	4.31	6.44
10-95	4.86	4.81	6.35	4.88	7.40	6.74	7.00	6.48	4.56	4.79	5.07	5.17	4.90	4.75	4.94	6.12	4.74	5.22	4.38	6.60
1-96	5.00	4.70	5.81	4.89	6.32	5.42	5.65	5.42	4.59	5.04	4.93	5.20	5.00	4.68	4.85	4.62	5.41	4.99	4.41	5.53
4-96	4.84	4.66	5.84	5.10	6.84	6.43	6.43	6.04	4.78	4.90	5.21	5.36	4.96	4.70	4.94	5.42	5.21	5.48	4.77	6.15
7-96	4.83	4.74	5.33	4.84	6.95	6.80	7.06	6.60	4.57	4.71	4.72	5.10	4.85	4.62	4.81	5.80	4.75	5.06	4.37	6.61
10-96	4.61	4.61	5.87	4.86	6.52	6.73	6.54	5.19	4.56	4.70	4.87	4.94	4.81	4.65	4.88	5.55	4.84	4.94	4.53	5.98
1-97	4.70	4.59	5.28	4.86	6.79	6.66	6.66	5.93	4.63	4.85	4.84	5.09	4.76	4.65	4.99	5.50	5.08	4.98	4.64	6.02
4-97	4.65	4.59	4.53	4.87	6.39	6.31	6.42	5.03	4.60	4.77	4.72	4.77	4.57	4.43	4.75	5.01	5.05	4.98	4.60	6.00
7-97	4.65	4.59	4.50	4.85	6.40	6.30	6.40	5.00	4.65	4.80	4.68	4.82	4.55	4.40	4.72	5.02	5.10	5.00	4.65	6.02
10-97	4.59	4.15	4.55	4.55	6.48	6.64	6.72	6.17	4.53	4.53	5.00	4.85	4.60	4.50	4.93	5.44	4.82	4.82	4.66	6.05
1-98	4.70	4.60	5.61	4.82	6.44	6.47	6.73	5.91	4.60	4.89	5.26	5.05	4.98	4.65	5.05	5.69	5.14	4.99	4.67	5.08
4-98	4.76	4.85	5.78	4.96	6.81	6.50	6.58	5.66	4.78	4.97	5.16	5.02	4.89	4.72	5.04	5.70	5.03	5.22	4.59	5.65
7-98	4.85	4.71	5.21	4.94	6.75	6.56	6.69	6.22	5.06	4.85	5.24	5.22	4.73	4.88	5.03	5.66	5.62	4.97	4.97	6.15
10-98	5.03	4.93	6.04	5.01	6.92	7.06	6.89	6.39	5.03	5.10	5.22	5.23	5.08	4.89	5.32	6.06	5.56	5.04	5.18	6.64
1-99	4.54	4.47	5.40	4.60	6.48	6.42	6.38	5.81	4.77	4.35	4.65	5.03	4.83	4.64	4.96	5.68	5.12	4.89	4.59	5.66
4-99	5.04	4.89	5.61	4.91	6.71	6.64	6.69	5.85	4.95	5.01	5.08	5.42	5.01	4.66	5.07	5.64	5.41	5.14	4.64	5.98
7-99	4.87	4.79	5.59	4.86	7.07	6.35	7.25	6.82	5.18	4.80	5.09	4.85	5.21	4.96	5.14	5.86	5.18	4.94	4.56	7.01
10-99	5.08	4.98	5.96	4.93	6.87	7.02	7.02	6.55	4.80	4.94	5.15	5.33	5.00	5.42	5.27	6.08	5.01	4.96	4.65	5.75
1-00	4.97	4.9	5.48	4.97	6.91	6.97	7.04	6.02	4.78	4.8	5.14	5.25	5.02	4.91	5.06	5.3	5.4	4.65	5.85	6.4

Appendix 4: Alkalinity

Month-year	DUCK(W)	DYER	GREAT(T)	GREAT(W)	GULL	HERRING PD.	HIGGINS	HORSELEECH	KINNACUM	LONG 1	NORTHEAST	ROUND EAST	ROUND WEST	RYDER	SLOUGH	SNOW	SOUTHEAST	SPECTACLE
2-83	-0.8		1.4		3.2				-1.7	-0.2			-0.2	1.4				1.3
4-83	-1.0		1.2		2.8					-1.3				0.7				4.1
7-83	-1.0		1.1		2.5					-1.2				0.3				-0.9
10-83	-0.8		1.3		2.6					-0.3				0.2				-0.6
1-84	-1.2		1.1		3.1									0.2				
4-84	-1.2		1.2		2.9					-0.9				0.3				-0.4
7-84																		
10-84		-0.5		-0.6		6.0	2.9	1.2				-0.2	-1.0	0.0	-0.2	0.6	-0.2	
1-85																		
4-85		-0.5		-0.6		2.6	2.6	0.6				-0.3	-0.9		0.6	0.4	-0.4	
7-85		-0.5	9.8	-0.6		6.0	2.9	1.2	0.0	0.0		-0.2	0.0	0.0	-0.2	-0.2	-0.2	0.0
10-85				-0.9	3.0		1.9			-0.9				0.7				
1-86			3.7		3.5		0.5							0.5				
4-86	-0.9	-0.9	4.0	-1.0	3.0	2.1	2.1	-0.1	-0.9	-1.2	-0.9	0.1	-0.4	-0.3	-0.5	3.9	-0.4	0.3
7-86	0.5	0.2	5.4	-0.5	3.5	5.7	2.9	2.8	-2.0	-0.9	-1.3		-0.2	1.9	-0.9	1.4	-0.2	0.4
10-86	-1.0	-1.7	3.8	-1.3	3.5	4.1	2.2	1.2		-1.2	-1.2	0.2	-0.3	0.3	-0.5	0.7	-0.7	-0.4
1-87	-1.0	-0.9	3.7	-1.1	3.5	2.3	2.4	0.2	-1.0	-1.0	-0.9	0.2	-0.2	0.1	-1.0	0.2	-0.6	-0.1
4-87	-1.0	-0.6	3.1	-0.9	3.3	2.7	3.3	0.6	-1.2	-1.1	-0.6	0.0	-0.4	-0.1	-1.0	0.3	-0.4	-0.3
7-87	-1.3	-0.5	3.6	-0.8	3.3	4.2	3.9	1.6	-1.6	-0.9	-1.0	0.3		-0.4	-0.5	0.2	-1.0	-0.3
10-87	-0.8	-0.5	3.0	-0.8	3.8	4.0	2.4	0.5	-1.7	-1.1	-0.6	0.2	-0.8	0.2	-0.9	0.5	-0.6	-0.4
1-88	-1.2	-0.4	2.5	-1.0	3.5	2.8	2.9	0.0	-1.3	-0.8	-0.8	0.0	-0.6	-0.4	-0.7	0.6	-0.6	-0.4
4-88	-1.0	-0.3	1.8	-1.4	3.6	3.2	3.1	-0.1	-0.3	-0.5	-1.1	-0.8	-0.2	-0.3	-0.8	0.2	-0.1	-0.1
7-88	-1.2	-0.8	2.4	-1.1	3.7	4.3	3.9	1.3		-1.2	-1.1	-0.1	-0.9	-0.5	-1.2	0.6	-0.7	-0.4
10-88	-0.7	-0.7	4.0	-0.8	2.9	6.0	2.6	1.4		-1.0	-0.7	0.1		0.3	-1.2	0.6	-0.5	-0.3
1-89	-0.5	0.7	2.5	-0.7	2.8	3.6	2.4	0.3		-0.7	0.7	-0.6	-0.3	0.0	-0.6	0.0	-0.3	1.2
4-89	-0.7	0.1	1.5	-0.6	3.3	3.3	3.3	-0.9		-1.2	0.1	0.0	-0.7	-0.7	-0.1	-0.1	-0.1	-0.3
7-89	-0.6	-0.5	1.3	-0.8	3.0	4.1	3.5	0.9		-1.2	-0.3	0.3	-0.9	-0.2	-1.3	0.6	-0.2	-0.3
10-89	-0.6	-0.4	2.1	-0.8	3.4	6.6	3.6	1.4		-1.4	-0.6	0.2	-1.1	-0.2	-0.7	0.3	0.0	0.0
1-90	-0.9	-0.6	1.1	-0.8	2.6	4.0	2.8	-0.1	-1.9	-1.3	0.3	-0.6	-0.7		-0.8	0.7	-0.3	-0.4
4-90	-1.0	-1.2	0.6	-0.7	3.2	3.0	2.8	0.2	-1.8	-1.3	-0.3	-0.1	-0.7	-0.9	-0.8	0.1	-0.4	-0.6
7-90	-0.8	-0.7	1.0	-1.2	2.9	4.1	3.4	1.5	-2.3	-1.3	-0.3	-0.3	-0.8	-0.8	-1.1	0.6	-0.3	-0.5
10-90	-0.4	-0.9	1.7	-0.9	2.2	6.1	2.9	1.0	-2.5	-1.1	-0.2	-0.4	-1.4	-0.6	-0.9	0.3	-0.6	-0.9
1-91	-0.7	-0.8	1.7	-3.8	4.1	5.6	4.1	1.0	-1.2	-0.7	0.1	-0.4	-0.4	-3.0	-0.4	1.2	-0.2	0.8
4-91	-0.1	-0.7	1.7	-0.2	3.6	4.5	3.8	-0.2	-2.4	-1.1	-0.3	0.8	-1.0	-2.3	-0.2	1.0	0.2	0.1
7-91	-0.2	-0.6	3.1	0.0	3.5	5.7	4.8	1.2	-2.9	-0.7	-0.4	0.4	0.0	-0.2	-0.2	2.3	-0.4	-0.1
10-91	-0.8	-1.1	1.6	-0.9	3.1	8.4	3.7	0.9	-2.4	-1.1	0.3	-0.1	-0.4	-2.0	-0.8	0.9	-0.5	0.0
1-92	-0.5	-1.0	0.5	-0.4	2.9	3.2	3.6	-0.1	-2.0	-0.8	-0.4	-0.4	-0.1	-3.4	-0.9	0.3	-0.3	0.1
4-92	-0.8	-0.9	0.8	0.4	3.5	3.2	0.1	0.9	-1.2	-1.1	-0.1	-0.1	-0.4		-0.4	0.0	-0.8	0.1
7-92	-0.7	-0.8	0.7	-1.0	3.2	5.5	4.6	0.1	-2.0	-0.7	-0.1	0.2	-0.3	-2.0	-0.4	0.8	-0.1	0.3
10-92	-0.4	-0.3	1.5	0.1	3.8	8.6	2.0	1.3	-3.0	-0.3	0.1	-0.5	-0.3	-2.3	-0.5	0.4	-0.5	0.1
1-93																		
4-93	-0.7	-0.7	-1.7	-0.8	3.5	2.6	3.6	-0.7	-1.4	-1.1	-0.6	-0.4	-0.3	-2.3	-0.7	0.1	-0.4	-0.4
7-93	-0.7	-1.2	1.2	-0.6	3.6		5.3	0.6	-2.2	-0.8	-0.5	-0.2	-0.6	-2.7	-0.1	0.0	-0.7	-1.0
10-93	-0.3	-0.7	0.8	-0.5	3.6	8.6	5.6	0.4	-2.1	-0.6	-0.2	-0.5	-1.1	-2.7	-0.9	0.7	-0.5	-0.8
1-94	-1.0	-1.1	0.6	-0.7	3.8	4.2	4.2	0.6	-1.2	-1.0	-0.6	-0.4	-1.5	-1.5	-0.7	0.3	-0.4	-0.5
4-94	-0.5	-0.9	0.7	-0.3	3.4	3.2	3.7	0.0	-0.9	-0.6	-0.3	-0.3	-0.9	-1.6	-0.4	0.3	-0.1	0.0
7-94	-0.8	-1.1	0.9	-0.5	3.3	3.8	3.5	0.6	-1.3	-0.8	-0.8	-0.3	-1.2	-2.1	-0.6	0.2	0.2	-0.8
10-94	-0.5	-1.2	1.0	-0.7	3.2	7.2	3.8	0.9	-0.9	-0.5	-0.2	-0.2	-0.8	-1.2	-0.6	0.8	0.0	-0.2
1-95	-0.5	-0.8	0.8	-0.2	3.6	4.3	3.2	0.5	-0.8	-0.6	-0.7	-0.3	-0.6	-1.1	-0.7	0.4	-0.4	0.0
4-95	-0.5	-0.5	1.1	-0.3	3.4	3.6	3.3	0.5	-1.1	-0.7	-0.2	0.2	-0.4	-1.1	-0.4	-0.1	-0.1	-0.2
7-95	-0.8	-0.8	1.00	-0.75	3.25	5.00	4.00	1.00	-1.50	-1.00	-1.25	-0.25	-0.90	-1.75	-0.75	0.50	-1.25	-0.50
10-95	-0.8	-1.0	1.25	-1.00	3.50	7.50	4.75	2.00	-1.75	-7.50	-0.25	-0.25	-0.75	-0.75	-0.75	1.25	-1.00	0.00
1-96	-0.5	-0.8	0.75	-0.75	1.50	0.25	2.50	0.50	-1.25	0.00	-0.50	-0.25	-0.50	-1.00	-0.75	-1.25	0.25	-0.25
4-96	-0.5	-1.3	1.25	-0.50	3.50	4.25	3.50	1.25	-1.25	-0.50	0.00	0.00	-0.50	-1.25	-0.50	1.00	-0.25	0.25
7-96	-0.8	-0.5	1.00	-0.75	3.25	5.50	4.75	1.50	-1.50	-1.00	-1.00	-0.25	-0.75	-1.25	-0.75	0.50	-1.00	-0.25
10-96	-0.75	-1.25	0.50	-0.75	3.25	5.75	3.75	0.00	-1.50	-1.00	-0.75	-0.50	-0.75	-1.25	-0.75	0.50	-0.75	-0.50
1-97	-1.00	-1.00	0.00	-0.75	3.00	3.75	3.50	0.75	-1.00	-1.00	-0.75	-0.50	-1.00	-1.00	-0.50	0.25	-0.50	-0.50
4-97	-1.00	-1.25	-1.00	-0.75	2.75	3.00	3.25	-0.25	-1.25	-1.00	-1.25	-0.50	-1.00	-1.50	-0.25	-0.25	-0.25	-0.50
7-97	-1.25	-1.25	-1.25	-0.50	2.75	2.50	3.50	-0.75	-1.25	-1.00	-1.50	-9.75	-1.50	-1.50	0.00	0.25	1.25	-0.50
10-97	-0.50	-0.25	-1.25	-0.25	1.25	3.25	2.50	1.00	-0.25	0.00	0.00	-10.00	-1.50	-1.00	-0.25	0.00	-0.25	0.00
1-98	1.25	-1.25	1.75	-0.50	4.00	5.00	3.25	0.75	-1.25	-0.75	0.00	-0.75	-0.25	-1.25	0.00	0.50	0.00	-0.75
4-98	-0.50	-0.50	-0.25	-0.25	3.25	2.75	3.25	0.50	-0.50	-0.25	0.50	0.00	-0.50	-1.00	-0.25	0.25	0.00	0.00
7-98	-1.00	-1.00	0.25	-0.50	3.25	3.75	3.50	1.25	-0.25	-0.50	0.00	-0.25	-1.00	-0.75	-0.50	0.50	-0.75	-0.50
10-98	-0.50	-0.65	0.65	-0.60	3.50	7.15	4.55	2.30	-0.80	-0.55	-0.15	-0.55	-0.35	-0.85	-0.20	1.00	0.25	-0.25
1-99	-0.80	-1.05	0.25	-1.05	4.20	5.15	3.95	0.70	-0.85	-1.50	-1.00	-0.65	-1.00	-1.40	-0.65	0.15	-0.25	-0.80
4-99	-0.60	-0.70	0.05	-1.15	3.75	3.75	3.55	0.35	-0.50	-0.60	-0.30	-0.05	-0.60	-1.30	-0.45	-0.05	0.20	-0.25
7-99	-0.65	-0.80	0.40	-0.70	4.00	6.35	5.75	2.40	-0.10	-0.75	-0.20	-0.70	-0.30	-0.50	-0.20	0.75	-0.05	-0.45
10-99	-0.35	-0.50	0.90	-0.70	4.00	7.90	6.50	2.30	-0.90	-0.65	-0.25	-0.05	-0.40	0.05	-0.15	1.15	-0.40	-0.50
1-00	-0.6	-0.7	0.35	-0.50	4.90	6.50	6.30	0.65	-0.90	-0.85	-0.10	-0.15	-0.45	-0.55	-0.35	-0.10	0.10	-0.30

Appendix 5: Major Cations and Anions

1992

Micromolar

Pond	Cl	SO4	Na	Ca	Mg	K
DUCK	829	60	767	55	81	33
DYER	550	70	469	28	61	18
GREAT(T)	788	90	700	65	73	18
GREAT(W)						
GULL	861	82	768	51	114	29
HERRING	879	72	774	45	97	18
HIGGINS	829	106	726	43	97	24
HORSELEECH	1125	127	984	44	134	26
KINNACUM	507	72	446	19	61	16
LONG	594	76	497	32	59	21
NORTHEAST	699	81	606	35	87	20
ROUND (east)						
ROUND (west)	445	66	368	27	53	9
RYDER	921	140	865	50	91	23
SLOUGH	824	102	709	38	95	25
SNOW	584	57	485	26	66	23
SOUTHEAST	758	85	661	31	88	26
SPECTACLE	783	80	667	23	89	27
TURTLE						
WILLIAMS	871	77	774	46	106	27

1993 micromoles/L

Pond	Cl	SO4	Na	Ca	Mg
Duck	684	80	587	23	73
Dyer	536	68	461	25	56
Great T	761	76	674	53	69
Great W	745	86	670	30	82
Gull	861	80	761	51	105
Herring	886	89	787	52	103
Higgins	874	74	766	51	100
Horseleech	1143	112	987	46	136
Kinnacum	603	69	526	21	63
Long	573	81	500	29	61
Northeast	737	75	648	29	83
Round East	813	94	722	28	105
Round west	452	69	383	26	56
Ryder	895	153	813	46	84
Slough	812	106	713	35	97
Snow	591	58	505	26	69
Southeast	730	80	626	33	83
Spectacle	874	79	739	25	100
Turtle	691	96	596	36	86
Williams	952	65	979	46	134

1994 micromolar

Pond Name	Cl	SO4	Na	Ca	Mg	K
Duck SF	590	68	539	21	63	19
Dyer SF	455	56	431	24	50	16
Great(T) SF	801	72	687	44	63	20
Great(W) SF	706	77	626	26	72	23
Gull SF	884	86	770	46	96	26
Herring SF	827	72	748	49	93	24
Higgins SF	822	68	731	46	92	25
Kinnacum SF	586	76	444	16	48	16
Long1 SF	644	71	496	28	57	23
Long2 SF	599	70	457	27	55	23
Northeast SF	573	48	544	22	65	19
Round(East) SF	763	83	670	24	92	22
Round(West) SF	433	62	339	20	45	14
Ryder1 SF	866	118	800	38	75	19
Ryder2 SF	816	116	796	38	75	19
Slough SF	747	90	666	32	89	21
Snow SF	1310	83	531	24	63	19
Southeast SF	607	56	544	25	61	21
Spectacle SF	873	67	735	22	88	19
Turtle SF	531	49	479	20	53	23
Williams SF	812	49	753	33	86	31

1995 micromolar

Pond Name	Cl	SO4	Na	Ca	Mg	K
Duck SF	641	78	525	21	79	27
Dyer SF	559	77	391	24	60	22
Great(T) SF	813	72	628	39	75	26
Great(W) SF	770	86	593	25	86	30
Gull SF	879	83	697	42	108	34
Herring SF	896	84	748	46	115	36
Higgins SF	832	77	727	44	114	36
Horseleech1 SF	1121	100	989	40	149	39
Horseleech2 SF	1226	107	985	40	145	38
Kinnacum SF	601	56	404	18	63	21
Long1 SF	585	74	404	27	64	26
Long2 SF	594	75	452	27	64	25
Northeast SF	862	79	589	30	91	30
Round(East) SF	847	92	632	26	110	29
Round(West) SF	472	64	335	21	56	17
Ryder1 SF	926	115	688	36	84	28
Ryder2 SF	901	95	765	36	91	30
Slough SF	860	107	619	32	104	28
Snow SF		232	486	27	85	27
Southeast SF	730	73	529	32	79	33
Spectacle SF	944	73	757	24	105	33
Turtle SF	681	136	443	51	94	36
Williams SF	949	152	774	65	131	32

Appendix 5: Major Cations and Anions

1996 micromolar

Pond Name	Cl	SO4	Na	Ca	Mg	K
Duck SF	712	75	492	21	72	20
Dyer SF	563	68	396	25	56	17
Great(T) SF	886	73	622	40	67	18
Great(W) SF	767	84	565	26	79	22
Gull SF	860	87	670	43	103	26
Herring SF	917	72	679	48	103	26
Higgins SF	859	72	600	47	96	24
Horseleech1 SF	1151	98	805	41	124	27
Horseleech2 SF	1154	99	805	41	124	27
Kinnacum SF	519	55	405	19	58	17
Long1 SF	659	77	418	106	61	21
Long2 SF	614	76	413	29	58	20
Northeast SF	662	71	452	30	72	21
Round(East) SF	790	83	596	29	102	23
Round(West) SF	426	58	331	24	50	14
Ryder1 SF	864	107	687	39	78	20
Slough SF	1231	116	618	37	94	21
Snow SF	593	50	448	36	66	22
Southeast SF	764	90	539	34	77	22
Spectacle SF	1124	79	900	27	97	25
Turtle SF	493	110	396	44	71	8
Williams SF	832	71	674	40	97	24

1997
Micromolar

Pond	Cl	SO4	Na	Ca	Mg
DUCK	803	84	518	22	83
DYER	615	75	593	21	65
GREAT(T)	952	71	631	35	78
GREAT(W)	868	82	651	24	92
GULL	1012	86	641	44	116
HERRING	1038	85	666	44	119
HIGGINS	1039	81	680	46	114
HORSELEECH	1428	112	735	44	142
KINNACUM	684	63	866	26	69
LONG	664	79	683	27	71
NORTHEAST					
ROUND (east)	976	89	934	31	114
ROUND (west)	499	62	778	22	60
RYDER	994	109	687	31	87
SLOUGH	961	101	755	50	111
SNOW	646	56	780	22	79
SOUTHEAST	770	67	738	40	79
SPECTACLE	1044	81	801	29	114
TURTLE					
WILLIAMS	1160	72	755	54	119

1998
Micromolar

Pond	Cl	SO4	Na	Ca	Mg	K
DUCK	835	79	440	19	86	24
DYER	693	73	373	21	68	23
GREAT(T)	1024	78	568	33	81	25
GREAT(W)	948	89	528	25	99	31
GULL	1077	91	605	45	119	36
HERRING	1084	94	611	43	113	34
HIGGINS	1067	92				
HORSELEECH	1277	112				
KINNACUM	722	54				
LONG	714	72	410	24	96	26
NORTHEAST	877	56				
ROUND (east)	1106	93				
ROUND (west)	550	59				
RYDER	1151	122	645	34	95	25
SLOUGH	1062	107				
SNOW	775	56	696	21	80	25
SOUTHEAST	851	63				
SPECTACLE	1145	78	691	22	124	32
TURTLE	822	100				
WILLIAMS	1221	118				

1999
micromolar

STATION	Cl	SO4	Na	Ca	Mg
Duck	773	65	480	18	77
Dyer	497	47	384	20	59
Great (T)	1002	64	703	33	74
Great (W)	800	69	563	22	85
Gull	982	78	691	44	108
Herring	989	72	684	43	124
Higgins	711	53	686	40	129
Horseleech	1083	82	847	34	152
Kinnacum	655	29	416	12	52
Long	641	58	417	22	64
Northeast	775	53	493	19	72
Round east	1023	78	603	22	116
Round west	451	41	304	16	50
Ryder	995	85	671	26	84
Slough	889	83	605	28	114
Snow	657	42	422	17	64
Southeast	781	55	499	26	68
Spectacle	1049	75	692	20	105
Turtle	667	63	411	21	59
Williams	992	80	755	54	119

Appendix 6: Secchi Transparency

Duck Pond

	Secchi depth (m)																		
	Jan	**Feb**	**Mar**	**Apr**	**Apr**	**May**	**May**	**Jun**	**Jun**	**Jul**	**Jul**	**Aug**	**Aug**	**Sep**	**Sep**	**Oct**	**Oct**	**Nov**	**Dec**
				1-15	16-30	1-15	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-31		
1956									17	16	12.5	12	10						
1957										16.5	15.5	14.5	14.5						
1958																			
1975		4	5.2						14.3	13.85				10.1					
1976		14.1	11.4					10.2	13	13.3	13.4		10.5	10.1					
1977			6							9.8	10.2	9.3	9.2	9.1	8.55	8		4	
1978																			
1979																			
1980						12.8		11		9		7.5		6		4.3		10	
1981	3.5		10.4	11.2		17													
1982																			
1983																			
1984	13																		
1985	7		13.5			14.5				10.75	8.5								
1986				8.5	13	10.5	12.25		9	10	9	8	6	8.7	9		7.5	7.5	10
1987					12.6	12		9.75		11.5	9.5	8.8		8.75					
1988								11	13.5	11.7	7.9	7	6	7.2	7.3	5.2	8.8		
1989								12.2	7.8	5.6	6.2	7	6.9	7.7	7.3				
1990								11.1	11.7	10.5	8.2	6.8	5.7	4	3.4				
1991																			
1992							10.9	10.6	9.3	8.7	6.7	7.5	7						
1993						12.95	12.6		10.8	8.5	8								
1994					8.5			8.25	5.8	6.9	6.25								
1995					10.75			10.55	9.5	4.875	7.5	6.5							
1996					11	10	10.5		12.5	9.6	8.25	8.6		6.5				6.3	
1997					4				6	6.85	8.35			9.4					
1998					>18.5	10.75		11	10	8	5			3.75					
1999				15		12.15	12.1	6.3	7.5	5.9	3.15		4	4.84	4.15		6	4.48	
2000			8.95	8.5	8.5	8.45		8.52	7.8		6.8	7.32							

Dyer Pond

	Secchi depth (m)																		
	Jan	**Feb**	**Mar**	**Apr**	**Apr**	**May**	**May**	**Jun**	**Jun**	**Jul**	**Jul**	**Aug**	**Aug**	**Sep**	**Sep**	**Oct**	**Oct**	**Nov**	**Dec**
				1-15	16-30	1-15	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-31		
1975					8.7										10				
1976																			
1977																			
1978																			
1979								9.1											
1980																			
1981																			
1982																			
1983																			
1984																			
1985													4.5						
1986					10.80	9.55	10.6	10.8		8		7.9	3.25	3.75	5.65		7	8.5	
1987					8	9	7.3	7.5	9	9.38	8.13	5.5	5.88	5.08					
1988									8.23	7.55	7	7.5	4.03	3.25	4.68	7.5	7.73		
1989									8.6	7.8	7.75	5.5	5.4	6.3	5.2				
1990									9.4	9.25	9.1	8.3	7.55	5.4					
1991									9.7	9.77	8.55	5.85	4.2	4.45					
1992																			
1993						>10.7													
1994				07-Jan															
1995					>8														
1996						8.1	8.1	9.8		8.5	5.5		8.7						
1997						8.6		11	9.75	10	8.875		5.45						
1998				>10.9			8.75	>8.4	8	9	7			4	6				
1999				10		10.25	9	9.33	6.29	6.65	5.4	3.35		3.65	4.94				
2000				8.95	6.60	8.62		7.98	8.85		9.21	6.37							

Appendix 6: Secchi Transparency

Great (Truro) Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr	Apr	May	May	Jun	Jun	Jul	Jul	Aug	Aug	Sep	Sep	Oct	Oct	Nov	Dec
				1-15	16-30	1-15	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-31		
1973					5.2											7.6			
1974																			
1975								8.5							9				
1976	9							7.5	7.9	7.3	6.25	4.5			5.3				
1977																			
1978																			
1979																			
1980																			
1981																			
1982																			
1983																			
1984	7.4	7.35					6.4	6.5		8.1		6.37		5.53			6.35	8.2	7.3
1985	5	9	7.1	6.6		6.10		7.5			6.6	6.5			7		6	5.2	
1986	7.9	6.8	4.5	3.7	5	5.47	5.3	7			6.2	5.3	4.5	4.85	3.9		4.8		
1987							3.5		4.6		5		5.88						
1988									4.83	4.18	2.2	4.05	4.33	3.53	3.93	3.78	4.05		
1989									5.25	5.15	5.27	5.83	5.7	6.1					
1990									6.55	4.95	6.1	8.2	839	8.4					
1991									7.2	7.65	7.35	7.83	7	7.35					
1992								6.8	6.4	7.3	6.5	7.3	7	6.9	6.6				
1993						7.25													
1994				5.85				4.7	4.175	6.22	4.2								
1995				6.45															
1996				7.25			5.5	5.625	5.7		5.5	5.6			4.5			4.4	
1997					5.25			4.2	4.5		5.35	5.1							
1998				6.5			4.25	4	4.5	4.75	4.5	5.6		4.5	6.4	6	5	4	
1999				9.7	8.79		8.05	6.8	5.5	6.1	6.75	6.39	6.61	7.04	7.32		5.4		
2000				7.2		7.48	7.5	5.6	5.8		6.10	5.85							

Great (Wellfleet) Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr	Apr	May	May	Jun	Jun	Jul	Jul	Aug	Aug	Sep	Sep	Oct	Oct	Nov	Dec
				1-15	16-30	1-15	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-31		
1955													7.77						
1957											7.62								
1975				10.7			8.05	6.8			11.67					14.9	15		
1976																			
1977																			
1978																			
1979																			
1980																			
1981																			
1982																			
1983																			
1984																		10.5	
1985			9			12.3				6.5	7.5				8.3		8		12
1986				9	>15.4		>14.2			7.5		9.5		9.25	8.75		9.5		
1987						9.5	10		12.5		12.3		10.6						
1988									11.13	12.23	11.08	10.15	8.45	7.55	6.9	7.23	8.68		
1989									8.6	6.55	10.37	11	10.55	9.15					
1990									10.75	10.5	10.65	9.77	10.6	9.85					
1991									9.4	11.13	10.75	10.5	9.25	7.75					
1992																			
1993						>15.5													
1994				13.25															
1995					>14.9														
1996					9.4		13.1	10.75	13.75		11.5		6.8		7.7				
1997					7.1				11.6		9.675	7.1							
1998				11			11.25	15	10	10	8		7	5.5	7.5				
1999				15.5		16	12.5	12.4	10.22	8.65	5.1	7.15		4.65	3.87				
2000			13.72		9.9	10.65		11.6	10.1		6.71	6.75							

Appendix 6: Secchi Transparency

Gull Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr 1-15	Apr 16-30	May 1-15	May 16-31	Jun 1-15	Jun 16-30	Jul 1-15	Jul 16-31	Aug 1-15	Aug 16-31	Sep 1-15	Sep 16-30	Oct 1-15	Oct 16-31	Nov	Dec
1975				3.02	4.2	4.08		8.23	7.45	8.1				10.3	9.4				
1976		4.55						8.5	7.5						10.1				
1977	5.2	4.55	6.05				5.2			7.1	8.55				8			6	5.4
1978				14.5					7					10.1					
1979																			
1980					4	4.1			4.7	5.2		7.2			7.2	4.7		4.5	
1981	2.3		3.25		3.5														
1982																			
1983																			
1984																		3.5	
1985	4.5		3			7.5				5.7	6		8.2			4.75		5	4
1986	5				3.5	6.7	6.4			5.2				5.6	6.1	5	4.2		
1987						4		6.5		7.4	7	6.75		8					
1988									5.17	5.85	5.35	5.28	7.08	7.1		6.1	4.95		
1989									6.75	6.6	6.6	6.77	7.45	6.95					
1990									6.35	6.6	6.2	7.77	9.15	9.3					
1991									6.45	8.6	8.9	7.77	8.25	8.85					
1992								7.6	7.3	7.2	7.7	7.6	8.5	8.3	8.7				
1993					8	8		6.95	6.13	6.9		7.25							
1994				4				4	5.9	6	5.5	5.87	6.25						
1995					4.25			4.75	4.5	5	5.5	5							
1996					3.5	7.5		5	6.6	5.05		5.24			5	4.8	3.7		
1997					5.5		5.1	5.025	5.5		6.875	7.5							
1998			3.7		5.75	6.5	20	4.75	4	6	6	5.5	5.5		5.9	4.75		2.25	
1999				3.5		7.25	8.62	7.1	6.75		7.11	7.2	7.5	8.8	7.7		4.7	3.35	
2000				4.62	3.2	5.65		7.55	8.45	6.84		7.31							

Herring Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr 1-15	Apr 16-30	May 1-15	May 16-31	Jun 1-15	Jun 16-30	Jul 1-15	Jul 16-31	Aug 1-15	Aug 16-31	Sep 1-15	Sep 16-30	Oct 1-15	Oct 16-31	Nov	Dec
1975				2.27		3.8													
1976																			
1977																			
1978																			
1979																			
1980																			
1981																			
1982																			
1983																			
1984																			
1985																			
1986													1.8						
1987												2.2							
1988																			
1989																			
1990																			
1991																			
1992																			
1993						>4.5													
1994				3.5															
1995					3														
1996				2.5		2.75		3.31		2.25	2.9	2.65		1.98		1.9			
1997					4.6			2.875	3.05		2.9	2.9							
1998				3.25			2.75	2.5	3.5	3	2.5		1.3	1.65	1.15				
1999				3.22		3.88	3.7	3.4	3.47	2.65	1.55	1		1.06	1.44				
2000				4		3.77	3.92	2.88	3.55		1.55	2.27							

Appendix 6: Secchi Transparency

Higgins Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr	Apr	May	May	Jun	Jun	Jul	Jul	Aug	Aug	Sep	Sep	Oct	Oct	Nov	Dec
				1-15	16-30	1-15	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-31		
1975				2.78		3.95				5					5.65				
1976																			
1977																			
1978																			
1979																			
1980																			
1981																			
1982																			
1983																			
1984																			
1985																			
1986							4.4												
1987												4.5							
1988																			
1989																			
1990																			
1991																			
1992																			
1993					>4.7														
1994				4															
1995					3.75														
1996					3.75							3.5							
1997				3.7										2.75					
1998				3.5										4.3					
1999				4.7									5.08						
2000				5.8								3.5							

Horseleech Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr	Apr	May	May	Jun	Jun	Jul	Jul	Aug	Aug	Sep	Sep	Oct	Oct	Nov	Dec
				1-15	16-30	1-15	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-31		
1952							4.4												
1975																			
1976																			
1977																			
1978																			
1979																			
1980																			
1981																			
1982																			
1983																			
1984																			
1985																			
1986							7.45												
1987												>4							
1988																			
1989																			
1990																			
1991																			
1992																			
1993						>4.5													
1994				4.50															
1995				>4.1															
1996					4.3							3.9							
1997					4.6							4.4							
1998				>5								>4.1							
1999				4.5									4						
2000				4.3								4.32							

Appendix 6: Secchi Transparency

Kinnacum Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr	Apr	May	May	Jun	Jun	Jul	Jul	Aug	Aug	Sep	Sep	Oct	Oct	Nov	Dec
				1-15	16-30	15-Jan	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-30		
1985																			
1986						4.4													
1987												4.5							
1988																			
1989																			
1990																			
1991																			
1992																			
1993						3.80													
1994				3.65															
1995				>3.3															
1996					3.5								2.8						
1997				2.85										2.83					
1998				1.75								1.1							
1999				1.64									1.55						
2000				1.25								0.95							

Long Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr	Apr	May	May	Jun	Jun	Jul	Jul	Aug	Aug	Sep	Sep	Oct
				1-15	16-30	15-Jan	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15
1970													8.2			
1971													4			
1972																
1973					4.3											7.32
1974																
1975				7				10.2							6.6	
1985									6.5							
1986					8.20	6.9	6.45		10.50	10	7.92	7.6	7.15	8.25	6.5	
1987						6.5		9		10.75	7		9.5			
1988									8.87	9.08	5.05	5.73	4.2	7.43	5.4	4.95
1989									12	10.03	9.07	8.83	9.55	10.3		
1990									11.85	12.7	11.1	7.93	6.95	7.9		
1991									12.2	10.85	8.03	8.23	7.4	7.35		
1992																
1993																
1994				8												
1995					8.5											
1996						7.25			9.5	9.7	7.75	7.3				
1997					5.65		4.1	5.6	6.5		6.85			5.25		
1998				7.5			8.25	8	9	6	5	4.5	3	5	6	
1999				8.28		6.5	6.36	9.85	7.5	7.5	6.4	4.8		3.9	5.1	
2000				10.6	6.65	6.5		7.3	9.8		5.26	6.76				

Northeast Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr	Apr	May	May	Jun	Jun	Jul	Jul	Aug	Aug	Sep	Sep	Oct	Oct	Nov	Dec
				1-15	16-30	15-Jan	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-30		
1985																			
1986																			
1987																			
1988																			
1989																			
1990																			
1991																			
1992																			
1993						3.70													
1994				*															
1995					>1.5														
1996					3.2														
1997				5.75															
1998					>4							>3							
1999				3								2.9							
2000			3.2									3.26							

Appendix 6: Secchi Transparency

Round (East) Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr	Apr	May	May	Jun	Jun	Jul	Jul	Aug	Aug	Sep	Sep	Oct	Oct	Nov	Dec
				1-15	16-30	15-Jan	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-30		
1957								0.3											
1985																			
1986																			
1987												5.3							
1988																			
1989																			
1990																			
1991																			
1992																			
1993						7.6													
1994				7.80															
1995				6															
1996					5.5								5.4						
1997				5.75															
1998					>8								5						
1999				7.3									5.8						
2000				7.39								6.38							

Round (West) Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr	Apr	May	May	Jun	Jun	Jul	Jul	Aug	Aug	Sep	Sep	Oct	Oct	Nov	Dec
				1-15	16-30	15-Jan	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-30		
1956													5.79						
1975										4.95				7.7		4.65			
1976							5.2												
1985																			
1986																			
1987													3						
1988																			
1989																			
1990																			
1991																			
1992																			
1993						4.9													
1994				4.80															
1995				4															
1996					6								2.8						
1997					4.925										4.7				
1998				4.1									4						
1999					7.3								4.56						
2000				4.5								5.17							

Ryder Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr	Apr	May	May	Jun	Jun	Jul	Jul	Aug	Aug	Sep	Sep	Oct	Oct	Nov	Dec
				1-15	16-30	15-Jan	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-30		
1975							8.77								7				
1984	7.4	6.35					5.8	9.1				6.3		8.25			5.4	5.2	5.9
1985	10	>11.8	8.6	8.5		7		9		7		5.25			8.8		6.9	5.4	6.7
1986	9	6	6.7	8.1		7		8.1			8		9.05				5.5		
1987										6.75		6.5		6					
1988																			
1989																			
1990																			
1991																			
1992								4.8	4.3	4.8	6.5	6.8	5.9		4.7	5.7			
1993						11.6		9	10.8	10.2		9.25							
1994				6.85				10	10.15	8.03	6.8	6.4	5.5						
1995				7.5				8.55	7.5	4.5	5.5	6	5.5		1.8				
1996							4.5	3.75	7.5	5.55			5.6						
1997					3.5			5.65	5.5		2.28		5.2						
1998				6.5			6.25	5	4	6	3	2.1		2.33	1.4				
1999				6.6	7.35	8.05		4.75	4.4	5.3	4.6	2.5	2.16	4.15	2.94		3.3		
2000				4.25		3.19	3.73	4.65	5.85		3.82	4.65							

Appendix 6: Secchi Transparency

Slough Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr	Apr	May	May	Jun	Jun	Jul	Jul	Aug	Aug	Sep	Sep	Oct	Oct	Nov	Dec
				1-15	16-30	15-Jan	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-30		
1952													7.3						
1975							7.1												
1985																			
1986					7.5	8.25	7.67			6.8	4.73	2.8	5	4.73	3.75		3.95		
1987						5.75		4.75		5.5	6.2	6.2	3.5						
1988									5.88	6.1	5.28	6.4	5.48	3.53	3.63	4.43	5.73		
1989									6.65	5.45	5.63	5.4	4.15	5.35					
1990									7	6.8	6.7	7	6.45	6.85					
1991									6.4	6.7	6.7	6.5	5.4	4.45					
1992																			
1993						>7.3													
1994				7															
1995					>6.3														
1996			7										5.9						
1997			6										5.05						
1998			8									5							
1999			5.97										3.82				3.3		
2000				6.05								5.5							

Snow Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr	Apr	May	May	Jun	Jun	Jul	Jul	Aug	Aug	Sep	Sep	Oct	Oct	Nov	Dec
				1-15	16-30	15-Jan	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-30		
1975						7.5													
1985																			
1986													5.5						
1987								2.5					3.25						
1988																			
1989																			
1990																			
1991																			
1992																			
1993						5.25													
1994				6.00															
1995			>6.1																
1996							6.65		6.5	5	5.5	5.9							
1997					4.15			3.45	3.25	3.45	4.05	4.75							
1998				>7.5			4	3	4	4	3.75		4	5.4	5.58		4		
1999				4.2	5.4	7		7	7.2	4.3	5		5.16	5.85	5.7		3.3		
2000				6.7		7.15	7.05	7.25	7.1		5.9	6.2							

Southeast Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr	Apr	May	May	Jun	Jun	Jul	Jul	Aug	Aug	Sep	Sep	Oct	Oct	Nov	Dec
				1-15	16-30	15-Jan	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-30		
1985																			
1986																			
1987																			
1988																			
1989																			
1990																			
1991																			
1992																			
1993						>3.6													
1994				4.75															
1995					>3.6														
1996				3.7								3.8							
1997				2.9								5.53							
1998					>3							2							
1999				3.27								3.38							
2000			3.45									3.76							

Appendix 6: Secchi Transparency

Spectacle Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr 1-15	Apr 16-30	May 15-Jan	May 16-31	Jun 1-15	Jun 16-30	Jul 1-15	Jul 16-31	Aug 1-15	Aug 16-31	Sep 1-15	Sep 16-30	Oct 1-15	Oct 16-30	Nov	Dec
1975						7			5.2		3.18								
1985																			
1986																			
1987											5.6	4.7			6.8				
1988																			
1989																			
1990																			
1991																			
1992								6.25		5.48	6.1	6.4	5.7	5.7	5.9				
1993							>8	7.4	5.4	2.9	6.35								
1994				5.5				6.25	4.03	5.1	2.5	3.55	6.15						
1995				>5.2				5	5.03	4.75	2.5	1.75	2.5						
1996						4	4	3.75	4.7		4.95	4.4							
1997					4.65		4.3	6.75	5.85		6.15		6.65						
1998				>5.9			5	4	4	4.5	3.6	5		3.6	6	5.75			
1999				6.25		7	7.3	6.675	6.02		6.8	6.04	6.04	4.65					
2000				7	6.82	6.3		6.85	6.25		6.65	6.59							

Turtle Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr 1-15	Apr 16-30	May 15-Jan	May 16-31	Jun 1-15	Jun 16-30	Jul 1-15	Jul 16-31	Aug 1-15	Aug 16-31	Sep 1-15	Sep 16-30	Oct 1-15	Oct 16-30	Nov	Dec
1985																			
1986																			
1987																			
1988																			
1989																			
1990																			
1991																			
1992																			
1993																			
1994																			
1995																			
1996				1.1															
1997														1.03					
1998					>1.2							0.6							
1999				1.53									1.3						
2000			1.3								1.3								

Williams Pond

Secchi depth (m)

	Jan	Feb	Mar	Apr 1-15	Apr 16-30	May 15-Jan	May 16-31	Jun 1-15	Jun 16-30	Jul 1-15	Jul 16-31	Aug 1-15	Aug 16-31	Sep 1-15	Sep 16-30	Oct 1-15	Oct 16-30	Nov	Dec
1975				1.44	1.6			0.66		1.05				1.7	1.8				
1976																			
1977																			
1978																			
1979																			
1980																			
1981																			
1982																			
1983																			
1984																			
1985																			
1986																			
1987																			
1988																			
1989																			
1990																			
1991																			
1992																			
1993							>2												
1994				>2															
1995					>1.3														
1996					1.8							1.2							
1997				1.55								1.5							
1998				>1.5								0.75							
1999				1.7									1.5						
2000				1.65								1.6							

Appendix 7

Total Phosphorus

(ug/L)

	Note 1				Note 2														
	Apr-75	Mar-76	Apr-82	Jun-82	Feb-84	May-84	Oct-84	Feb-85	Apr-85	Feb-86	Aug-92	Aug-94	Aug-95	Apr-96	Apr-97	Apr-98	Aug-98	Apr-99	Aug-99
Duck	7	4	6.5	6.4							18	4.8	6.9	12	9.075	1.331		11.2	12.8
Dyer		8		6.4										10	9.922			5.3	5.5
Great T		8	14	14	50	80	60	50	30	30	17	7.8	18	14	9.922	1.694		18.4	5.1
Great W	8	4		4									8	8.5	5.929			21.4	7.8
Gull	19	16	16	8.3							27	6.5	17	18	26.257			14.3	5.9
Herring		24		27									68	32	75. 2	4.598		24.6	25.1
Higgins		26		16											47.19	1. 89		24	8
Horseleech	8	12		8.2											9.6	1. 89		1.2	5.6
Kinnacum	13	9		14											8.8	5.7		34.4	21.3
Long		5												13	7. 18			9.8	13.5
Northeast	14	9	11													1 .164		14.6	7
Round East		7													7.5 2			7.8	5.6
Round West		14		8.7											7.5 2	3.3		18.6	9
Ryder	15	7			40	60	40	50	40	30	7.2	8.6	21	18	2 .328			10.0	7
Slough	8	9		14											7.1	1.5		8.2	6.7
Snow	13	10												16	9.6	. 363		28.4	6.5
Southeast	21	16													11.9	1.6		13.5	6.7
Spectacle	14	6		11							15	7.2	27		24.9			14.6	9.3
Turtle	46	16														9.3		24.0	13.3
Williams		25													37.5	3. 25	36.3	27.7	50.2
Note 1: Soukup 1977																			
Note 2. These suspiciously high values were reported to Shortelle & Colburn (1987) by Mass DEQE, DWPC, during the Truro Lake Liming Project.																			

Appendix 8: Chlorophyll α

MEANS, N=3

chlorophyll (ug/L) - surface samples only

	Note1		Note 2		Note 3	CACO data									
	Apr-75	Jul-75	Sep-75	Sep-76	Apr-78	Aug-86	Sep-86	Aug-87	Aug-96	Apr-97	Aug-97	Apr-98	Aug-98	Apr-99	Aug-99
Duck	0.10	2.50	1.50		0.49	1.45		1.21	2.18		0.79	0.82	1.16	1.22	1.50
Dyer	0.90		0.70		0.28	1.11	1.10	1.74	1.42		1.72	0.17	0.80	0.85	1.14
Great T	5.00	0.80		1.70	2.10	0.38		1.09	0.57		0.37	0.18	0.93	1.50	0.92
Great W	1.80	0.80	0.90		0.62			2.86	1.55		1.05	0.52	1.87	0.92	3.47
Gull	7.60	2.60	1.50		8.30	1.34		0.68	0.35	0.53	0.39	1.94	0.31	2.72	1.37
Herring	9.20		7.90		6.10	3.24		10.22	1.22	0.74	1.39	1.25	6.65	2.24	15.51
Higgins	6.40		1.90		2.40			2.98	1.60	0.73	0.55	1.69	1.92	1.46	0.84
Horseleech	2.10				2.70			1.04	0.79	0.25	0.34	1.02	0.62	0.52	0.11
Kinnacum	5.30				5.90				3.98	1.95	1.19	10.06	8.28	10.55	7.97
Long	1.80		1.50		1.10	2.04		0.91	1.88	0.59	2.98	0.54	1.11	1.35	1.29
Northeast	1.50								1.32				1.07	1.15	2.33
Round East	2.60							2.57	1.54	0.50	0.97	0.45	0.80	2.36	1.47
Round West		5.90			1.60			3.50	10.48	0.14	1.37	0.53	1.14	0.42	2.48
Ryder	13.30				3.90	2.69			1.65		0.51	2.17	8.19	0.74	8.63
Slough	1.80				1.90	13.77		2.29	0.49	0.58	1.03	5.96	2.76	0.46	1.83
Snow					2.10			4.51	0.30		0.11	1.68	0.67	1.77	1.05
Southeast	1.40				1.20				0.27	1.11		0.58	14.46	2.62	3.14
Spectacle	2.40	3.20			1.40			1.30	1.17	0.36	0.26	0.71	1.87	0.79	0.99
Turtle	3.60				2.80				0.77	3.06	3.06	1.43	10.46	1.89	16.15
Williams	18.80	14.10	2.30		12.20				4.35	1.25	7.59	2.09	12.46	2.49	12.61

Note 1: Soukup 1977

Note 2. Data from Bruce Peterson (Marine Biological Lab, Woods Hole, MA).

Note 3: Coe & Soukup 1978.

Appendix 7

Total Phosphorus

(ug/L)

	Note 1				Note 2														
	Apr-75	Mar-76	Apr-82	Jun-82	Feb-84	May-84	Oct-84	Feb-85	Apr-85	Feb-86	Aug-92	Aug-94	Aug-95	Apr-96	Apr-97	Apr-98	Aug-98	Apr-99	Aug-99
Duck	7	4	6.5	6.4							18	4.8	6.9	12	9.075	1.331		11.2	12.8
Dyer		8		6.4										10	9.922			5.3	5.5
Great T		8	14	14	50	80	60	50	30	30	17	7.8	18	14	9.922	1.694		18.4	5.1
Great W	8	4		4									8	8.5	5.929			21.4	7.8
Gull	19	16	16	8.3							27	6.5	17	18	26.257			14.3	5.9
Herring		24		27									68	32	75. 2	4.598		24.6	25.1
Higgins		26		16											47.19	1. 89		24	8
Horseleech	8	12		8.2											9.6	1. 89		1.2	5.6
Kinnacum	13	9		14											8.8	5.7		34.4	21.3
Long		5												13	7. 18			9.8	13.5
Northeast	14	9	11													1 .164		14.6	7
Round East		7													7.5 2			7.8	5.6
Round West		14		8.7											7.5 2	3.3		18.6	9
Ryder	15	7			40	60	40	50	40	30	7.2	8.6	21	18	2 .328			10.0	7
Slough	8	9		14											7.1	1.5		8.2	6.7
Snow	13	10												16	9.6	. 363		28.4	6.5
Southeast	21	16													11.9	1.6		13.5	6.7
Spectacle	14	6		11							15	7.2	27		24.9			14.6	9.3
Turtle	46	16														9.3		24.0	13.3
Williams		25													37.5	3. 25	36.3	27.7	50.2

Note 1: Soukup 1977

Note 2. These suspiciously high values were reported to Shortelle & Colburn (1987) by Mass DEQE, DWPC, during the Truro Lake Liming Project.

Appendix 8: *Chlorophyll α*

MEANS, N=3

chlorophyll (ug/L) - surface samples only

	Note1		Note 2		Note 3	CACO data									
	Apr-75	Jul-75	Sep-75	Sep-76	Apr-78	Aug-86	Sep-86	Aug-87	Aug-96	Apr-97	Aug-97	Apr-98	Aug-98	Apr-99	Aug-99
Duck	0.10	2.50	1.50		0.49	1.45		1.21	2.18		0.79	0.82	1.16	1.22	1.50
Dyer	0.90		0.70		0.28	1.11	1.10	1.74	1.42		1.72	0.17	0.80	0.85	1.14
Great T	5.00	0.80		1.70	2.10	0.38		1.09	0.57		0.37	0.18	0.93	1.50	0.92
Great W	1.80	0.80	0.90		0.62			2.86	1.55		1.05	0.52	1.87	0.92	3.47
Gull	7.60	2.60	1.50		8.30	1.34		0.68	0.35	0.53	0.39	1.94	0.31	2.72	1.37
Herring	9.20		7.90		6.10	3.24		10.22	1.22	0.74	1.39	1.25	6.65	2.24	15.51
Higgins	6.40		1.90		2.40			2.98	1.60	0.73	0.55	1.69	1.92	1.46	0.84
Horseleech	2.10				2.70			1.04	0.79	0.25	0.34	1.02	0.62	0.52	0.11
Kinnacum	5.30				5.90				3.98	1.95	1.19	10.06	8.28	10.55	7.97
Long	1.80		1.50		1.10	2.04		0.91	1.88	0.59	2.98	0.54	1.11	1.35	1.29
Northeast	1.50								1.32				1.07	1.15	2.33
Round East	2.60							2.57	1.54	0.50	0.97	0.45	0.80	2.36	1.47
Round West		5.90			1.60			3.50	10.48	0.14	1.37	0.53	1.14	0.42	2.48
Ryder	13.30				3.90	2.69			1.65		0.51	2.17	8.19	0.74	8.63
Slough	1.80				1.90	13.77		2.29	0.49	0.58	1.03	5.96	2.76	0.46	1.83
Snow					2.10			4.51	0.30		0.11	1.68	0.67	1.77	1.05
Southeast	1.40				1.20				0.27	1.11		0.58	14.46	2.62	3.14
Spectacle	2.40	3.20			1.40			1.30	1.17	0.36	0.26	0.71	1.87	0.79	0.99
Turtle	3.60				2.80				0.77	3.06	3.06	1.43	10.46	1.89	16.15
Williams	18.80	14.10	2.30		12.20				4.35	1.25	7.59	2.09	12.46	2.49	12.61

Note 1: Soukup 1977

Note 2. Data from Bruce Peterson (Marine Biological Lab, Woods Hole, MA).

Note 3: Coe & Soukup 1978.

Appendix 9

Statistical analysis of long-term trends in Kettle Pond water quality.

The statistical significance of long-term changes in pH was examined for ten Park ponds, Dyer, Duck, Great (Wellfleet), Long, Great (Truro), Gull, Southeast, Northeast, Ryder and Herring, where time series plots suggested trends. Kendall rank correlation (Kendall 1938, 1948) was performed on quarterly pH values. pH observations were grouped by season and seasonal trends were analyzed using the seasonal Kendall modification suggested by Hirsch and Slack (1984) and Loftis et al (1989). This modification minimizes bias in the data due to 1) serial correlation between consecutive years and 2) regular seasonal fluctuations in pond pH due to temperature- and light-dependent biogeochemical processes.

The non-parametric Kendall rank correlation is a powerful way of examining apparent trends in long-term water quality data. Applying non-parametric tests to water quality data for trend detection can cause inflated significance levels due to serial correlation. To compensate for this effect, quarterly data were de-seasonalized by subtracting from each year's seasonal record the average for all years within that season (Loftis et 1989). It should be acknowledged that the statistical power of this test, i.e. the probability of discerning a significant temporal change in pond pH, is low unless the trends are large and/or the dataset is sufficiently long; e.g. 20-30 years or more (Siegel 1956) and uninterrupted. Data used here are from 1983 to 1999. Depending on the season, these records comprise 13-16 years of data.

A Kendall rank correlation coefficient t of > 0.60 and an a of < 0.01 were chosen as critical values for statistical significance. Of all ponds tested only Long Pond and Great Pond (Truro) showed significant trends (increases) in pH with time for any season (Table A8-1). Great Pond's acid-base balance has been largely affected by the addition of agricultural limestone by the State in 1975 and again in 1985. These alterations likely overwhelm any changes due to increased productivity. The pH increase at Long Pond, however, is symptomatic of an anticipated increase in water column production, through both assimilative and dissimilative nitrate and sulfate reduction and accompanying alkalinity generation.

Table A8-1. Significant pH trends by year derived from corrected seasonal Kendall rank correlation.

Pond	Season	Trend direction	τ	p-level
Long	Spring	Increase	0.616	0.0008
Great (Truro)	Winter	Increase	0.707	0.0004

It is important to realize that the non-parametric tests used for this analysis are very sensitive to short (i.e. small sample sizes) and interrupted (i.e. missing data) periods of record. Successful trend detection in these kettle ponds will require extensive and uninterrupted records over the 25-30 years recommended for these tests (Siegel 1956; Hirsch and Slack 1984; Loftis et al 1989).

Appendix 10

Pond Bathymetric Data

Note: Volumes and areas below were computed in Arcview 3D Analyst based on TINS generated from point data. Contours are shown on the maps that follow for illustrative purposes.

Duck Pond

Planimetric area (m^2)	Cumulative volume (m^3)	Depth (m)
48180	291776	0
42374	246633	1
37626	206668	2
33091	171256	3
28757	140064	4
24687	112971	5
21288	90103	6
17573	70637	7
14385	53847	8
12512	40833	9
10301	29422	10
7933	20108	11
5940	13145	12
4122	8176	13
2541	4698	14
1641	2698	15
1122	1329	16
631	454	17
181	50	18

Gull Pond

Planimetric area (m^2)	Cumulative volume (m^3)	Depth (m)
444609	3751049	0
404865	3327735	1
376259	2937414	2
347966	2575303	3
318648	2242015	4
288448	1936577	5
261407	1662732	6
239708	1412710	7
220518	1182678	8
202223	971375	9
184133	778176	10
167031	601738	11
150851	442733	12
130909	301717	13
106264	182749	14
77292	90002	15
38315	32858	16
13002	8395	17
3252	1429	18
191	20	19

Dyer Pond

Planimetric area (m^2)	Cumulative volume (m^3)	Depth (m)
46562	239327	0
40816	195690	1
36284	157200	2
31910	123045	3
27869	93174	4
24196	67154	5
20453	44797	6
16207	26384	7
10711	12740	8
5909	4563	9
1649	487	10

Herring Pond

Planimetric area (m^2)	Cumulative volume (m^3)	Depth (m)
78385	213364	0
64614	142521	1
53165	82888	2
42095	34950	3
11652	2356	4

Appendix 10

Pond Bathymetric Data

(continued)

RyderPond

Planimetric area (m²)	Cumulative volume (m³)	Depth (m)
79585	500170	0
73869	423499	1
68521	352308	2
62739	286621	3
56757	226897	4
50784	173102	5
44435	125468	6
37699	84320	7
29986	50416	8
20058	25242	9
10347	9964	10
5138	2773	11
291	18	12

Snow Pond

Planimetric area (m²)	Cumulative volume (m³)	Depth (m)
26536	106255	0
23149	81382	1
19837	59572	2
17295	40982	3
14071	25284	4
10189	13028	5
6053	4937	6
2327	846	7
0	0	8

Spectacle Pond

Planimetric area (m²)	Cumulative volume (m³)	Depth (m)
5622	16196	0
4466	11047	1
3523	7050	2
2349	3991	3
1461	2050	4
917	877	5
395	220	6
10	1	7

Truro Great Pond

Planimetric area (m²)	Cumulative volume (m³)	Depth (m)
66363	270439	0
55009	209281	1
43726	159875	2
36120	120382	3
30035	87073	4
24044	59812	5
17693	38388	6
12267	23068	7
8768	12536	8
5377	5012	9
2307	965	10

Wellfleet Great Pond

Planimetric area (m²)	Cumulative volume (m³)	Depth (m)
171748	913599	0
156429	748748	1
141651	599248	2
120543	452713	3
104932	344685	4
83196	252912	5
57205	177448	6
42502	130613	7
34066	92576	8
26099	62591	9
16412	39090	10
11681	24964	11
6518	13833	12
5675	8519	13
2383	2976	14
1379	892	15
245	57	16