CHAPTER 6. LIMNOLOGY AND WATER QUALITY
A. LIMNOLOGY – SENECA LAKE

INTRODUCTION
Seneca's large size and economic importance are two of many reasons why we must monitor and protect the ecological health and water quality within the lake and its watershed. Here, we report on our current understanding on the limnology and water quality of Seneca Lake based on ongoing monitoring by Hobart and William Smith Colleges in conjunction with Seneca Lake Pure Waters Association, Inc., the watershed's local, citizen-based watchdog group. This chapter significantly expands on previous summaries by the author of this chapter (Halfman et al., 1998, Halfman, Maloney et al., 1997).

The limnological monitoring of Seneca Lake started nearly a decade ago with the addition of a limnologist / hydrogeologist to the geoscience faculty at Hobart and William Smith Colleges (HWS), first Dr. M. Wing followed by Dr. J. Halfman. The program builds upon earlier work that established a first-order understanding of the water quality and health of the lake by other university and governmental groups. In particular, base line limnological data are compiled from previously published and unpublished sources including Bloomfield's monographs, New York Department of Environmental Conservation, Seneca Lake Pure Waters Association, Water Resources Division at Ithaca (United States Geological Survey), and Water Pollution Control Board (New York Department of Health). The ultimate objectives are to monitor the ongoing water quality and ecological health of the lake, and educate the general public on these issues.

The specific goals of this chapter are to answer the following questions:

1. What is the water quality of the lake, especially in regards to chloride, hardness and selected pollutants?

2. What is the trophic status of the lake?

3. Does the water quality and/or trophic status change in different parts of the lake?

4. Does the water quality and/or trophic status of the lake change over time, e.g., have zebra mussels and/or other factors influenced the lake?

This report also contains introductory information on water temperature and aquatic biology because temperature controls the water column circulation, which in turn, regulates many biological processes in a lake (for more details see, e.g., Wetzel, 1983, Cole, 1994, Horne & Goldman, 1994). In general, limnological data are available to address but not completely answer the first two questions raised above. Unfortunately, data are lacking to completely answer the last two questions. Instead, trends in the data and hypotheses to explain these trends are discussed. Our inability to completely answer these questions, which are essential ingredients in any State-of-the-Lake Report, dictates continued monitoring of the lake in the future to better understand the water quality and ecological health of Seneca Lake.

METHODS

The current monitoring program at HWS utilizes undergraduate students to collect and analyze weekly, limnological data from four offshore (water depths > 20 m) stations within the northern portion of the lake (*Fig. 6A-1*). These four sites maximize the diversity in Seneca Lake while minimizing the expense during a ½ day cruise aboard the HWS Explorer, the Colleges' 65 ft steel-hulled research vessel. Samples were also collected from the end of a dock in Kashong Bay during 1997. During 1998, monthly limnological data were collected from five additional sites distributed from the northern survey area southward towards Watkins Glen to determine if the northern and southern portions of the lake were similar (Fig. 6A-1). The nine sites maximize coverage of the entire lake but require an entire day of intensive fieldwork and significantly more laboratory analyses. The sites, from north to south, are located mid-lake offshore of the Geneva Country Club, an east/west transect of three sites offshore of Kashong Point, offshore of Dresden, just south of the navy barge, mid-lake offshore of Lodi Landing, mid-lake offshore of Peach Orchard Point, and mid-lake offshore of Salt Point (Fig. 6A-1). Fieldwork typically clusters in the spring and fall semesters, and is less frequent in the summer.

At each deepwater site, surface water was analyzed for dissolved oxygen, pH, chloride, alkalinity, hardness, nutrients (phosphates, nitrates and silica), chlorophyll, and plankton enumeration. Bottom water samples (within 2 meters of the lake floor) were collected using a 10-Liter Nansen bottle and analyzed for the same parameters from all of the deepwater stations (1, 3 & 6-9). In addition, a CTD water-column profile was collected at each station. A CTD electronically measures and records conductivity (related to salinity) and temperature *versus* water depth every 0.5 seconds as the profiler is lowered through the water column. Our CTD (SBE-19, manufactured by Sea Bird Electronics) also has electronic sensors for pH, dissolved oxygen, and water transparency (related to water turbidity). All of the parameters except for a CTD cast and plankton enumeration were measured at the Kashong Bay site. Each analysis used standard limnological procedures; and the details are available upon request (Halfman, 1994, Wetzel & Likens, 1991).

WATER QUALITY OF SENECA LAKE

Water is one of our most precious natural resources since it is fundamental for survival. Seneca Lake is the drinking water source for over 70,000 people in central New York State, and for this reason alone it is important that the water quality be within EPA specifications.

The City of Geneva, for example, has operated a Water Plant since 1895, when the original installation on Glass Factory Bay was purchased from a private company established in 1887. Untreated water is drawn from Seneca Lake and divided between slow sand filters and diatomaceous earth vacuum filters. The filtered water is then chlorinated, stored, fluorinated and pumped into the water mains for delivery to the city.

In 1996, Geneva pumped an average of 2.1 million gallons of water a day to the 15,000 inhabitants in the city plus another 2,000 people in the surrounding community. The water meets all drinking water standards established by the Environmental Protection Agency under the Safe Drinking Water Act and enforced by the New York State Health Department. The water is annually tested for heavy metals (e.g., Arsenic, Mercury and Lead), volatile organics (e.g., Benzene, Vinyl Chloride and Xylene), and other contaminants including organics, microbes, pesticides and herbicides (e.g., Nitrates, Coliform Bacteria, Atrazine, and Arochlor).

Seneca Lake provides Class “AA” water, the best possible. Briefly, Class “AA” and “A” water supplies are used for drinking water and only requires disinfection and filtration treatments. Class “B” water can be used for swimming but not drinking. Class “C” and “D” water have greater restrictions.

Chloride Concentrations

Chloride typically is the most abundant anion (negative ion) dissolved in natural waters. Its concentration is higher than other ions because it is rarely removed from the water column by biological and chemical processes within the lake. Too much chloride, thus too much salt in drinking water is a health risk. Chloride concentrations above 250 mg/L (ppm) pose a health risk because the associated sodium ions hamper the development of kidneys in small children and aggravates heart problems in older individuals. Total dissolved ion concentrations above ~1000 mg/L are too salty to drink and will promote nausea and dehydration. Seawater, at ~35,000 mg/L, significantly exceeds drinking water limits.

Seneca Lake has chloride concentrations of 150 mg/L, which doesn’t pose an immediate health risk to the majority of the population. This concentration is a concern however, because it is 2 to 10 times larger than the chloride concentration of the other Finger Lakes (150 *versus* 20 to 50 mg/L). Why is Seneca more concentrated in chloride?

The concentration of any ion in a lake is dependent on how fast it enters the lake, how fast it leaves the lake, and the associated input, removal and volume of water. For chloride, sources include the weathering of bedrock, natural seepage from underlying salt beds, discharge from wastewater treatment facilities and salt mines, runoff from road salt. Chloride is removed by burial of chloride in lake water that accumulated with sediments, and flow through the outlet. In both removal mechanisms, chloride is an innocent companion to the movement of water. Typically the input and removal rates are equal and dictate a constant concentration in the lake over geologic time.

Prof. Mike Wing and his students, when at Hobart and William Smith Colleges, have determined that Seneca Lakes is saltier than the other Finger Lakes because this basin intersects the Silurian beds of commercial-grade salt 450 to 600 meters below the ground surface and percolating groundwater brings saline water into the lake from below (Wing et al., 1995). Their conclusion is based on a number of observations. First, analysis of numerous tributaries that enter Seneca and other Finger Lakes reveals chloride concentrations of 20 - 60 mg/L. Thus, all of the Finger Lakes experience similar inputs of chloride by surface runoff. This is consistent with the observation that all of the watersheds have similar glacial deposits, exposed bedrock, landuse practices and rainfall totals. Second, theoretical calculations indicate that the input of chloride by surface runoff explains the measured concentrations in the other lakes. The same calculations dictate that an extra 170 million kilograms (375 million pounds) of salt must be added to Seneca Lake each year to achieve the measured concentration in the lake. This calculated input significantly exceeds the amount discharged into the lake by salt mines and wastewater treatment plants. Third, bottom-water chloride concentrations increase during the summer months, only to return to a lake-wide average after the fall water-column overturn. The salt appears to fill the lake from below. Fourth, pore waters in the sediments are significantly saltier than the lake, and is consistent with groundwater flow of saline water upward to the lake from below. Finally, our glacially scoured lake basin is significantly deeper than the current lake floor, and the other Finger Lakes. Seismic reflection profiles reveal sediment thicknesses of up to 450 meters in Seneca Lake, deep enough to intersect the salt formations found at depth in the region and exposed to the north. The investigation highlights the possibility that lake chemistry is affected significantly by the deep-lying strata intercepted by its basin as well as by the surface lithology and landuse practices of its watershed.

Acidification of Seneca Lake?

The burning of fossil fuels have released sulfur and nitrogen oxides to the atmosphere, which readily convert to strong acids when mixed with water in the air or on the ground. These acids may runoff into lakes and streams and increase the acidity of the water body. Acidity is measured on a logarithmic pH scale from 1 (acidic) to 14 (basic). An acceptable range for pH in natural waters is neutral to slight basic, i.e., between 6.5 and 8.5; however many lakes in the Adirondacks have a much lower pH due to acid rain deposition, low enough to severely impact the biota.

Has acid rain altered the pH of Seneca Lake? The pH of Seneca Lake varies from 8.0 to 9.0 and recent data are similar to those collected in the past. Thus, acid rain has had minimal impact on the acidity of the lake. The difference between Seneca and lakes in the Adirondacks relates to the variability in buffering capacity (i.e., the ability to neutralize acids) of their respective watersheds. Acids react with and are neutralized by lime-rich soils, limestone bedrock, and carbonate and bicarbonate ions in the water. Limestone is found in the glacial tills and bedrock of Seneca's watershed, and the lake is alkaline, i.e., the water is rich in dissolved carbonate, bicarbonate and other acid neutralizing / buffering ions. Thus, acid precipitation is neutralized before it impacts Seneca Lake. Lakes in the Adirondacks are less fortunate.

Water Hardness

Water hardness is defined by the concentration of divalent cations (ionic charge of 2+) with hard water exceeding a total concentration of 80 mg/L. Its occurrence reflects the concentration of calcium (Ca^{2+}) and magnesium (Mg^{2+}) dissolved from limestones and other soluble calcium and magnesium-rich rocks. Hard water is not harmful to drink as long as the total salt concentration is less than 1000 mg/L, and some studies have shown that drinking hard water may reduce the risk of heart disease but the reason for the relationship is not completely understood. However, hard water is a nuisance problem. When soap is used in hard water, the calcium and/or magnesium reacts with the dirt removing chemicals in soap, diminishing the soap's cleaning abilities. It also forms a soap scum that fades white clothes to a dingy gray. When warmed, hard water also precipitates limestone (calcium carbonate) and it is more likely to precipitate in hot water than cold water. The scaly scum is difficult to remove, and frequently precipitates in hot-water pipes, pots, teakettles, and hot water heaters – shortening their life span.

Water softeners reduce water hardness by passing the water through an ion-exchange material. The process typically exchanges one calcium or magnesium ion for two sodium (or potassium) ions. Rock salt (NaCl) is used to periodically recharge the ion-exchange mineral with sodium (or KCl exchanging potassium). Softeners can effectively reduce the hard water problem for a household but the rock salt softeners create new problems for those on low-sodium diets and all softeners waste approximately 10% of the water used in the home.

Seneca water is moderately hard, with total hardness concentrations of 140 - 150 mg/L (ppm, $CaCO_3$). Thus, hardness is a concern for the residents around the lake. The lake water is not as hard as the local groundwater, however. The high concentrations of calcium, coupled with a high alkalinity (primarily bicarbonate, HCO_3^-, and carbonate, CO_3^{2-}, concentrations in Seneca Lake), allows for the occasional precipitation of calcium carbonate ($CaCO_3$) from the water column during warm, biologically productive summer months. Precipitation events are occasionally observed as white coating on stems and leaves of nearshore submerged plants. Dissolved calcium and carbonate ions are also required to precipitate calcium carbonate shells for zebra mussels, clams, snails and other shelled animals. Preliminary calculations suggest that zebra mussels remove approximately 30% of the calcium precipitated on the lake floor, however these calculations are based on crude estimates of zebra mussel populations.

Herbicide, Pesticide and Other Pollutants

Seneca Lake is believed relatively pollution free but not worry free. A number of recent concerns at neighboring lakes suggest a growing need to continue monitoring the health of Seneca Lake. The US Geological Survey Water Resources Division has analyzed water from the Finger Lakes for the occurrence of various herbicides (Callinan & Eckhardt, 1997, Phillips et al., 1998). They recently presented concentrations for atrazine and other herbicides that either exceed or are just below the EPA's minimum threshold for safe drinking water. Cayuga has the highest concentration of the Finger Lakes, perhaps due to its larger watershed and higher density of agricultural land. Seneca and other lakes are a close second.

The Environmental Protection Agency awarded a grant to John D. Halfman of Hobart and William Smith Colleges to investigate the atrazine "problem" in Seneca Lake. Atrazine is a common herbicide used to control broadleaf weds in corn and other common crops. It was the focus of this study because it is polluting the surface and groundwater supplies in the "corn-belt" of the nation's midwest, it is susceptible to surface runoff after application to the fields, and it causes cancer in laboratory animals. The preliminary results from Seneca Lake indicate that atrazine concentrations average 0.13 ppb and range from 0.05 to 0.23 ppb where 0.05 ppb is the minimum detection limit for the procedure (Halfman et al., submitted). These concentrations are below the maximum contaminant levels (MCLs) of 3.0 ppb established by the EPA. Stream samples reveal that the major source for atrazine if from surface runoff of agricultural watershed, i.e., nonpoint sources with the remainder from groundwater and atmospheric sources. (see discussion on atrazine in chapter 6B). Another concern is the fish health advisories related to elevated levels of PCB's in lake trout from Canadice and Canadaigua Lakes, and DDT in lake trout from Keuka Lake. This concern along with isolated heavy metal contamination of the sediments is under study by the Division of Water, New York State Department of Environmental Conservation (NYSDEC).

Unfortunately, data are not available to exclude the full range of potential pollutants in the watershed and/or detail changes in these water quality parameters over time. It indicates that the various agencies and labs should continue their monitoring of the lake and activities within the watershed that might discharge pollutants to the lake.

WATER TEMPERATURE

Most fishermen and swimmers understand that even on a hot summer's day, water temperature decreases with water depth for typical lakes in North America (*Fig. 6A-2*). The deep water is always cold, i.e., near 4°C (39°F) during the entire year. Yet, the surface water temperature varies seasonally with the warmest temperatures of over 20°C (70°F) during the summer and coldest temperatures near 0°C (32°F) during the winter. Those souls who brave the elements to measure water temperatures in the middle of winter notice that water temperatures are colder at the surface (near 0°C) than the bottom (near 4°C) of a lake.

The seasonal change in water temperature at the surface and constant temperatures at the lake floor is related to the seasonal cycle of sunlight (solar insolation) and its impact on water density. In a simplistic way, the seasonal solar cycle dictates warm surface water in the summer and cold surface water in the winter. In actuality, solar energy is the primary heat source to a lake whereas evaporation of water and conduction / radiation of heat are the primary heat removal mechanisms from a lake. A net surplus (gains > loses) of energy occurs in the summer so the lake warms; whereas a net loss (gains < loses) of energy occurs in the winter so the lake cools. Three more concepts are essential for this report. These heat transfer processes occur at or near the lake's surface. The extent of warming or cooling is inversely proportional to the volume of water, because energy transfer in liquids is mass/volume dependent. Translated, a larger lake requires more energy gain to warm, and more energy loss to cool than a smaller lake. Finally, the density of water varies with water temperature but the change is unlike most liquids. Most liquids increase density with decreasing temperatures and are most dense just above the freezing point. Water, in contract, is most dense at 4°C (39°F), and is increasingly less dense at warmer and colder temperatures.

The seasonal change in water temperature, thus water density, is critical because less dense liquids "float" on more dense liquids. During the summertime warm surface water (warmer than 4°C) is less dense than colder bottom water (4°C), thus warmer, surface water "floats" on colder, bottom water. The structure defines an upper, warmer, well-mixed epilimnion and a lower, colder, isolated hypolimnion. These layers are separated by the thermocline, the zone of rapidly changing temperatures in the water column. The temperature contrast between the epilimnion and hypolimnion increases through the summer as the surface gains energy from the sun. During the fall, solar insolation decreases, energy is lost from the lake, and the epilimnion cools to 4°C by late fall or early winter. At 4°C, the entire water column is at the same temperature and the lake may overturn (mix). Cool the surface water below 4°C, and the colder surface water is less dense and "floats" on the warmer, bottom water (4°C). The density contrast restricts mixing of the entire water column once again. If the surface water is cooled enough (0°C) and the water is very still, then ice forms on the surface of the lake. Increased solar energy in the spring warms the surface water to 4°C. At which point, the water column is once again at the same density and the lake can mix until the surface water warms to temperatures above 4°C. In summary, the surface water temperature changes seasonally, whereas the bottom water remains a constant 4°C in large lakes at our latitude.

In Seneca Lake, the seasonal cycle of surface water temperatures is from ~4 to ~25°C. Ice cover is extremely rare on Seneca Lake and is restricted to extremely cold winters. The temperature range and extent of ice cover on Seneca Lake is smaller than that observed at neighboring Finger Lakes, even though Seneca Lake experiences similar energy gains and losses to warm or cool the water as the other lakes, because Seneca is significantly larger size and requires significantly more energy to warm or cool the lake.

The annual thermal cycle and seasonal stratification of the water column is critical because it defines seasons when the water column can mix and when the water column is stratified and isolates the bottom water of the lake. The behavior influences the distribution and concentration of dissolved gases, ions, nutrients and other items essential for life. The temperature of the water also governs the rate of chemical, biochemical and physiological reactions. For example, summer stratification of the lake allows for the accumulation of chloride ions in the cold, hypolimnion of Seneca Lake during lake stratification. Biochemical and physiological reactions are exponentially faster in warmer than colder water. For example, bacterial respiration increases 1.5 to 4 times for every 10°C increase in water temperature. Different organisms have adapted to different conditions. For example, algae are dominated by one species of diatom (*Asterionella*) in the spring, green algae in the summer (*Ceratium*) with occasional but brief blooms of blue green algae (*Anabaena*) and microscopic plants (*Ecballocystis*), and another diatom species (*Fragilaria*) in the fall.

Want additional complications? Not only does the depth of the thermocline vary seasonally as described above but it also migrates upward and downward on shorter time-scales in response to wind and current induced internal waves (seiche activity, *Fig. 6A-3*). Storm winds, that blow parallel to the long axis of the lake, can push the epilimnion towards the downwind end of the lake. The epilimnion thickens by 15 or more meters at the downwind end due to the accumulation of the extra epilimnetic water and correspondingly thins by 15 or more meters at the upwind end from the loss of epilimnetic water. The lake's surface rises and falls by a few inches at the "thick" and "thin" ends of the lake, respectively, as well. When the wind event stops, the epilimnion sloshes back and forth in the lake like a standing wave in a bathtub, and simultaneously forces the surface of the lake and the thermocline to oscillate upward and downward. This "sloshing" is technically known as seiche activity. The surface seiche is along the lake's surface and internal seiche is along the lake's thermocline. The timing of the oscillations depends on many factors including the intensity and duration of the wind event, the thickness and density of the epilimnion and hypolimnion, and the length, width and depth of the lake. In Seneca Lake, the period of the internal seiche is approximately 3 days.

What does this complication mean to this chapter? First, the thermocline is probably not at the same depth from one day to the next, especially if you troll for lake trout at the same depth that you caught the big one a few days ago. More importantly, as water temperatures at a given location change from day to day and season to season, its influence on the thickness of the eplimnion and hypolimnion, and the biogeochemisty of the lake changes as well. Lakes are dynamic and impossible to quantify with isolated samples.

Decadal changes are also observed in the temperature of Seneca Lake. Dr. William Ahrnsbrak of Hobart and William Smith Colleges has systematically measured temperature profiles each week at the same site over the past 5 years. The data reveal that 1998 was the warmest and 1996 the coldest year in Seneca Lake during the previous 5 years. Both warmer surface water temperatures and a thicker epilimnion were observed in 1998 than in years past. Ahrnsbrak attributes the abnormal warmth in 1998 to El Nino and its associated climatic abnormalities. Data from 1999 are not yet available for analysis.

LAKE BIOLOGY – FUNDAMENTALS

The biology of any lake is primarily planktonic - microscopic floating forms that are at the mercy of waves and currents. Plankton are divided into three major groups: phytoplankton, zooplankton, and bacterioplankton. Each group performs a unique but interconnected ecological role. Phytoplankton (algae) are the primary producers of organic matter. They are the plants in the aquatic world that harness sunlight and synthesize organic matter by utilizing nutrients dissolved in the water column. They are the primary food source for zooplankton and other animals higher in the food chain. Zooplankton are animals, the first-order consumer in the food chain. They eat the smaller phytoplankton that are typically too small to be eaten by larger animals. Zooplankton are large enough to be seen and eaten by larger carnivores higher in the food chain like small fish. Large fish are typically close to or at the top of the food chain in most lakes, eating zooplankton, mussels, shrimp, insect larvae or smaller fish. Food chains dictate that the number of organisms at any level is limited by the amount of energy (organic matter) available and not used by a lower level in the chain.

Bacterioplankton are usually undetected but extremely important in the ecological web of a lake. They decompose organic matter and effectively recycle more than 90% of the nutrients encased in dead organisms back to the water column. This recycling is extremely important because algae can not photosynthesize organic matter without enough light or nutrients, and recycling by bacteria is the largest natural source for nutrients in aquatic systems.

Other organisms are less important in terms of their total biomass but are more familiar to the average person. They include fish, shallow-water weeds, and zebra mussels. Biologists categorize these organisms by where and how they live. For example, nekton are stronger swimmers like fish, neustron are insects and other organisms that are restricted to the lake’s surface, and benthos are microscopic and macroscopic plants and animals attached to the lake floor like Eurasian water milfoil and zebra mussels.

In Seneca Lake, the dominant phytoplankton are various forms of diatoms, which are phytoplankton that secrete siliceous frustules (shells). *Asterionella* dominates in the spring and *Fragillaria* dominates in the fall. *Certaium*, a green algae, may dominate in the summer months with occasional but brief blooms of blue green algae (*Anabaena*) and microscopic plants (*Ecballocystis*). The difference reflects the availability of specific nutrients, sunlight, and predation pressures. The dominant zooplankton are copepods, a class of organisms belonging to the phylum Crustacea that look like a miniature lobster. Along with benthic freshwater shrimp, rotifers and daphnia, copepods are the first-order consumers. The latter are an important source of food for young lake trout ages 1 to 4 years, whereas the former are eaten by forage fish which, in turn, are eaten by older lake trout. Nearshore, attached plants and other organisms are also important in Seneca Lake like Eurasian water milfoil and zebra mussels. Both impact the lake’s ecosystem. Milfoil provides a suitable habitat for various species of fish but is a nuisance for boaters and swimmers. Zebra mussels are an exotic species to Seneca Lake, and were first observed late in the summer of 1992. Today, they have colonized almost every suitable shallow-water habitat, filter-feeding on the plankton.

TROPHIC STATUS OF SENECA LAKE AND RECENT CHANGES

The trophic status of any lake is determined by the concentration of dissolved oxygen, soluble nutrients and the resultant biological productivity (*Table 6A-1*). Typically, higher concentrations of soluble nutrients support larger algae and nearshore plant populations. Larger plant populations, in turn, support larger animal populations higher in the food chain. Limnologists typically measure the amount of soluble nutrients and primary producers (plants) to estimate a lake’s trophic status because both parameters represent the total amount of ‘energy’ that supports organisms higher in the food chain. Trophic states span from oligotrophic to eutrophic lakes. Oligotrophic lakes are biologically sparse, transparent, nutrient poor, and not very fertile in fish, whereas, eutrophic lakes are more productive, turbid, green, nutrient rich, and fertile in fish. Additional terms are used to further subdivide the trophic states, e.g., mesotrophic lakes are between oligotrophic and eutrophic lakes. Dissolved oxygen concentrations, Secchi disc depths, nutrient concentrations, and chlorophyll concentrations are addressed below to determine the trophic status of Seneca Lake.

Table 6A-1. Trophic Status of Lakes (from Wetzel, 1983 and Berner & Berner, 1996).

Trophic Status units	Secchi Depth (meters)	Nitrate, N (N, µg/L, ppb)	Phosphate (P, µg/L, ppb)	Chlorophyll-a (µg/L, ppb)
Oligotrophic	> 5	< 250	< 10	< 3
Eutrophic	< 3	> 500	> 20 (> 30)	> 6 (> 10)
Seneca Lake	1 - 11 m	100 - 600	0.1 - 10.0	1.0 - 5.0

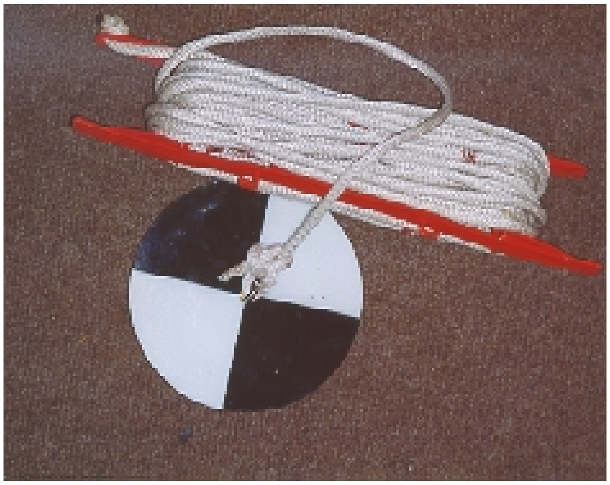
Dissolved Oxygen

The concentration of dissolved oxygen (DO) in lakes is influenced by water temperature, diffusion into the water column from the atmosphere, and biological reactions, e.g., photosynthesis and respiration. Even though oxygen is abundant in the atmosphere, its low solubility and slow diffusion from the atmosphere into water dictates low DO concentrations in the water column. Temperature dictates the greatest amount of a gas that can dissolve in a fluid with colder water dissolving more gas than warmer water. For example, cold sodas have more carbonation (i.e., more dissolved CO_2) than warm sodas (less dissolved CO_2). Saturation DO concentrations are approximately 13 mg/L at 4°C and 8 mg/L at 25°C. Biological activity through photosynthesis and respiration modify DO concentrations in lakes from saturated values.

In any lake, photosynthesis releases oxygen, primarily to the epilimnion, and respiration consumes oxygen, primarily from the hypolimnion. Both biological processes occur at rates faster than oxygen diffuses into the lake from the atmosphere. Thus, eutrophic lakes with correspondingly high rates of photosynthesis and respiration can supersaturate the epilimnion with oxygen and deplete oxygen from the hypolimnion with bottom water anoxia possible. Deepwater DO depletion can result in low fish production or in severe cases, suffocation or fish kills. Bottom water anoxia also stimulates bacterial production of methane and hydrogen sulfide (a foul, rotten-egg smelling gas). In contrast, DO concentrations are only slightly modified by biological activity in oligotrophic lakes and are primarily influenced by water temperature. Thus, DO concentration should increase with water depth during the summer in oligotrophic lakes.

In Seneca Lake, DO concentrations are at or near saturation throughout the water column during the entire year (*Fig. 6A-4*). Thus, DO concentrations are dictated by water temperature and are not modified by substantial biological activity. Seneca Lake is not eutrophic but instead oligotrophic or mesotrophic.

Secchi Disc Depths



The Secchi disc is a simple but robust method to measure water transparency, i.e., how far we can see through water. The penetration depth for sunlight defines the thickness of water that is warmed by sunlight and the maximum depth that sunlight is available for photosynthesis. The disc is 20 cm in diameter with opposing white and black quadrants and simple to use. It is attached to a rope and slowly lowered through the water column until it just disappears from view. This depth is noted. It is lowered some more, then slowly raised through the water column until it is just observed. This depth is also noted. The Secchi depth is the average of the two depths. It is proportional to water transparency and inversely proportional to water turbidity, but also influenced by cloudiness, position of the sun, roughness of the water, and observer bias. Plankton and suspended mud particles are the major contributors to water turbidity. Thus, shallow Secchi depths indicate larger plankton and/or suspended sediment concentrations.

In Seneca Lake, Secchi depths range from just under a meter to over 11 meters during the past decade (*Figs. 6A-5 & 6A-6*). Seasonal trends are observed in the data. Secchi depths are shallower during the summer months than early spring and late fall. The seasonal trend parallels the expected rise and fall of plankton concentrations, with the largest plankton concentrations in the summer months when sunlight is most abundant and nutrients are still available. Exceptions to this seasonal trend exist, and are attributed to unusually high, suspended sediment plumes related to runoff from the occasional large storm, rapid delivery of turbid spring meltwaters, or significant wave resuspension of nearshore sediments for a short period of time. On any given day, Secchi disc depths from across the lake are within 1 meter of each other. The differences are consistent with expected patchy concentrations of plankton. To a first approximation, Secchi depths reflect plankton concentrations and trophic status in Seneca Lake. The typical depths suggest that Seneca Lake is oligotrophic / mesotrophic lake. The depths shallower than 3 meters probably reflect localized suspended sediments or localized plankton blooms.

Nutrient Concentrations

Plants require carbon dioxide and water to photosynthesize organic matter using energy from the sun. Plenty of carbon dioxide and water are available in lakes for photosynthesis. However, a number of other elements are essential to synthesize a wide variety of organic molecules from cell walls to DNA. The most important elements are dissolved phosphorous and nitrogen. Diatoms also require dissolved silica at concentrations above 500 μg/L (ppb) to secrete their siliceous frustules (shells). These nutrients are very scarce in lakes (ppb concentrations), with phosphorous more scarce than the other nutrients in most freshwater systems. The scarcity of these elements limits plant growth during the non-winter seasons, which, in turn, limit the amount of food for organisms higher in the food chain.

Measurement of nutrient concentrations is difficult and time consuming. Typically, water is collected and immediately filtered to remove the plankton and other particles. Samples, blanks and standards are then reacted with an array of chemicals that eventually change the color of the sample to a red or blue. The intensity of the color, e.g., a range from light to dark blue, is proportional to the nutrient concentration and measured with a sensitive and expensive spectrophotometer.

In general, nutrient concentrations vary during the year and with water depth due to differences in biological uptake and water column stratification. Photosynthetically active algae are restricted to the epilimnion, where sunlight is available. Thus, these plants deplete nutrients from the epilimnion during the non-winter seasons. When algae die and sink to the lake floor, bacteria decompose the organic matter and excrete nutrients into the water column. Those nutrients that are released to the sunlit epilimnion are recycled into the next generation of algae; those nutrients released to the hypolimnion accumulate in the hypolimnion because bottom waters are too dark for photosynthesis. Thus, nutrients are enriched in the hypolimnion relative to the epilimnion through the spring, summer and fall of the year. The accumulating nutrients in the hypolimnion eventually return to the lake’s surface when the lake overturns during the late fall and early spring. Nutrient concentrations can reveal significant variability in surface waters because the distribution of photosynthesis/respiration, the influx of nutrients from the land and/or from the hypolimnion due to runoff and/or wind-induced upwelling events is patchy.

Nutrient concentrations are a good indicator of trophic status. Remember, higher concentrations allow for more biological growth and are more typical of eutrophic lakes, whereas lower concentrations restrict growth and are more typical of oligotrophic lakes (Table 6A-1). Lately, lakes are becoming increasing more eutrophic due to human activities. The reasons are typically complicated but relate to the increased nutrient loading to lakes. Nitrates, the usable form of nitrogen in oxygenated lakes, are introduced through the deposition of acid rain (nitric acid is a main acid causing component). Other sources of nitrates include vegetation changes in the watershed by fires, flooding or artificial clearing. The main anthropogenic (human caused) sources of nitrates to lakes are runoff from agricultural land, especially after the application of fertilizer, runoff from farm animal feed lots, and discharge from the improper treatment of sewage, especially private septic systems. Phosphates, the usable form of phosphorous, are naturally eroded from bedrock and soils but at very slow rates. Thus, phosphates are typically more limiting to growth than nitrates. However, domestic, agricultural and some industrial wastes are major anthropogenic sources of phosphates to lakes, especially from use of phosphate-rich soaps and improper sewage treatment within the watershed. The ban on phosphate soaps and better sewage treatment has led to the reversal of eutrophication and the partial restoration of Lake Erie.

In Seneca Lake, nitrate concentrations range from 100 to 600 μg/L (*Fig. 6A-7*), soluble reactive phosphate from 0.1 to 10 μg/L (*Fig. 6A-8*), and dissolved silica from 50 to 4,000 μg/L (*Fig. 6A-9*). The nitrate and phosphate data indicate that Seneca Lake is either oligotrophic, mesotrophic or somewhere in between depending on which nutrient is used to qualify the ranking (phosphates suggest oligotrophic but nitrates suggest mesotrophic), and which year supplies the nutrient data (1997 data suggest oligotrophic yet 1998 suggest mesotrophic). The nutrients reveal similar or larger concentrations in the hypolimnion than the epilimnion, probably due to the differential uptake in the epilimnion by algae and release to the hypolimnion by bacteria as explained above. Within either the epilimnion or hypolimnion on any given day, nutrient concentrations are ~2 μg/L for phosphate (when the values are above the detection limit of the instrument), ~100 μg/L for nitrate, and ~100 μg/L for silica. The largest range is in the hypolimnion. The exact reason for the variability is not completely understood but probably reflects the patchy distribution of nutrient concentrations in aquatic systems. The daily variability proves that one sample does not characterize a lake.

Which nutrient is limiting in Seneca Lake? Algae require nitrogen and phosphorous in a fixed P:N ratio of 1:7. In Seneca Lake, the P:N ratio is significantly smaller than 1:7, and indicates that Seneca Lake is severely “phosphorous limited.” In practical terms, this means that excess loading of phosphorous from sewage treatment facilities, septic systems and elsewhere could result in algal blooms and possible eutrophication of the lake.

Chlorophyll-a

Chlorophyll-a is the most common pigment used to capture sunlight for photosynthesis. Thus, its concentration is typically proportional to the total algal biomass and trophic status of the lake (Table 6A-1). Concentrations change seasonally and with water depth. Seasonally, the largest chlorophyll concentrations are during the summer months and parallel the expected summer rise in algal populations. Algae only grow where sunlight is available. Thus, chlorophyll concentrations are largest in the epilimnion, whereas hypolimnion chlorophyll typically represents sinking dead algae. Algal blooms may occur locally in a patchy distribution if nutrients are added to the epilimnion from, for example, intense storm runoff events, sewage spills, runoff of agricultural fertilizers, or seiche induced upwelling of nutrient-rich bottom waters.

Measurement of chlorophyll concentrations is difficult and time consuming. A water sample is filtered to retain the microscopic algal on the filter. The filter and algae are digested in acetone, to dissolve the filter and release the chlorophyll from the algae into the acetone. Subsequent centrifugation isolates the pigment in the acetone, and the pigment’s concentration is measured with a sensitive and expensive spectrophotometer.

In Seneca Lake, chlorophyll-a concentrations range from below the detection limit of the technique (reported as zero) to slightly greater than 10 μg/L (*Fig. 6A-10*). The bulk of the values are between 1 and 5 μg/L, and indicate that Seneca Lake is borderline oligotrophic

– mesotrophic. Bottom water values are similar or lower than surface values as expected, especially at the deeper sites.

LONG TERM CHANGES IN THE LIMNOLOGY OF SENECA LAKE

Very few data are available to investigate changes before 1990. Secchi disc data reveal deeper depths in 1910 and 1927 (8 and 9 m) and shallower depths in the 1970’s (3.6 m average) compared to average 1990’s depths. The progression from more transparent to more turbid waters during the middle part of the century may correspond to an increase in nutrient loading and corresponding increase in trophic status related to a human-induced eutrophication of the lake. The decrease from 1970 to 1990 may reflect better sewage treatment systems and better farming practices. However, other limnological and landuse data are unavailable to confirm these suspicions.

Over the past decade, all of the biologically related parameters have changed in Seneca Lake with different changes before and after 1998. Average Secchi depths have increased from ~3 meters in the early 1990’s to ~8 meters in 1997 but returned to ~6 meters in 1998 and 1999 (*Fig. 6A-6*). Nitrates appear less concentrated today than during the early 1990’s although the trend may be an artifact of limited data in the early *1900s (Fig. 6A-7*). Nitrate concentrations increased during 1998 and 1999, especially after the middle of the summer in 1998. Phosphates have remained the same, very close to the detection limit of the analysis except for 1998 and 1999, when values were significantly higher, especially after the middle of the summer in 1998 (*Fig. 6A-8*). Dissolved silica was higher in 1996 and 1997 than in the past although the earlier trend may be an artifact of limited data. The 1998 and 1999 data are lower than the 1996 or 1997 concentrations (Fig. 6A-9). Mean chlorophyll-a concentrations and the number of samples with chlorophyll-a concentrations greater than 5 μg/L have decreased over the past decade to 1998 then increased in 1998 through 1999 especially after 1998’s mid-summer bloom (Fig. 6A-10). These trends are probably not the result of the patchy distribution of biological parameters, because the trends are larger than the ranges observed on any single day.

Deeper Secchi depths and less chlorophyll-a in the lake from 1990 to 1998 suggest fewer plankton with time and significantly clearer water over time. The trends may reflect a continued reversal of the lake’s eutrophication; however, this hypothesis is not consistent with the observed constant nitrate and phosphate concentrations or higher concentrations dissolved silica concentrations over this time frame.

Alternatively, the 1990 to 1998 trends may reflect the observed rise in zebra mussel populations within Seneca Lake because the exotic bivalve eats plankton and was first detected in the lake during the summer of 1992 (*Fig. 6A-11*). A time lag of a few years is observed between the first sighting of the mussel and the observed change in Secchi depths and chlorophyll-a concentrations. The lag probably reflects the time it took for zebra mussels to become sufficiently established in the lake to impact the lake’s ecosystem. The apparent increase in dissolved silica from the early 1990’s to 1997 supports this hypothesis because zebra mussels selectively consume plankton. Since the plankton are primarily diatoms, if they are consumed, nothing else will remove the accumulated dissolved silica from the lake.

As the phytoplankton populations decreased from 1992 to 1998, they should consume less and less dissolved nutrients over the same time period. This was observed in the silica concentration trends. However, the phosphate and nitrate concentrations have remained relatively constant over this time period. Why? Perhaps these nutrients are being removed by another species of plant in the lake that does not require dissolved silica thus their concentrations do not increase with time. This scenario parallels the recent rise in Eurasian milfoil and other nearshore plant populations. Alternatively, these nutrients are incorporated into the accumulating biomass of zebra mussels.

The drastic reduction in the phytoplankton biomass over the past decade must impact the lake's ecology. Less and less food was available from the early 1990s to 1997 to feed the other organisms higher up the food chain, like fish (*Fig. 6A-11*). The scarcity must have reduced their populations although no systematic sampling has been performed to confirm this likely result. However, this scenario is consistent with numerous but unofficial reports of less and smaller fish catches by local fishermen.

What happened in 1998 and 1999? The mid-summer increase of 1998 in nutrient concentrations and chlorophyll-a, and a decrease in Secchi disc depths are internally consistent but are inconsistent with pre-1998 trends. The 1998 and 1999 data suggest an influx of nutrients to the lake that triggered an increase in algal productivity and more turbid water, especially during the 1998 summer. Other observations support increased algal productivity in 1998. Dissolved silica was severely depleted in the epilimnion, and enriched it in the hypolimnion. The epi/hypolimnetic segregation of dissolved silica was larger in 1998 than previous years. Green (*Ceratium*), blue-green (*Anabaena*) and other microscopic plants (*Ecballocystis*) dominated the plankton community to a greater extent in the summer of 1998 than previous in years. Pinpointing the exact source for these extra nutrients is difficult because data are insufficient to completely exclude a number of possibilities.

Perhaps the zebra mussel impact on the lake's limnology was drastically reduced in 1998 compared to years in the past due to a significant reduction in their population. However, the available evidence contradicts this hypothesis. Dredge samples from a number of shallow water locations taken during the late Spring of 1998 recovered approximately 10 times more zebra mussels per dredge sample than in 1996. This observation may be fortuitous since the number of zebra mussels recovered by a sediment dredge only approximates the zebra mussel population because the dredge numbers are also influenced by sediment recovery of the dredge and uneven distribution of zebra mussels on the lake floor. Yet this change is consistent with two additional observations. The calcium budget suggests that zebra mussels are a significant and growing presence in the lake, and zebra mussel larvae were a significant portion of the plankton community for the first time in 1998.

Perhaps more nutrients were introduced to the lake by a change in human activities within the drainage basin. This is also unlikely. The largest known change is the conversion of a few family farms near the watershed to large-scale pig farming. However, preliminary stream chemistry data suggest that the streams with pig farms in the watershed are not statistically different from that of streams draining other agricultural land in the local area, and none of the pig farms in within the Seneca Lake Watershed. The long-term record does not reveal significant changes in nutrient loads to the lake by surface runoff as well (see chapter 6B).

Perhaps more nutrients were delivered to the lake by larger than normal snowmelt or spring runoff in 1998. We suspect minimal differences because rainfall amounts were not drastically different this spring compared to other springs in the past, and spring-time air temperatures in 1998 were only slightly warmer. Previous years with similar precipitation and temperature data as this past spring did not experience significant nutrient loading to the lake as was observed this year. In addition, most of the limnological parameters changed mid-summer and not in the spring. Thus, unusual runoff may have contributed to the increased nutrient loading to the lake during the spring and subsequent algal growth this past spring, but probably did not force the mid-summer change.

Perhaps decomposition of dead zebra mussels provided a previously unavailable source of nutrients to the epilimnion of the lake in the summer of 1998 (*Fig. 6A-11*). According to the Secchi disc and chlorophyll-a data, zebra mussels did not have a major impact on the limnology of the lake until ~1994, a few years after their first sighting in 1992. Thus, Zebra mussels would not have a major impact on the flow of nutrients up the food chain until ~1994. Once established, zebra mussels would incorporate nutrients within their living tissue and feces thus effectively remove the nutrients from the rest of the lake. Zebra mussels typically live a few years before they die and decompose. Thus, decomposition of dead zebra mussels and the associated recycling of the nutrients in their biomass probably would not impact the lake until 1997 or 1998, at least a few years after their significant impact on the lake's limnology in 1994. This delay provides a mechanism to release previously isolated nitrates and phosphates to the epilimnion of the lake during 1998 and 1999.

Surface water temperatures were much warmer and depth to the thermocline was much deeper in 1998 than in the recent past. This would have contributed to faster and more complete decomposition of the recently available dead zebra mussels in 1998 because bacterial respiration increases exponentially with increasing temperature. The decomposition would be fastest during the warmest months of the year, the mid-summer season. Once nutrients are recycled to the epilimnion, an algae bloom would quickly follow. This scenario conveniently explains the increase in trophic status of the lake during 1998. However, it provides many more questions than answers. To what extent was the change in 1998 the result of warmer water, zebra mussel life cycles, or an alternative hypothesis? This is a tough question to answer. Interestingly, the limnological data in 1999 are very similar to the 1998 results, and suggests the same scenario is continuing. More importantly, 1999 marks the first year for significant accumulations of dead zebra mussels accumulating along the shoreline and littering the lake floor. The occurrence is consistent with our nutrient recycling hypothesis.

SUMMARY

1. **Water Quality:** Seneca Lake provides Class “AA” drinking water to 70,000 residents within its watershed. The water is chloride rich and hard but is not acidic and is believed pollutant free. This assessment however, is based on a limited amount of data, especially historical data.

2. **Trophic Status:** Biological parameters indicate that Seneca is borderline oligotrophic / mesotrophic. Very low nutrient concentrations, especially low phosphate concentrations, prevents unsightly algal blooms and associated green coloration observed in smaller lakes of the region, and prevents dissolved oxygen depletion in the hypolimnion during the late summer. In many respects, Seneca is a pleasant lake to drink, live by, swim in and fish.

3. **Limnological Changes over Time:** Changes in Secchi disc depths, nutrient concentrations and chlorophyll-a concentrations from the early 1990s to 1998 suggest that zebra mussels have decreased the algal concentrations in Seneca Lake and increased the water clarity. The change must impact the food availability to organisms higher in the food chain, like fish. In 1998 and continuing through 1999, these trends reversed. In addition, nitrate and phosphate concentrations dramatically increased in 1998, especially after the middle of the summer, and stayed high through 1999. Perhaps decomposition of dead zebra mussels during the unusually warm year of 1998 triggered the observed limnological changes in 1998 and 1999, and recent reports of dead zebra mussels supports this hypothesis, but other hypotheses are possible. The variability indicates that continued research is essential to statistically prove and completely understand the extent of the zebra mussel’s impact on the ecology of the lake.

4. **Recommendation:** The lake changes on many temporal and spatial scales, thus dictates continual monitoring of the lake and its watershed to preserve this vital resource and completely understand its ecology.

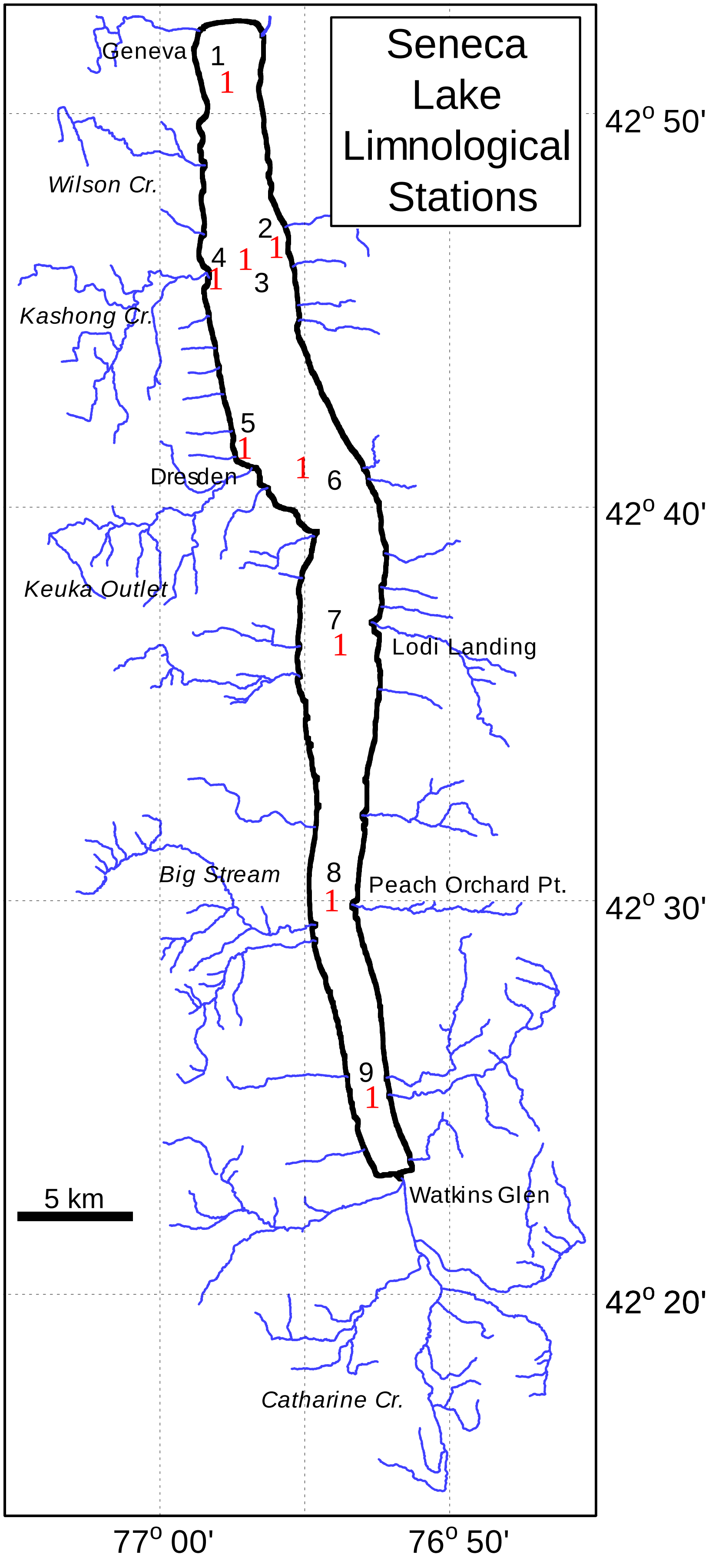


Figure 6A-1. Station locations for limnological monitoring. Most of the data comes from Stations 1-4.

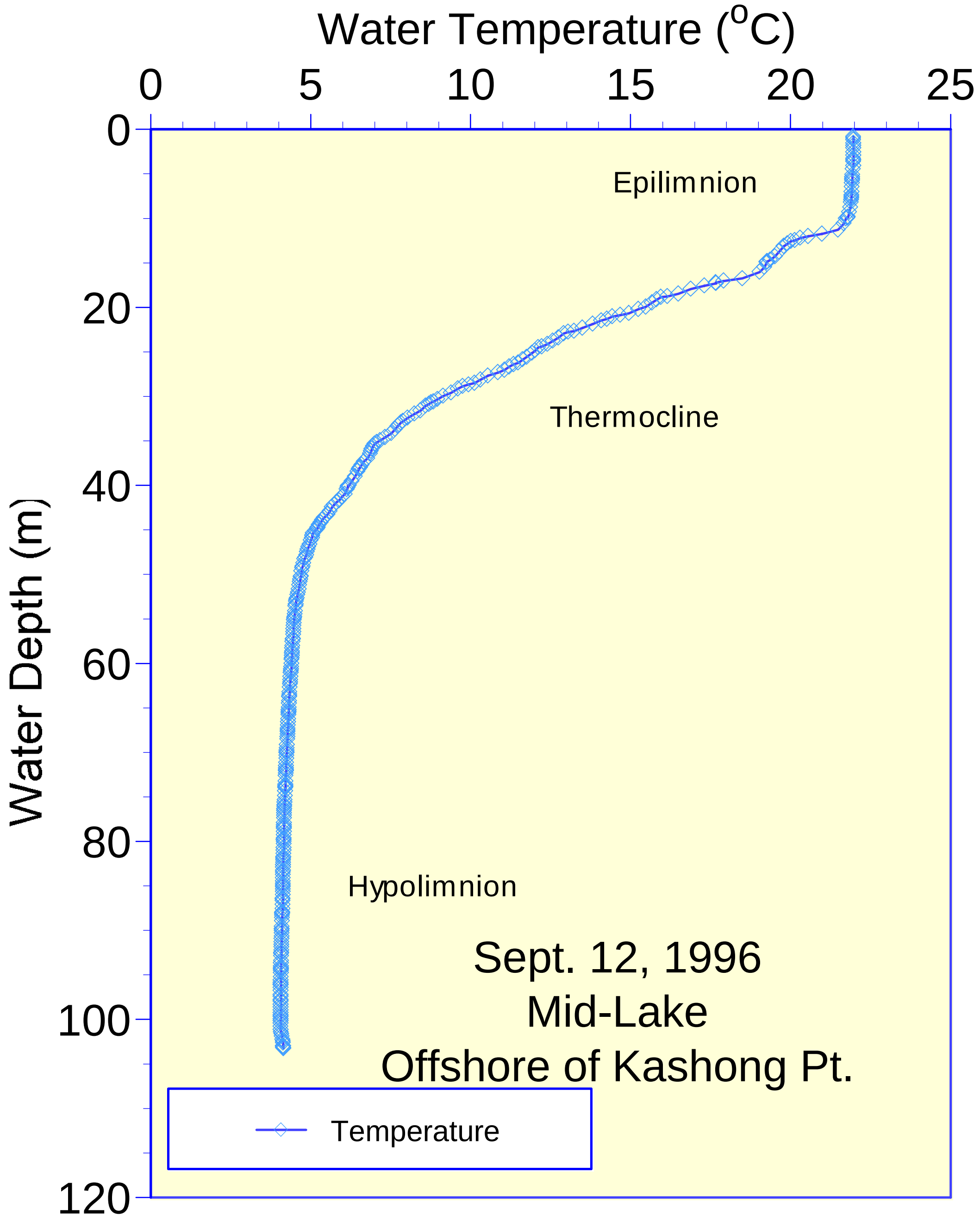


Figure 6A-2. Water column profiles of temperature and dissolved oxygen.

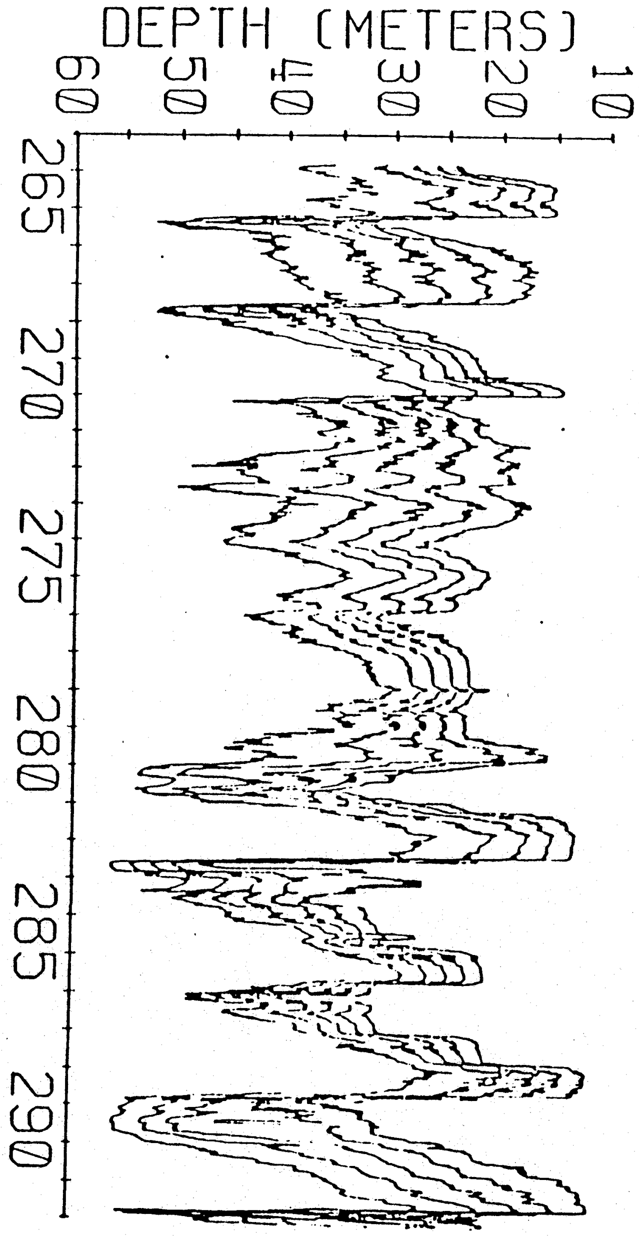


Figure 6A-4. Depth of various isotherms over time.

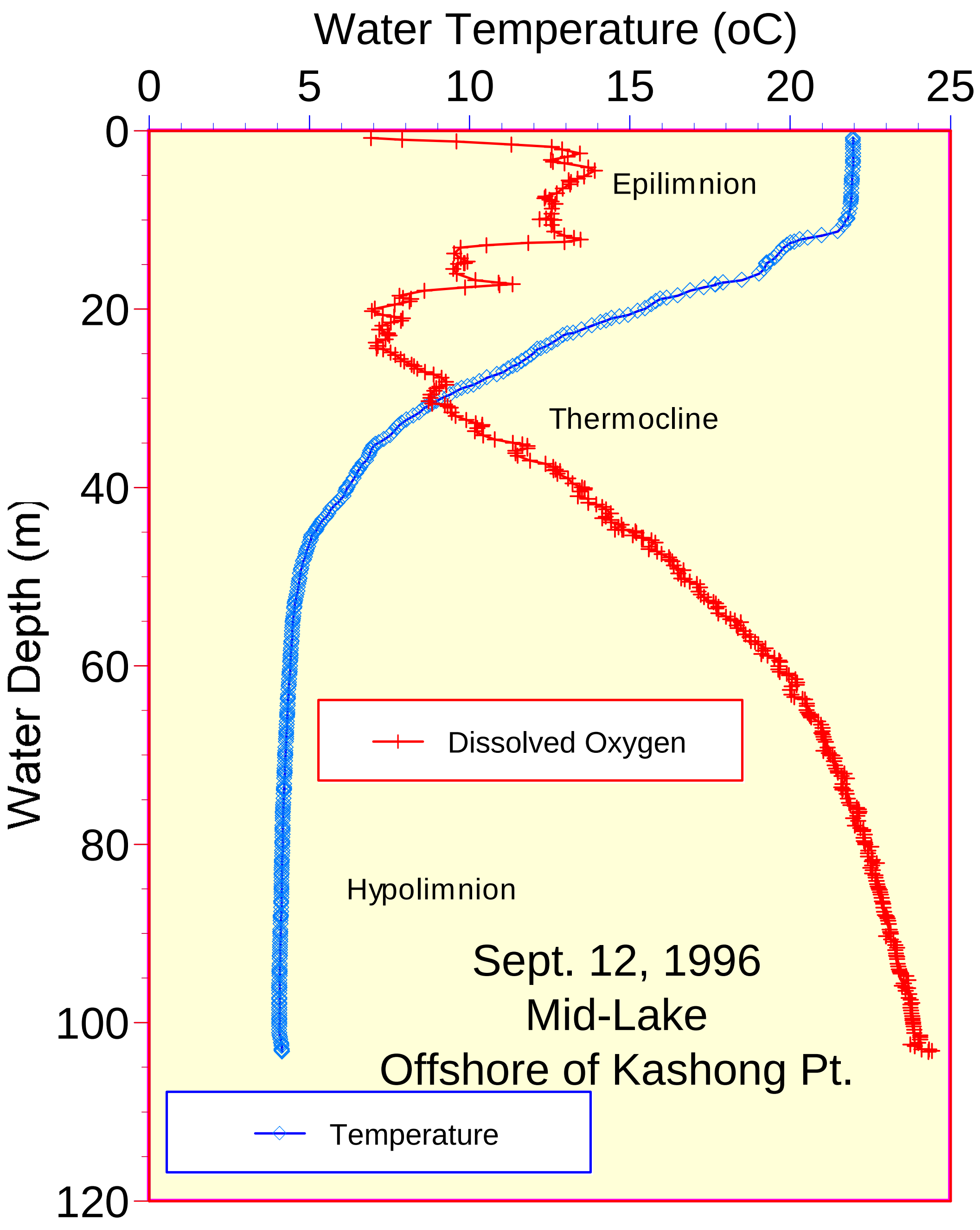
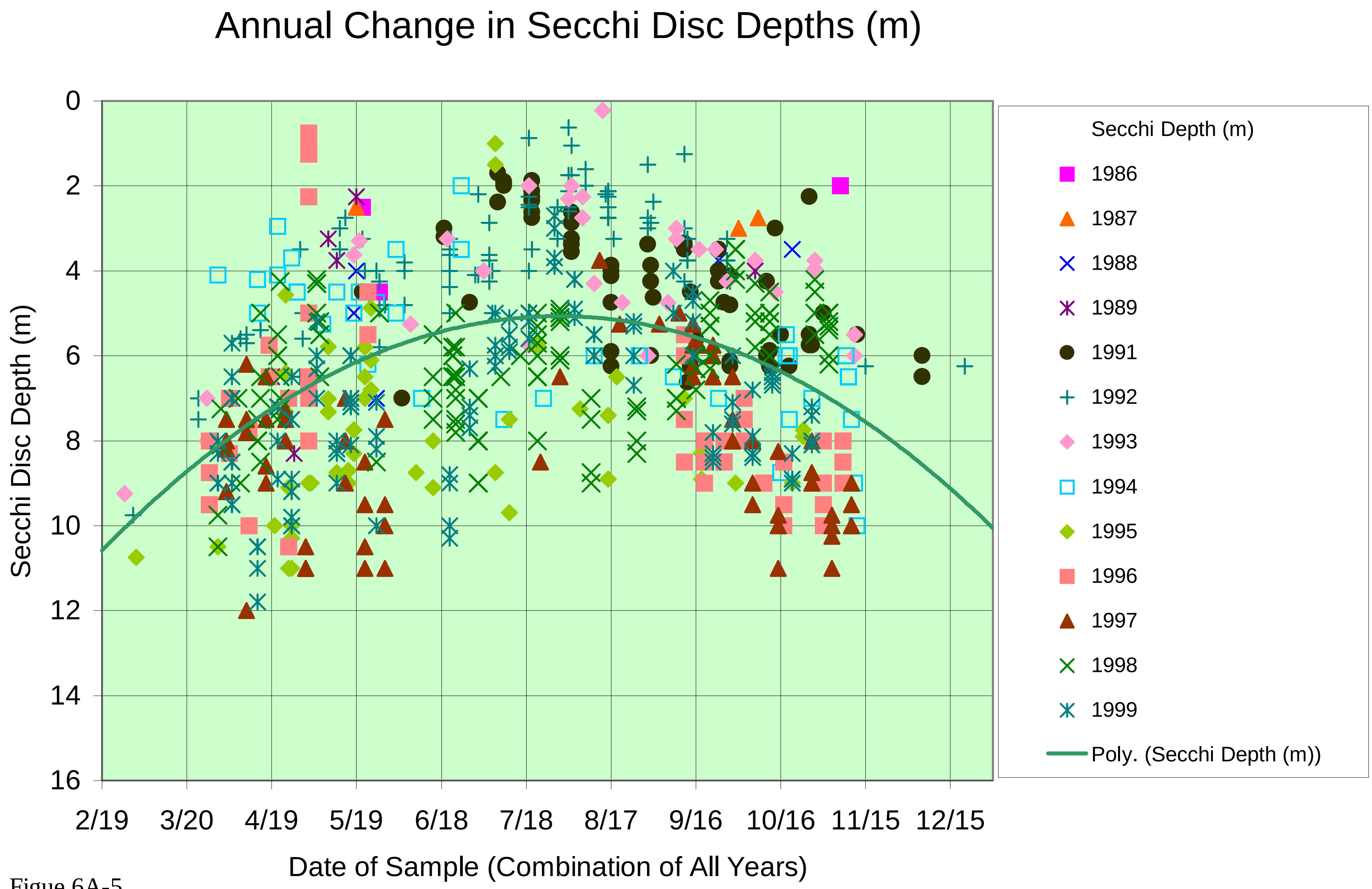
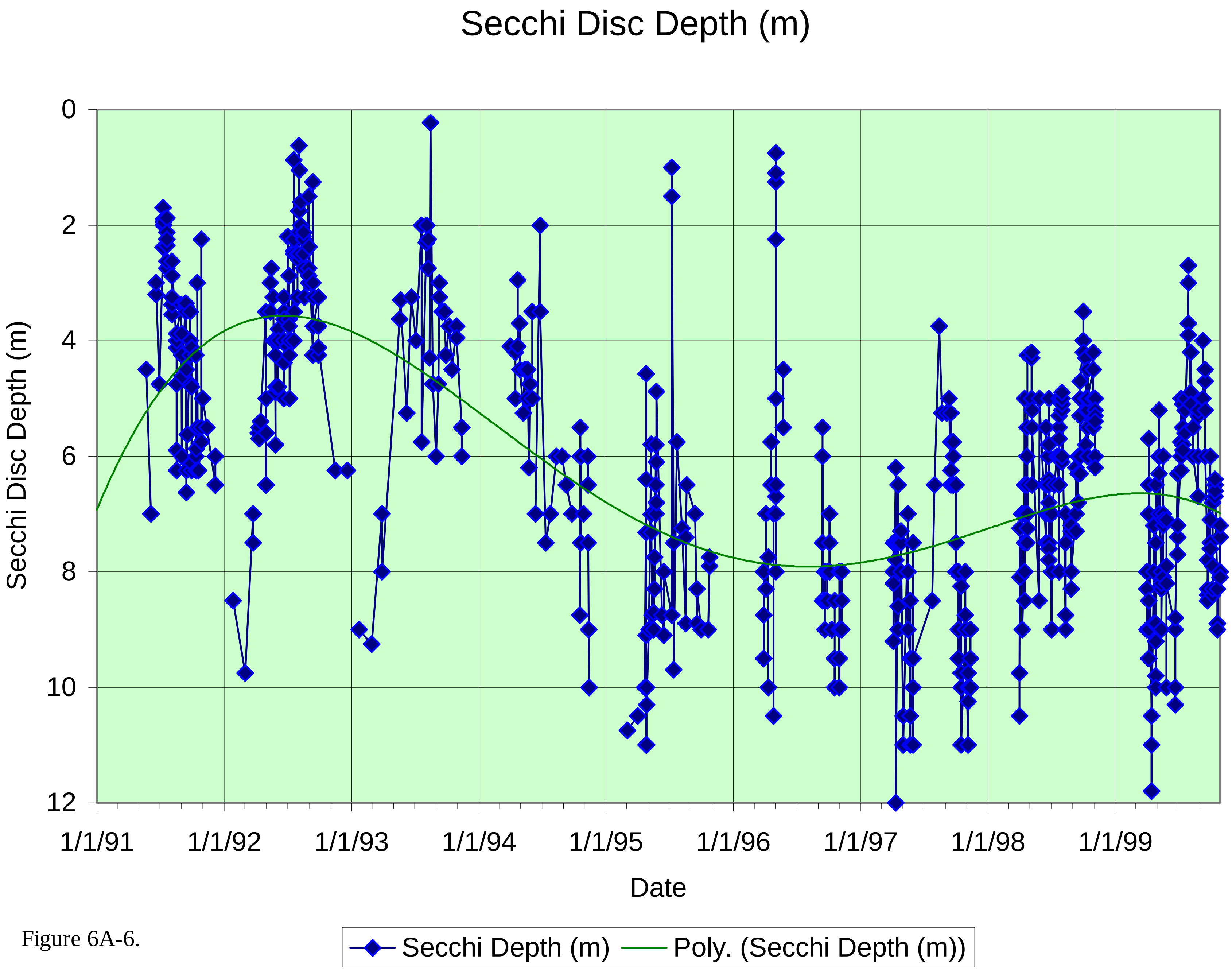


Figure 6A-4. Water column profiles of temperature and dissolved oxygen.


Annual Change in Secchi Disc Depths (m)
Secchi Disc Depth (m)
0
2
4
6
8
10
12
14
16
2/19
3/20
4/19
5/19
6/18
7/18
8/17
9/16
10/16
11/15
12/15
Date of Sample (Combination of All Years)
Secchi Depth (m)
1986
1987
1988
1989
1991
1992
1993
1994
1995
1996
1997
1998
1999
Poly. (Secchi Depth (m))

Figue 6A-5.



Secchi Disc Depth (m)
0
2
4
6
8
10
12
Secchi Disc Depth (m)
1/1/91
1/1/92
1/1/93
1/1/94
1/1/95
1/1/96
1/1/97
1/1/98
1/1/99
Date
Secchi Depth (m)
Poly. (Secchi Depth (m))

Figure 6A-6.

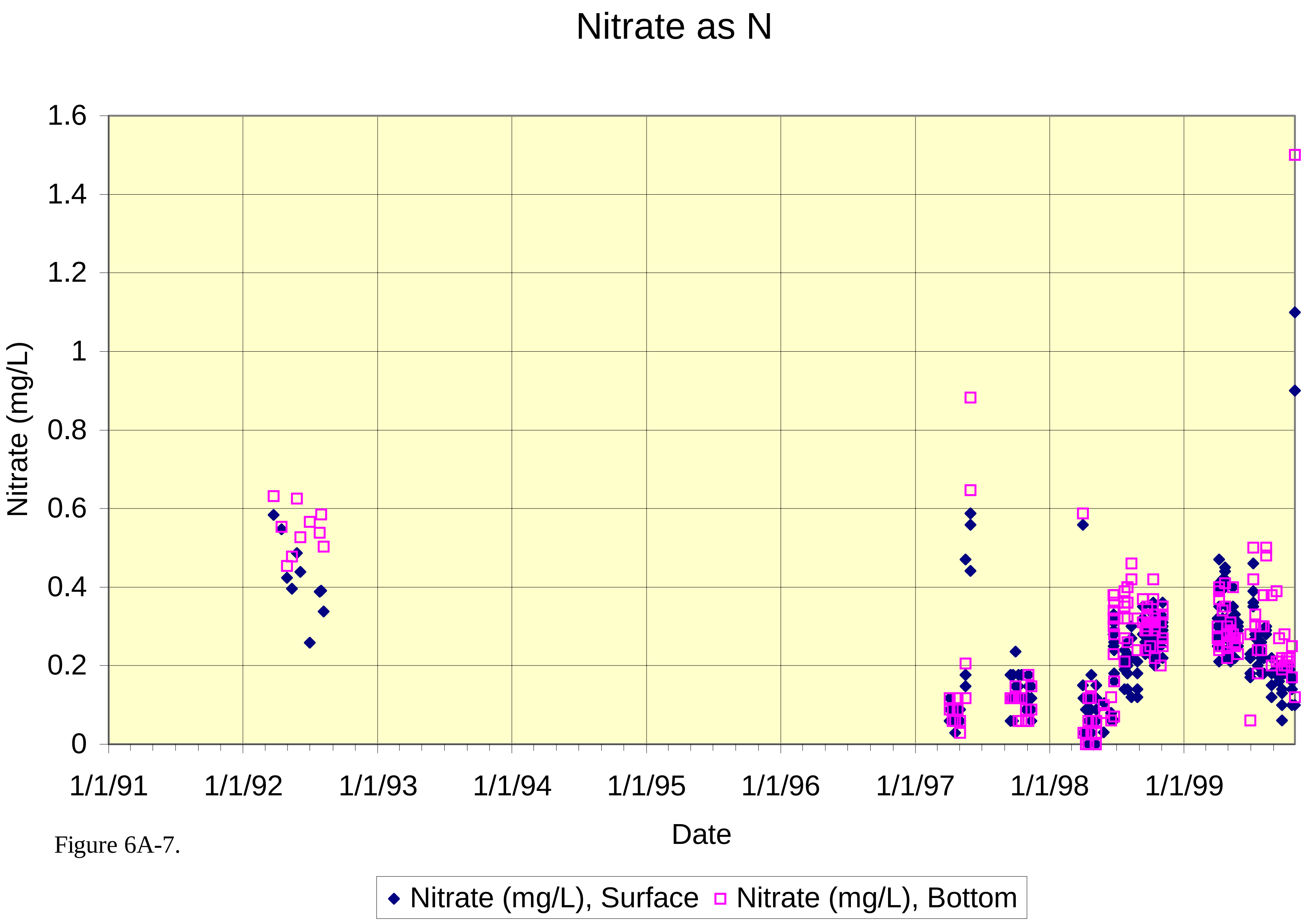
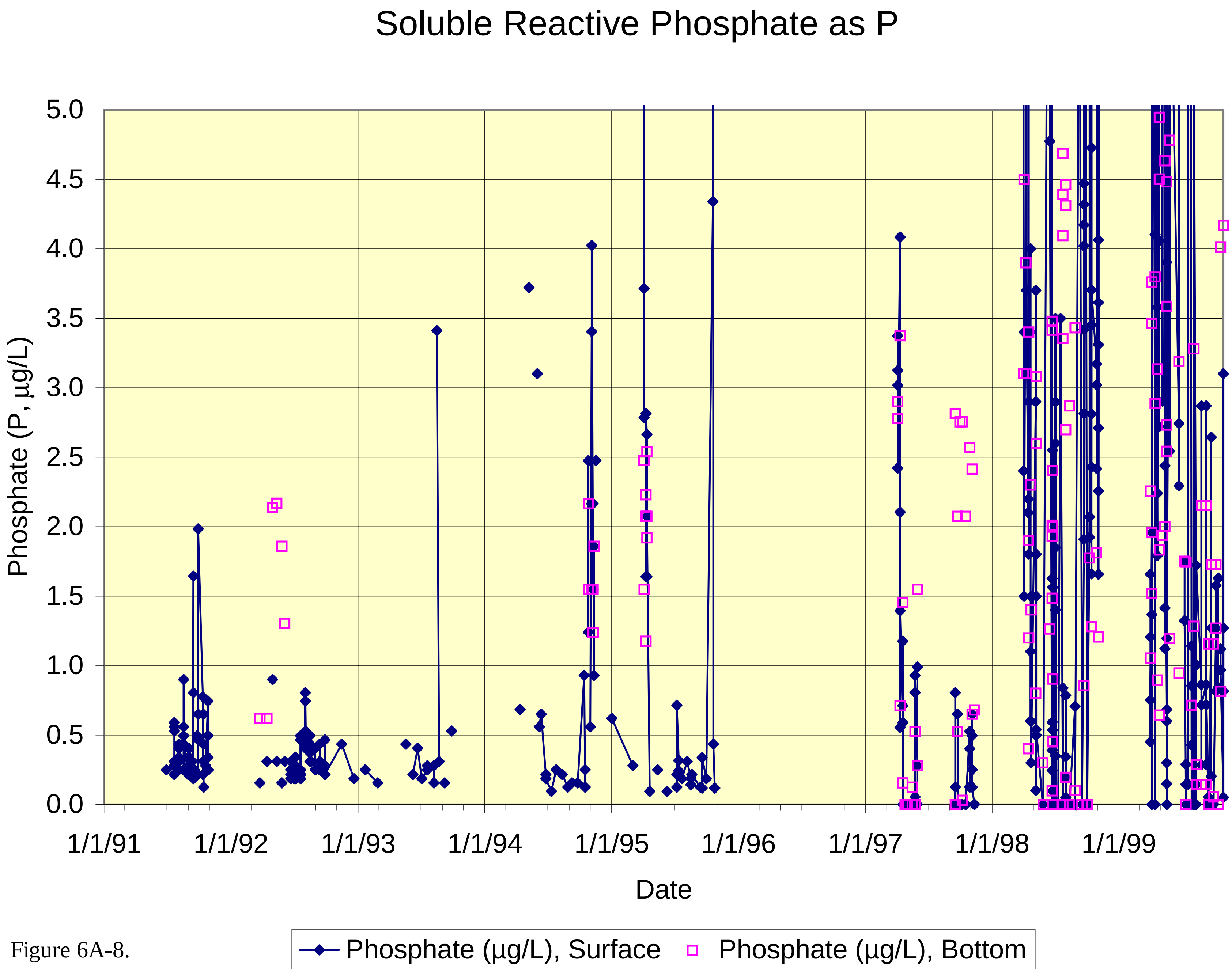

Nitrate as N
Nitrate (mg/L)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1/1/91
1/1/92
1/1/93
1/1/94
1/1/95
1/1/96
1/1/97
1/1/98
1/1/99
Date
◆ Nitrate (mg/L), Surface
□ Nitrate (mg/L), Bottom

Figure 6A-7.



Soluble Reactive Phosphate as P
Phosphate (P, µg/L)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1/1/91
1/1/92
1/1/93
1/1/94
1/1/95
1/1/96
1/1/97
1/1/98
1/1/99
Date
Phosphate (µg/L), Surface
Phosphate (µg/L), Bottom

Figure 6A-8.

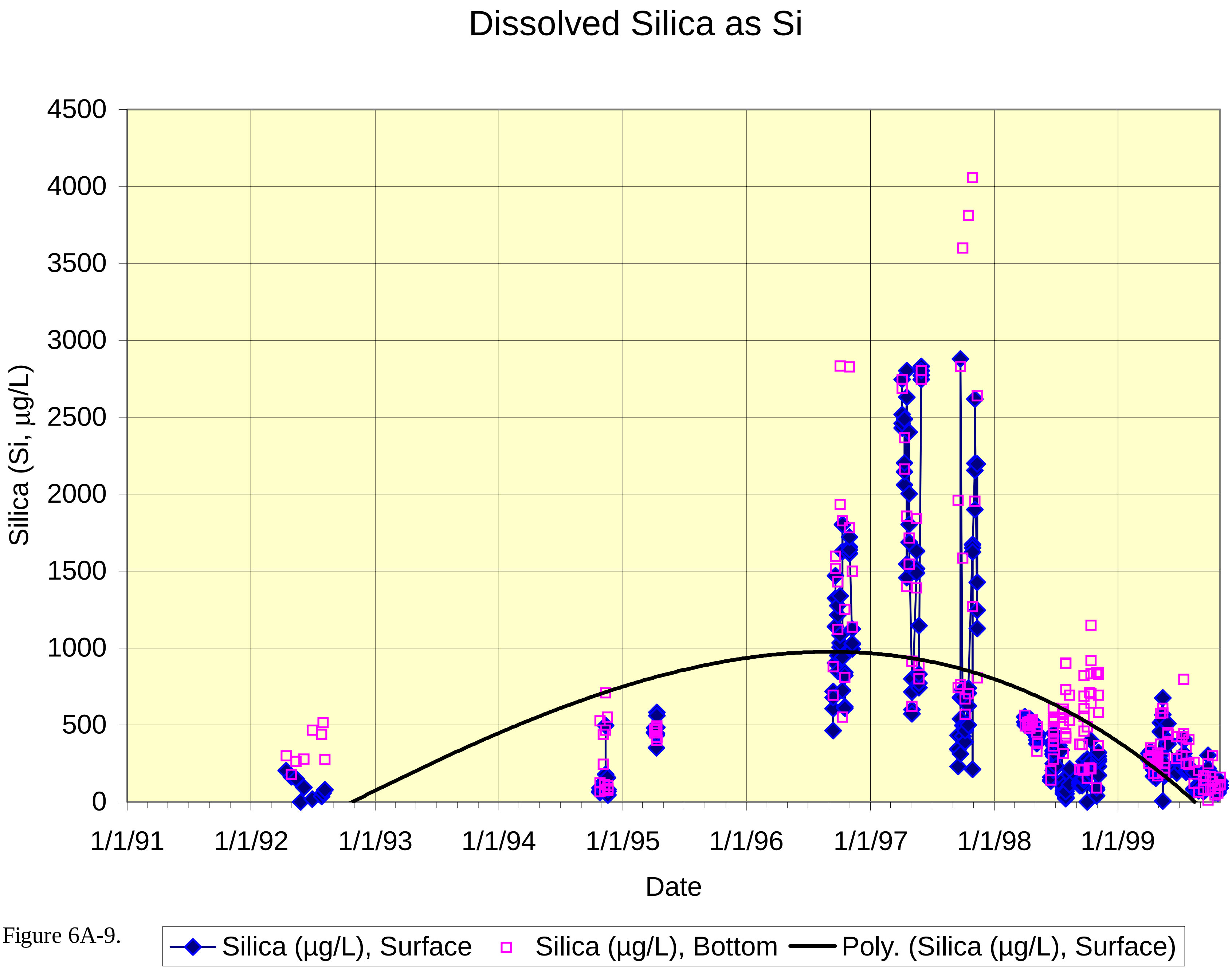

Dissolved Silica as Si
Silica (Si, µg/L)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1/1/91
1/1/92
1/1/93
1/1/94
1/1/95
1/1/96
1/1/97
1/1/98
1/1/99
Date
Silica (µg/L), Surface
Silica (µg/L), Bottom
Poly. (Silica (µg/L), Surface)

Figure 6A-9.

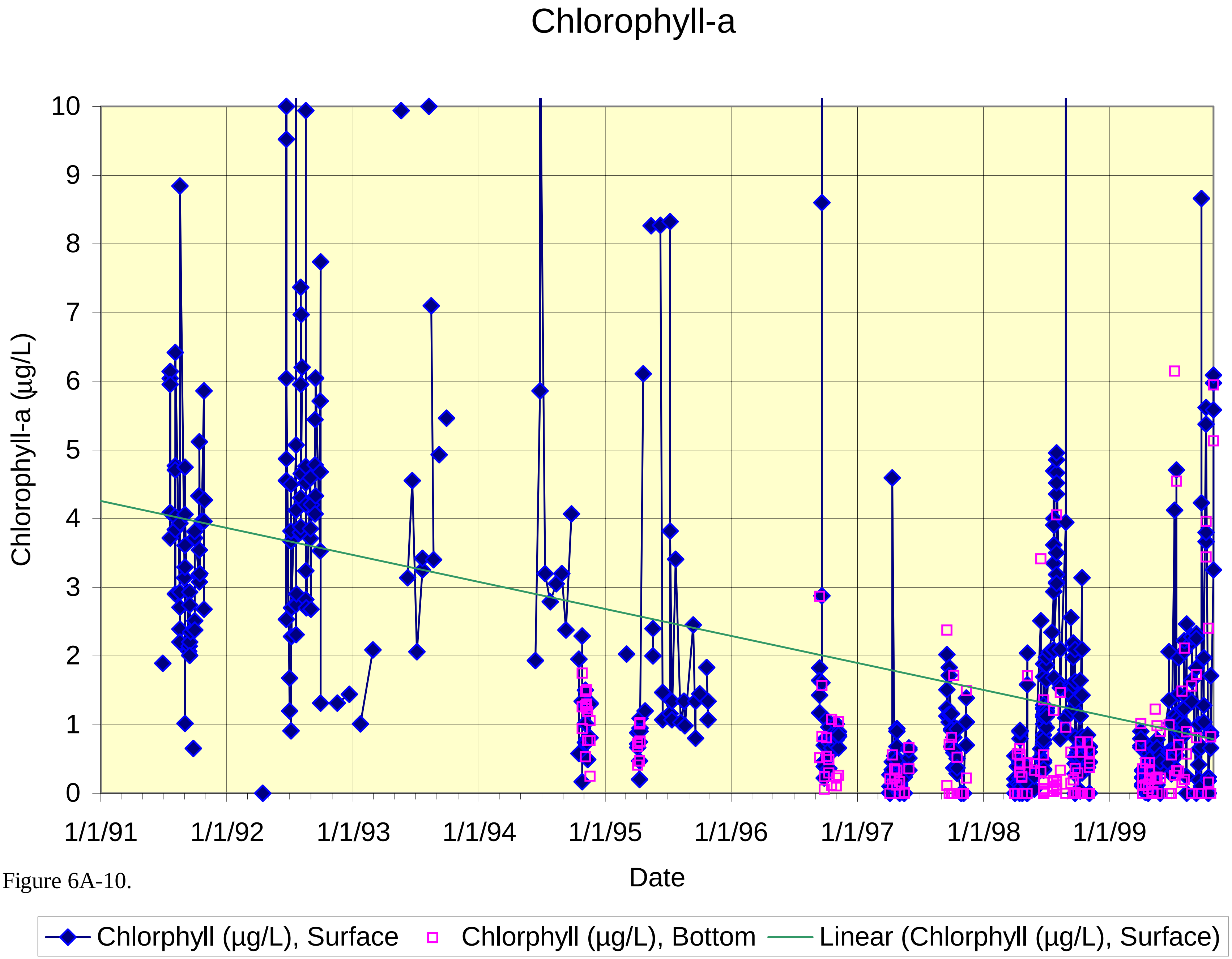

Chlorophyll-a
Chlorophyll-a (µg/L)
10
9
8
7
6
5
4
3
2
1
0
1/1/91
1/1/92
1/1/93
1/1/94
1/1/95
1/1/96
1/1/97
1/1/98
1/1/99
Date
Chlorphyll (µg/L), Surface
Chlorphyll (µg/L), Bottom
Linear (Chlorphyll (µg/L), Surface)

Figure 6A-10.

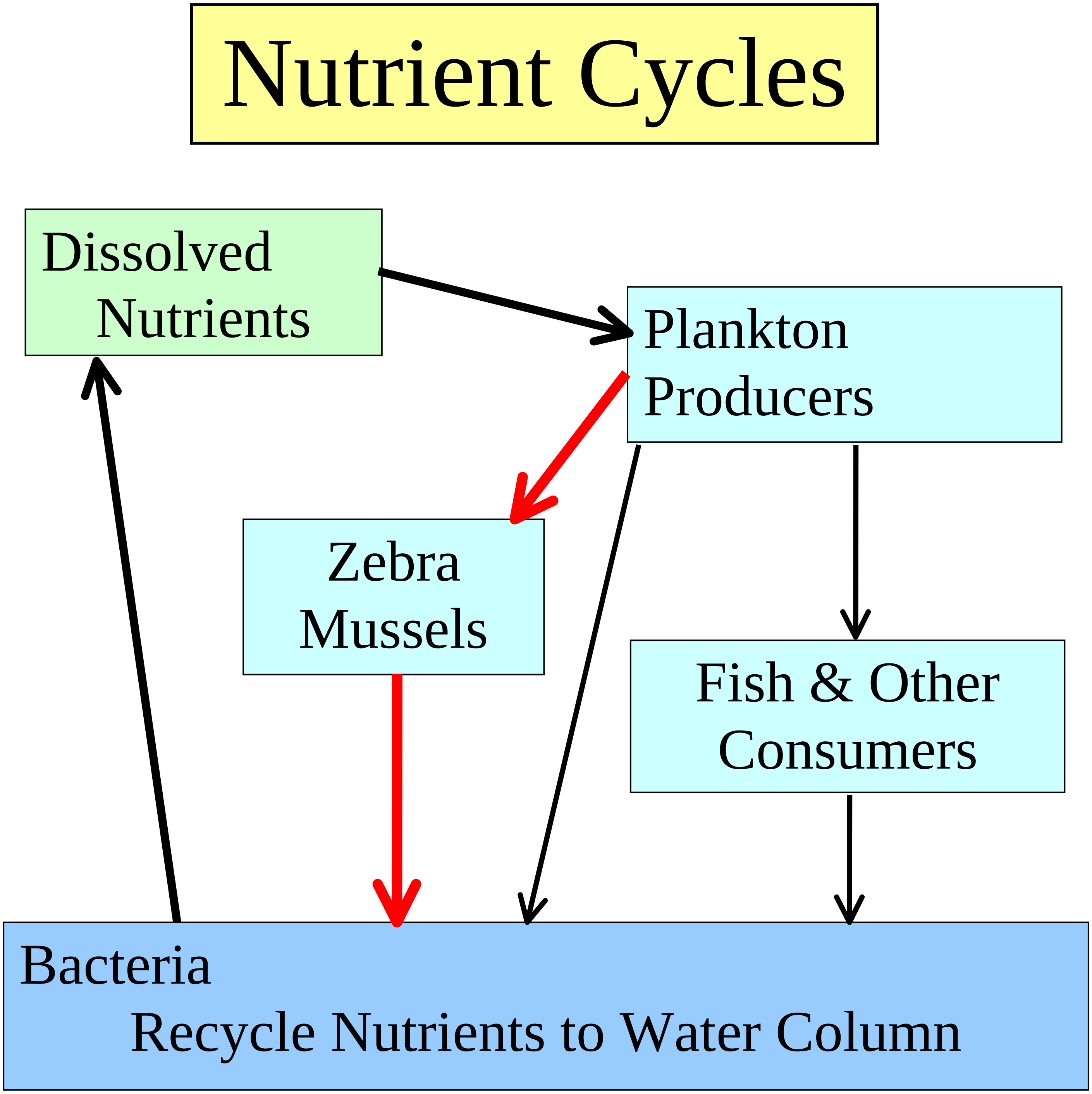


Figure 6A-11. Nutrient cycles in lakes, and the impact of zebra mussels on these cycles.