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THE EFFECTS OF LAKE DYNAMICS ON
THE WATER QUALITY OF
ABEL LAKE RESERVOIR

by

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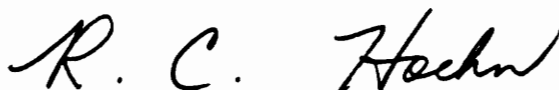
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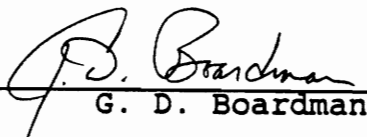
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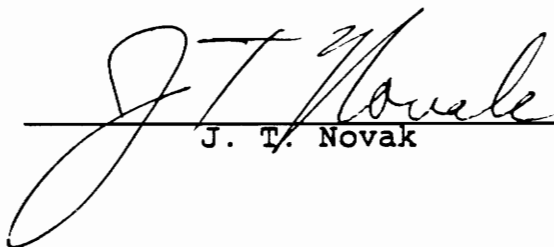
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Committee Chairman: Robert C. Hoehn

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(ABSTRACT)

The Abel Lake Reservoir in Stafford County, Virginia, was investigated to evaluate the lake's temporal and spatial dynamics with respect to water quality and water treatment problems. A limnological survey was conducted. The survey included all conventional parameters for the characterization of hydrodynamics and lake-water quality.

Abel Lake was found to be a typical temperate-zone lake that stratifies thermally in the summer, and the hypolimnetic water quality subsequently degrades with the depletion of oxygen. The lake then circulates in the fall in a process that begins in the shallow, upstream area of the lake and progresses downstream gradually until the deepest regions have circulated. The circulation process brings poor quality water from the hypolimnion to the surface where it is drawn into the treatment facility and creates treatment problems. Results also show that algal growth and nutrient concentrations were moderate during the study, however, the potential for cultural eutrophication is present should unmonitored development of the watershed occur.

In addition, organic matter in the reservoir and its primary feeder stream, Potomac Creek, were characterized according to molecular-size and THM-formation potential. Organic matter size-distributions varied among the lake surface, bottom and creek samples with more large molecular-size organics present in bottom samples than in surface and creek samples. THM-formation potential data indicated that the small percentage of large molecular weight organics present in the creek sample created the greatest THM-yield and these allocthonous organics may contribute to the THM-precursor pool in reservoir surface waters.

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CHAPTER I

INTRODUCTION

The Able Lake Reservoir

Able Lake, an impoundment created by the Potomac Creek Dam No. 1 in Stafford County, Virginia, is the principal source of drinking water for residents of Stafford County. Impounded in 1970, the reservoir is about 2.5 miles long, has a surface area of 185 acres, and contains 2.84 billion gallons at normal pool level. The flood storage capacity includes another 1.85 billion gallons.

In addition to Potomac Creek, a smaller, unnamed tributary flows into the lake at the southwestern end of the reservoir. There is also a minor tributary at the southwestern end that carries stormwater runoff following periods of rain and is dry at other times. The total watershed area is 19,520 acres (30.5 square miles). The portion of the watershed adjacent to the reservoir is moderately to steeply sloped and is densely forested, primarily with hardwoods. Wildlife, including herons and beavers, abounds.

The reservoir's water characteristics are typical of those of many lakes in eastern Virginia. The alkalinity is moderately low (25-30 mg/L as CaCO_3), and the water is characterized as soft (25-35 mg/L as CaCO_3 hardness). In addition, the water pH varies from slightly acidic to slightly alkaline (pH 6.6-7.7), the dissolved mineral content is low (approximately 50-70 mg/L), and the dissolved

organic content is moderately high, total organic carbon (TOC) concentrations ranging from 3.5 mg/L during stratification to 9.5 mg/L during overturn. The soils in the area, hence the lake sediments, are rich in iron (Fe) and manganese (Mn). Both metals create seasonal treatment problems. The water-treatment-plant (WTP) personnel maintain an algal control program (copper sulfate applications near the WTP intake) through the summer months to keep algal growth with all its attendant problems at a minimum.

The reservoir depth gradually increases from the headwaters to the dam. The reservoir is approximately 50 feet deep near the WTP intake, and, consequently, it stratifies thermally (as does most of the reservoir) during the summer. The seasonal, water-treatment problems that develop result from changes in chemical characteristics in the deep sediments and the hypolimnetic waters that are isolated from the atmosphere during stratification. With no source of oxygen, the hypolimnion becomes anaerobic which causes serious degradation of the water quality. These temporal and spatial variations in water quality within the reservoir are consequential to WTP operations. The characterization of stratification patterns and circulation phenomena of the reservoir is important to the function of the water supply system. Prior to this study, few data describing the Abel Lake Reservoir were available, and no data were available describing the hydrodynamics of the lake.

Water-Treatment Problems

In 1983, Stafford County was faced with compliance to a new regulation that set the maximum contaminant level (MCL) for organic compounds known as trihalomethanes (THMs) at 0.10 mg/L. Prior to 1983, the average concentration of THMs in the County's distribution system was approximately 0.15 mg/L. In order to meet the MCL requirement, the County modified the water-treatment process.

In late February, 1984, prechlorination of the raw water at the treatment plant - a common chlorination practice at the time - was terminated. Instead, chlorination took place at a point between the clarifier and the filters thus allowing the removal of organic THM precursors by coagulation, flocculation, and settling before chlorine was applied. This action successfully reduced the THM concentrations to levels below the MCL. At this time, the coagulant dose was also increased to insure adequate removal of the dissolved-organic-precursor material for THMs.

These modifications were satisfactory until further problems developed in the summer of 1984. Water in the clarifiers at the WTP developed an odor. The most likely cause of the odor was biological activity in the basins that was formerly limited by the presence of chlorine. In the fall of 1984, manganese removal problems developed. The increased Mn concentrations in the raw water in the fall were related to the normal circulation phenomena occurring in the lake. The problem usually persists at least through January.

These treatment problems and their potential solutions were the subjects of a study (1) conducted in conjunction with the study reported here.

The objectives of this research project were: 1) to establish a data base describing the water quality of the Abel Lake Reservoir in order to better understand the variations in water-treatment practices, and 2) to characterize and differentiate the organic distributions found in stream inflows, surface and bottom waters of Abel Lake with respect to molecular-size distributions and THM-formation potentials.

CHAPTER II

LITERATURE REVIEW

The Water-Treatment Facility and Problems

The historical information included in this discussion of water-treatment plant problems was gleaned from a report prepared for the Director of Public Utilities of Stafford County, Virginia by the Department of Civil Engineering at Virginia Polytechnic Institute and State University and entitled "An Investigation of Water Quality in Stafford County's Water-Supply Reservoir and Treatment Procedures at the Abel Lake Water Treatment Plant" (2).

The Abel Lake Water Treatment Plant is a conventional filtration plant with a design capacity of 2.0 million gallons per day (MGD). Alum is used as a coagulant, lime for pH adjustment, and chlorine for disinfection. Before 1983, the treatment process was effective at producing drinking water that met or exceeded all drinking-water standards. In 1983, the process was modified in order to comply with a new regulation that established a maximum contaminant level (MCL) for trihalomethanes (THMs) at 0.10 mg/L. The average concentration of THMs in Stafford County's drinking-water distribution system until this time was approximately 0.15 mg/L.

Trihalomethanes are produced when water containing naturally occurring organic matter, which is abundant in the reservoir, contacts chlorine, the most common drinking-water disinfectant.

Because chloroform, the most common THM, is a suspected human carcinogen, there is considerable concern over the presence of THMs in drinking-water supplies. The problem of meeting the THM MCL was solved at many water utilities throughout the United States by simply moving the point of chlorine addition from the head of the plant to a point after sedimentation (where much of the organic matter had been removed) most often just prior to filtration.

In late February, 1984, the Abel Lake WTP personnel terminated prechlorination of the raw water and instead began chlorinating at a point in the process between clarification and filtration. This modification reduced the THM concentrations in the Stafford County system to a level below the THM MCL. At this time, the coagulant dose was increased to improve the removal of dissolved matter, the precursor material for THMs. These two changes in the treatment process, delayed chlorination and increased coagulant doses, appeared to be adequate solutions to the THM problem.

Additional problems developed at the Abel Lake WTP during the summer of 1984. Odors developed in the clarifiers, most likely because biological activity which formerly was eliminated by chlorine, increased when chlorine was removed. Later in 1984, as Abel Lake began to destratify, manganese removal became a problem. While levels of manganese were low in the surface waters and tributaries of the reservoir, they increased in the bottom waters of the reservoir throughout the summertime as anoxic conditions developed. As the lake cooled in the fall and began to circulate, the manganese, as

well as other materials, were brought to the surface. The period of circulation typically lasts from November through at least January. Table 1 shows selected Abel Lake water characteristics at the raw-water intake of the treatment plant during both stratification and circulation periods. The contrast emphasizes the problems faced at the treatment plant during the fall and early winter.

Table 1

Effect of turnover on raw water quality at Abel Lake (3)

Water Quality Characteristic	<u>Value During Lake Condition</u>	
	Stratified	Overturn
Soluble Mn (mg/L)	0.01	0.30
Soluble Fe (mg/L)	0.15	0.45
TOC (mg/L)	3.5	7.0
THMFP (ug/L)	265	570
Turbidity (NTU)	2	11

Manganese is of no health concern, but its presence in water creates a brownish color, and it can stain clothes and porcelain fixtures in the home. To prevent these undesirable effects, a secondary maximum contaminate level (SMCL) of 0.05 mg/L for manganese has been established. In addition to manganese, iron is brought to the surface during reservoir circulation. The SMCL for iron is 0.3 mg/L, higher than that for manganese; the manganese, however, is much more difficult to remove. In the past, prechlorination of the raw water had effectively oxidized both metals to a form that was easily removed during flocculation and filtration thus reducing concentrations below the SMCLs. An increase in the TOC (total organic matter) concentrations is also observed during overturn, as shown in Table 1. The TOC creates not only a oxidant demand, but also a potential for increasing the finish-water THM concentrations.

This sequence of events at the Abel Lake Reservoir WTP has led to the need for seeking solutions to the water- treatment problems. Extensive research was conducted varying the oxidation and disinfection processes at the WTP. Modifications in the processes, including the application of potassium permanganate and chlorine dioxide, have been effective and were the subject of a doctoral dissertation (1).

Classic Limnology

The discussion of classic limnology included here will be limited to topics that are relevant to this research. This

information has been gathered from two well-known limnology references, Limnology by Wetzel (3) and Textbook of Limnology by Cole (4). Although this review may seem academic to the reader, it is intended to serve as an aid in the interpretation of the data developed in this study.

Thermal Stratification

Annual, thermal-stratification patterns vary widely. Some of these patterns have been associated with lakes by geographical location and climate. This discussion of thermal stratification in lakes is limited to typical conditions in temperate-zone lakes that are affected contrasts in seasonal conditions.

In the temperate zone, there are generally two stratification patterns observed. These are defined by the number of periods of circulation that the lake exhibits annually. In regions where climate and lake morphology cause a lake to develop ice on the surface in the winter, the lake will typically have two mixing periods. With the onset of cold weather in the fall, the gradual cooling of surface waters destroys lake stratification and initiates circulation of the lake. This period of circulation is known as the fall or autumnal overturn. As the surface waters cool a density gradient develops and the cooler water sinks because it is heavier. This density-mixing phenomenon is aided by wind-induced mixing. The circulation and cooling process will continue ideally until the entire mass of water is at 4°C. Water is most dense at 4°C and any further cooling will

result in a colder layer of water at the surface. On a calm night, when the surface gives off enough heat to reach the freezing point, a thin film of ice can develop. At this point, the period of winter stagnation, with no circulation, begins.

As the ice melts in the spring and the lake is again exposed to winds, another period of circulation, the vernal overturn, begins. The density of water at the surface increases as the ice melts and the water warms to 4°C. If the water beneath the surface is less than 4°C then the surface waters will sink and, with the aid of wind energy, the water begins to circulate. The duration of both circulation periods depends on the intensity of the winds, the morphology of the lake and the degree to which it is protected by surrounding topography. With the progression of spring, surface waters heat, becoming less dense, and a thermal resistance to mixing develops. A warm, calm period of several days usually contributes to the creation of a temperature gradient. At this time, the lake begins to stratify into three distinct regions that become resistant to mixing with each other.

The surface stratum of the lake, the epilimnion, is of fairly uniform temperature and is thoroughly mixed by the wind. The bottom-most stratum, the hypolimnion, is a relatively stagnant zone of cold water. The zone between the epilimnion and the hypolimnion is called the metalimnion. It exhibits a thermal gradient or discontinuity. The term "thermocline" is also used to describe the metalimnion. The most widely used definition of a thermocline is from Hutchison's 1957

publication A Treatise on Limnology (6) in which he defines the thermocline as "that point between the epilimnion and hypolimnion where the rate of change of temperature with respect to depth is greatest". This point may then be represented by a horizontal plane that separates the wind-stirred epilimnion from the darker, less turbulent hypolimnion. Controversy over the definition of a thermocline exists and the terms metalimnion and thermocline are often used interchangeably. The point of greatest thermal discontinuity in the transition from spring circulation to summer stratification begins deep in the lake and gradually rises to a level of metalimnetic stability.

Heating of a stratified lake continues by a combination of direct solar radiation, turbulent conduction, and density currents. Through these mechanisms, the hypolimnion gains small amounts of heat throughout the period of stratification. The transparency of the water and the degree to which the lake is protected from wind action determines the dominant mechanism of hypolimnetic temperature increases.

Lakes that do not freeze over in the winter and stratify thermally in the summer may exhibit only one circulation period annually. A mild winter will cause the water temperature to decrease and the lake to circulate at temperatures above the freezing point. The winter circulation period will continue until the air temperatures increase enough to again initiate the stratification process.

Vertical Distribution of Oxygen

Dissolved oxygen is a requirement for most aquatic organism metabolism. In addition, oxygen distributions affect the oxidation-reduction potential, which in turn affect the solubility of inorganic nutrients, especially phosphorus and ammonia-N, and metals such as iron and manganese. The seasonal dynamics of aerobic-anaerobic conditions govern nutrient availability in lakes.

Sources of dissolved oxygen include the atmosphere, photosynthesis, and hydromechanical transport. These inputs are counter-balanced with consumption of oxygen by the metabolic processes of respiration and decomposition. Oxygen is also consumed by chemical oxidation processes.

The solubility dynamics of oxygen are significantly complex. For this study, however, it is sufficient to realize that oxygen solubility in fresh water increases non-linearly with decreasing temperatures and that with a decrease in pressure -- for example, an increase in altitude -- the solubility of oxygen decreases.

In temperate zone lakes, the vertical distribution of oxygen is nearly uniform during periods of circulation. At this time, if oxygen concentrations (milligrams per liter) were plotted with respect to lake depth, the curve produced would be nearly straight. This oxygen profile is termed an "orthograde" curve. Oligotrophic (low in nutrients and productivity) lakes exhibit orthograde oxygen profiles throughout thermal stratification periods because oxygen demands are low.

During the stratification period of productive or eutrophic lakes, atmospheric exchange and photosynthetic processes increase oxygen concentrations at the surface, while respiration and decomposition consume oxygen in the hypolimnion. The intensity of consumption in the hypolimnion is relative to the amount of organic matter that reaches the hypolimnion from the surface stratum. Bacterial decomposition and respiration are the most significant mechanisms by which oxygen is lost throughout the lake, but because there is no renewal of oxygen in a stratified hypolimnion, the losses are most pronounced at the sediment-water interface. When oxygen concentrations under these conditions are plotted with respect to depth, a "clinograde" curve is produced. Clinograde curves characterize stratified, eutrophic lakes where the hypolimnion is oxygen deficient or anaerobic.

With the fall overturn, oxygen is once again returned to the hypolimnion. Through the winter, the same oxidative processes occur as in the summer but at a slower rate due to colder temperatures.

Anomalies of the general oxygen distributions often are observed. The most common variation is termed a "metalimnetic oxygen maximum". In this case, a peak in oxygen concentration occurs in the metalimnion during summer stratification. When these oxygen concentration data are plotted with respect to depth the result is known as a positive heterograde curve.

The metalimnetic oxygen maxima are usually created by algal populations that have adapted to growing at low temperatures and

light intensities and take advantage of nutrient concentrations that are higher than those found in the epilimnion. The depth at which these phenomena occur is related to the transparency of the water. Another explanation ascribes the phenomenon to a population of zooplankton predators depleting the algae and consuming oxygen by respiration in the surface water (7). The frequency of observed oxygen maxima is related to the stability of lakes. Lakes that exhibit this phenomena usually have high relative depths and are protected from wind by the surrounding topography. Metalimnetic maxima have been observed to occur annually at approximately the same location and depth of a lake that has characteristics suitable for supporting the phenomena.

The converse phenomenon, a "metalimnetic oxygen minimum", is much less frequently observed. Several causal mechanisms have been associated with this metalimnetic decrease in oxygen concentration. It is believed that more than one mechanism simultaneously create the reduction. As oxidizable material settles from the surface water, its rate of settling slows through the more dense, cooler waters of the metalimnion allowing more time for decomposition. As a result, the oxidizable material is decomposed and oxygen is consumed by bacterial respiration. Metalimnetic oxygen minima have also have been explained by high concentrations of zooplankton in the metalimnion that also consume oxygen with respiration. Basin morphometry is also a contributing factor to metalimnetic minimum phenomena. Where the slope of the basin is gentle, a greater percentage of sediments will be in contact with the metalimnion as they settle.

Color

Sunlight radiates to the surface of a lake, passes through the water, is absorbed by particles in the water and is then scattered upward to the surface. This process produces the observed color of a lake. Most color results from the presence of dissolved organic material and its light absorption properties. Even low concentrations of dissolved organic material increase the absorption of UV light, relative to that absorbed by distilled water, and aids in warming the first meter of surface water.

Other factors that can impart apparent color to lake waters include: pigmented algal, bacterial and protozoan populations; reflections from objects such as dark vegetation below the surface; inorganic particles that have eroded from the shoreline; hypolimnetic ferrous sulfide; and the presence of humic acids. These materials and organisms affect lake color both by changing the light-absorption characteristic and transmission properties of the water and by virtue of the fact that they themselves are colored.

Comparative scales for color analyses have been developed to eliminate individual subjectivity from color description. Color produced by dilutions of a standard platinum cobaltous chloride solution are compared to the color of lake water. An unfiltered sample exhibits what is termed "apparent" color and a filtered sample exhibits "true" color.

It is common for color values to increase with depth in stratified lakes, most likely because concentrations of ferric compounds

and dissolved organic materials increase at the sediment-water interface of the hypolimnion.

Secchi Disc Transparency

In the mid-1800s, an Italian scientist named Secchi developed a method to evaluate the transparency of water. A white disc was lowered into the water and the depth at which the white disc was no longer visible was observed. The technique is still used today and has come to be known as the "Secchi disc transparency", expressed as a depth.

The contemporary version of the disc is 20 centimeters in diameter with alternating white and black quadrants. Because of the erratic nature of transparency data observed early and late in the day, transparency is best determined around mid-day and should be measured off the shady side of the boat.

The transparency of water is the combined result of the reflection of light, absorption characteristics of the water and the dissolved and particulate material present.

Iron and Manganese

The chemical reactivity of iron and manganese are similar and so the two are discussed together in this section. Wetzel (4) stated that "the biogeochemical fluxes of iron and manganese reflect the combined spatial and temporal variations in physical chemistry of the lake systems which are controlled almost totally by the dynamic conditions regulating bacterial metabolism." Iron is necessary for

plant photosynthesis and manganese is an essential nutrient for plant growth.

Iron exists in two states in solution, the reduced ferrous (Fe^{++}) state and the oxidized ferric (Fe^{+++}) state. In general, ferrous compounds, except FeS , are soluble; the ferric compounds are insoluble, and iron precipitates as the hydroxide in alkaline, oxidized, aqueous environments. The reduction and oxidation reactions of iron are in many cases mediated by microorganisms. Enzymatic processes transfer valence electrons between the iron species, speeding reactions that would otherwise proceed very slowly.

In most lake systems, iron exists primarily in the form of ferric hydroxide [$\text{Fe}(\text{OH})_3$] floc, which has limited solubility over a wide pH range (pH 5-8). As the colloidal $\text{Fe}(\text{OH})_3$ settles through the strata, other suspended particles adsorb to the floc and are coprecipitated with the ferric hydroxide. Iron, thus, is usually found only in acid to neutral waters that are low in oxygen such as those in the hypolimnion waters of a stratified, enriched lake. In this stratum, iron exists in the soluble, reduced state.

The seasonal behavior of iron in the hypolimnion is, in fact, the most important limnologic feature of iron cycling. In the lake sediments, iron exists as ferric hydroxide, ferric phosphate, ferric silicate and ferric carbonate complexes. The nutrient-rich sediments are essentially sealed by colloidal ferric compounds that form a thin layer termed the "oxidized microzone". The sediments remain in this

condition until oxygen becomes scarce or absent with the progress of summer stratification. With the oxygen depletion, the conversion of ferric to ferrous iron begins. The oxidized microzone then disappears with the solubilization of iron. Some of the elements such as phosphorus, ammonia, iron and manganese that were trapped in the sediments are also released into the hypolimnion.

At the time of the fall overturn, the hypolimnion is reoxygenated and the ferrous iron is converted to ferric iron. The insoluble form precipitates rapidly, retrapping most of the released nutrients. Therefore, the iron that exists in the hypolimnion is generally retained there by this process and alternates between the soluble and insoluble states.

Iron also complexes with organic material. The formation of these complexes alters the solubility and availability of iron. Epilimnetic waters with a high concentration of dissolved organic matter are often enriched with iron. "These high concentrations of complexed-soluble iron are associated with high levels of humic acids, tannic acids, and other lignin derivatives" (4).

Manganese behaves similarly to iron in lake-water systems. With four valence states, manganese fluctuates between the reduced-soluble and oxidized-insoluble forms. The form of manganese is thermodynamically unstable and the tetravalent manganese compounds are insoluble in normal aquatic environments and pH. These oxidized species exist with iron in the microzone seal over lake sediments.

With the degradation of the hypolimnion during summer stratification, manganese is reduced and released into solution before iron. In addition, the rates of oxidation of manganese are slower than for iron and, therefore, manganese remains in solution longer than iron after the fall overturn. The hypolimnion does not trap manganese as effectively as it traps iron.

Although manganese is an essential micronutrient for plants and animals, high concentrations of manganese ($>1\text{mg/L}$) have been found to inhibit green and blue-green algal growth.

Nutrient Cycling and Lake System Management

The primary constituents of cellular protoplasm of organisms are nitrogen, phosphorus, carbon, and hydrogen. These elements are necessary for growth, and their abundance affects the productivity of fresh waters. Of these elements, nitrogen and phosphorus are known as fertilizer elements and are necessary for algal growth. Knowledge of the availability of fertilizer elements is important in managing fresh water systems. As nitrogen may be derived from the atmosphere and cycled by certain microorganisms in water systems, the supply of nitrogen does not usually limit growth. Phosphorus supplies, however, have more frequently been found to limit productivity in lakes.

Both nitrogen and phosphorus have natural sources within a lake-watershed system as well as inputs resulting from human activity. Because excessive nutrient additions can create a decline

in water quality, the control of human input and even the manipulation of natural processes have become important factors in water management practices (11).

Considerable effort has been devoted to understanding the natural cycles and the biological availability of the various forms of both nitrogen and phosphorus. The forms of nitrogen that occur in fresh water include dissolved molecular N_2 , a large number of organic compounds including amino acids, amines, proteins, and refractory humic compounds, ammonia (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-). The natural cycling of these forms is generated by microorganisms and the availability is affected by many factors including stratification and circulation patterns, phytoplankton and bacterial populations, watershed characteristics, and loads resulting from human activity.

Nitrogen concentrations in natural waters are measured in terms of total Kjeldahl nitrogen (TKN), ammonia, and oxidized nitrogen. The TKN concentration includes organic nitrogen and ammonia. Organic nitrogen, the most abundant form of nitrogen, may be particulate or soluble and is found in the tissues of living plants and animals and in their waste products. Ammonia, a product of decomposition, is usually most abundant in the anoxic waters of the hypolimnion. Oxidized nitrogen includes nitrates and nitrites. Nitrates and nitrites are usually transitional forms of nitrogen, and their abundance is determined by biological activity, water quality, and quantities of human input from agricultural runoff.

Phosphorus is present in both organic and inorganic forms. The forms present have been labeled orthophosphate-phosphorus, dissolved phosphorus, particulate phosphorus, and total phosphorus. The orthophosphate-phosphorus and total phosphorus are the forms of major interest in the management of water systems. The form of phosphorus that is readily available for cell growth is the soluble-inorganic orthophosphate. Concentrations in lake water are often negligible because this form of phosphorus is rapidly used by organisms in the system. Another hypothesis to explain negligible amounts of orthophosphorus in water systems comes from a study by Stewart and Wetzel (12). They hypothesized that in an aquatic system containing low alkalinity and high iron concentrations, orthophosphate availability is limited by its tendency to bind with dissolved humic materials. Total phosphorus is the measure of phosphorus that is available and potentially available and is the best form to use in quantifying phosphorus in a lake. The current trend in lake management is to base decisions on the total phosphorus concentration and supply to a lake (13).

In addition to chemical availability, seasonal and positional availability are also considered. Seasonal availability is most critical when considering the time of release or delivery of a phosphorus load relative to the time when algae are actively growing (13). Positional availability refers to the location of the input of phosphorus relative to the demand by organisms in that location for the phosphorus (13). Phosphorus entering the system from shoreline

erosion is available mainly to organisms near the shoreline, and the particulate forms (e.g. organic-P in debris and sediment-adsorbed P) usually settle out rapidly. Particulates in open water zones also settle through the water column to the sediments and then become potentially available again when the lake circulates. Dissolved phosphorus is constantly being recycled by algal and bacterial growth, death, and decomposition throughout the water column. Internal regeneration of phosphorus occurs with periods of circulation.

The water quality of a lake can be defined by its trophic status. Eutrophication is defined by Wetzel as "the unnatural acceleration of productivity due to perturbation of the system". The rate of eutrophication is affected by human activities in the watershed. Increasing rate of growth of algae and other plants is the best indicator of eutrophication. "Excessive nutrient additions which increase plant production can disrupt the natural oxygen balance of the system by increasing the amount of plant respiration and decomposition demanding more oxygen" (13). Moderate levels of productivity and eutrophication may be desirable in a water body where high fish yields are desired. However, there is a level where high algal productivity can create nuisance conditions and become deleterious to fish and particularly undesirable for water supply purposes. Thus, nutrient supplies, specifically phosphorus, and algal productivity are fundamental criteria for assessing lake water quality. Intimately related to algal productivity and lake health,

transparency and oxygen distribution (previously reviewed) are also fundamental in assessing the trophic status of a lake (11).

Algal biomass is most commonly estimated by measuring chlorophyll-a, the major pigment in photosynthesis, concentrations. The need for defining levels of algal production that are problematic is of recent concern. Chlorophyll-a concentrations of at least 20-30 ug/l tend to pose problems for water use, and chlorophyll-a concentrations above 30 ug/l are defined as representing severe nuisance conditions (13).

Seasonal and spatial variations in phosphorus concentrations create difficulties in defining problematic levels. Instead of phosphorus concentrations, phosphorus loading values are currently encouraged in lake management strategies. Phosphorus loading rates to a lake are calculated on the basis of morphometric characteristics, lake depth, and hydraulic residence times.

Nutrient loading from the watershed (nonpoint sources) has also been characterized. Phosphorus loading potential for nonpoint sources within a watershed can be predicted with the watershed acreage to lake-surface area (WA:SA) ratio. Nonpoint source nutrient and sediment loads can be significant if the WA:SA ratio exceeds 20:1 (13). "Experience has shown that lakes with larger WA:SA ratios (greater than 100:1) are less likely to respond to lake protection measures and are most difficult to improve due to their large watershed magnifying even low rates of non-point source pollution, and frequent inflows of runoff containing high levels of soil and

associated nutrients" (13). In addition, because phosphorus has a high affinity for clay particles and organic matter, the type of quantity of soil transported with runoff to a water body can be more important factors than watershed size (13).

With the knowledge of relationships among nutrients, productivity, and water quality, water supply management practices have evolved to include methods for controlling both human and internal nutrient inputs. Point-source pollution can be controlled with improved wastewater treatment systems where effluents are discharged directly into water bodies. Efforts to control nonpoint pollution, both urban and rural, are also incorporated into development and restoration practices. These are known as "Best Management Practices" (BMPs) and include ordinances requiring minimization of erosion and runoff, and establishing structural controls for these, incorporating conservation into agricultural practices, and utilizing silvicultural (forestry) practices in the watershed. Internal process management practices include algae and macrophyte harvesting, sediment removal, introduction of biological organisms to manipulate the food chain, and the use of aeration devices to alter the stratification and circulation patterns of lakes (11).

In summary, the character of a lake or reservoir can be evaluated with a complex set of physical, chemical, and biological factors that vary with lake origin and current conditions (11). It may be necessary to manage or even attempt to restore a lake to a

condition suitable for its intended use. "The best situation is one where steps are taken to protect the lakes watershed before problems develop" (11). There is no single management approach or restoration solution. Each lake system requires individual evaluation and management tools. Finally, because lakes are tightly coupled with their watersheds, the use of conservation practices in the watershed, in addition to understanding lake dynamics, are essential for protecting and improving lake and reservoir quality.

Organic Compounds

Origin and Classification

Organic compounds in natural waters originate from a variety of sources including wet and dry deposition (14), allochthonous watershed input, extracellular products of plankton and macrophytes, the decay products of plankton and macrophytes, and excretions and decay products of aquatic fauna (5). These compounds may be separated with respect to solubility into particulate organic material (POM) and dissolved organic material (DOM) by filtration (5). The distinction between the two is operational, and an arbitrary cut-off between dissolved and particulate fractions has been established as 0.45 μm (15). Concentrations of DOM in surface waters can range from 0.1-50 mg/L (5). The majority of organic material in river and lake systems is dissolved, and the ratio of DOM to POM is approximately 6:1 to 10:1 (4).

Most of the naturally occurring organic compounds can be classified into six major groups (listed in order of decreasing abundance): humic substances, hydrophilic acids, carboxylic acids, amino acids, carbohydrates, and hydrocarbons (14). Aquatic humic substances, representing from 40 to 60 percent of the dissolved organic carbon (DOC), account for the largest fraction of naturally occurring organic material in water (14). The hydrophilic acid fraction, about 30 percent of the DOC, is a relatively unknown fraction (14). The identifiable compounds represent the remaining 20 percent of the DOC.

The carbohydrates, proteinaceous compounds, fatty acids and other low-molecular-weight, labile compounds are easily degraded by microorganisms and thus are rapidly utilized and transformed under aerobic conditions. The humic substances, which are polyelectrolytic organic compounds derived from terrestrial plants, plankton, and aquatic plant material, are relatively resistant to microbial degradation and tend to persist (4,14,16).

Characterization of Humic Substances

Interest in aquatic humic substances dates back to 1806 (14). Although much is known about aquatic humic material, there is yet more to learn (14,15). Current interest in humic substances lies in the area of drinking water quality. In particular, humic substances produce THMs in water upon chlorination (17) (subsequently discussed) and humic substances also complex with trace metals and organic compounds (14,16).

Humic substances are defined by Thurman (14) as the colored, polyelectrolytic, nonvolatile acids isolated from water by sorption onto XAD or weak-base ion exchange resins. There are three fractions of humic substances, defined in terms of their solubilities. "Humin" is the fraction that is not soluble in water at any pH and, "humic acid" is the fraction that is not soluble in water below pH 2, and "fulvic acid" is the fraction that is soluble under all pH conditions (15). Evaluation of humic substances has been focused on the humic and fulvic acid fractions because their solubility facilitates their isolation and study (15).

Elemental analysis of humic substances has revealed that humic substances are composed of approximately 50 percent carbon, 4-5 percent hydrogen, 35-40 percent oxygen, 1-2 percent nitrogen, and less than 1 percent sulfur plus phosphorus (14). The major functional groups include: carboxylic acids, phenolic hydroxyl, carbonyl, and hydroxyl groups (14). The humin, humic acid, and fulvic acid fractions have similar structure but differ in molecular weight and functional group content (4). Although the structure of aquatic humic substances is unknown, some structures have been proposed in the literature (15).

Aiken et al. (15) emphasized the importance of characterizing humic substance samples from a range of environments. Differences among sources of humic substances and "geochemical processes controlling their transport and alteration may be expected to lead to major differences in humic substances from different environments "

(15). In addition to the need for addressing the diversity of environments that yield humic substances, there is a need to compare humic substances of similar environments to determine if variation among similar environments would be less than that among a diverse set of environments (15). Efforts to characterize THM precursor organic material by molecular size have produced data that meet these needs. There is a diverse range of literature available to begin addressing these questions (12,18-32) and some results will be discussed subsequently.

Molecular Size

Organic compounds can also be characterized by molecular weight and size-fractionation. Ogura (18) proposed that the distribution of molecular weight of DOM changes with the state of decomposition of organic material. In a study of coastal seawater, he found the greater portion of DOM in bottom waters to be high-molecular-weight compounds and, conversely, there was less low-molecular-weight DOM in bottom waters than in surface waters (18).

Four methods are most commonly used for estimating molecular weight with a measure of molecular size. Thurman (14) and Aiken (15) both describe these size-fractionation processes: gel-permeation chromatography, scattering of electromagnetic radiation, electron microscopy, and ultrafiltration. Each of these methods has advantages and disadvantages. Ultrafiltration was the method selected for size-fractionation in this study because it is relatively simple.

Ultrafiltration

Ultrafiltration has been widely used to fractionate, concentrate, and characterize aquatic organic compounds. Although results are often reported in terms of apparent molecular weight (AMW)(15,31,32), under ideal conditions, ultrafiltration yields a measure of molecular size (14,15). Separation of macromolecules according to molecular size is achieved by filtration under applied hydrostatic pressure through a membrane in a stirred cell (15). Membranes, which are manufactured and available from several companies, have nominal molecular-weight-cutoff values ranging from 50 to 1,000,000 daltons with many cutoff values between. The pore-size of each membrane may not be completely uniform and, thus, manufacturers qualify each cutoff value by stating that the nominal weight cutoff represents the particle size that will be 90 percent retained (15).

Although manufacturers' cutoffs are labeled in terms of molecular weight, ultrafiltration actually separates molecules according to molecular size. Molecular weight information for humic substances can be estimated by comparing the fractionation results with those obtained using suitable standards (15). However, Malcom and MacCarthy (34) in their study of commercially available humic substances strongly cautioned against using commercial products in the investigation of soil and water humic substances.

Several disadvantages of ultrafiltration have been observed. Buffle et al. (35) cautioned that as the volume of the solution in

the cell decreases during filtration, the concentration of the larger-size solutes in the cell increases, which can result in a breakthrough of large-molecular-size solutes. In addition, there is a possibility that humic and fulvic acids will react with other dissolved species, colloidal particles, and with each other to form aggregates. This phenomenon would increase the concentration of large-molecular-size material in the cell (35). The surface chemistry of the membranes may also create charge-charge and adsorptive interactions between the solute and the membrane that can interfere with the filtration process (15,20). Amy et al. (36), in a comparison study of gel-permeation chromatography and ultrafiltration to small angle x-ray scattering, caution that neither gel-permeation chromatography nor ultrafiltration provide precise, absolute values of AMW.

Although evaluation of ultrafiltration has revealed that adsorption, charge interactions, and agglomeration of colloids can create discrepancies, cautious use of the method can limit these interferences. Flow restrictions caused by deposition of macromolecules on the membranes can be avoided by keeping membranes clean and replacing the membranes frequently (36). Other methods used to prevent flow restriction are to keep the concentrations of the solute low by dilution or to use a series of filtration steps, described by Buffle et al. (35), to remove higher-molecular-weight molecules first. The breakthrough of high-molecular-weight organic matter can be avoided by limiting the filtration volume to 90 percent

of the initial, total volume in the cell (35). Agglomeration of molecules can be limited by performing ultrafiltration on freshly collected samples (35) and by using samples with low turbidity to minimize clay-humic interactions (36).

Interpretation and application of the data also requires care (12). Ultrafiltration is a fingerprint technique that can be used to operationally contrast relative differences in AMW of materials found in natural water systems and to monitor the effects of some chemical or biological treatment process (15,36).

Comparison of published data is difficult because operating conditions may not be clarified or unified. In addition to differences in technique, other differences among the data in the literature exist. Water system type, watershed and flow rate characteristics, seasonal conditions, and even the time of day that the sample was collected are variables that make data comparison difficult. These differences will be addressed with respect to THM-precursor-size characterization in the following section. There has been a range of values reported for any given molecular property of humic substances. The extent of the variation in molecular weight values reported has been "so great that an average or a mean value for that property conveys little information as to the true situation within the system as a whole" (15). Rather than reducing results to a number that can be used to compare one environment to another, descriptive studies that consider watershed characteristics may reveal more insight as to the geochemically and environmentally induced nature and differences of humic substances (15).

Chlorinated Organics

The formation of trihalomethanes (THMs) when chlorine reacts with naturally occurring organic material in water is a well-documented phenomenon that was first revealed in 1974 (17,37). The THMs that occur in drinking water in decreasing order of occurrence, are: chloroform, bromodichloromethane, chlorodibromomethane, and bromoform. In 1976, chloroform was identified as a carcinogen in rats by The National Cancer Institute (38) and in 1979 the U.S. Environmental Protection Agency (EPA) established a THM maximum contaminant level (MCL) drinking water standard at 0.10 mg/L (39).

As a result of these events, considerable research has been conducted into the nature of the THM precursors. Aquatic humic substances were specifically identified as precursors (17). Aquatic humic substances enter natural water systems through both autochthonous and allochthonous routes. Watershed runoff contributes soil and terrestrial plant material to the aquatic humic material pool, and plankton, macrophytes, and aquatic fauna contribute to the autochthonous pool (14). The complexity of aquatic humic material and its geochemical origins has made the characterization of humic substances difficult. The difficulties have most successfully been overcome with the use of molecular weight and size to characterize humic substances. Oliver (21) was the first to use size fractionation to characterize THM precursors. The term THM "yield" was coined by Rook (40) and expresses the relationship of haloform and precursor organic carbon on a mole per mole (haloform/organic

carbon) basis. The reaction mechanisms responsible for the formation of THMs have also been studied to gain insight into ways to prevent or avoid THM formation in water supply systems (1,41).

Algal sources of THMs have been evaluated. Both algal biomass and extracellular product (ECP) have been found to react readily with chlorine to produce THMs (23,25,30,42,43,44). Differences in THM formation potential (THMFP) observed seasonally in water supply systems, with higher THMFP in the summer than in the winter, led Hoehn et al. to hypothesize that algae may be contributing to the THM precursor pool (43). Seasonal variations of THM levels in water distribution systems, however, are most often explained by seasonal temperature effects on THM formation reaction rates. Additional explanations for seasonal differences in THM levels include: seasonal variations in organic material structure and thus changes in THMFP (27), rainfall intensity changes that affect runoff volume and water quality, and reservoir mixing conditions (44). Recently, the practice of applying copper sulfate to control algal biomass in drinking water reservoirs has been shown to contribute to observed THM problems in treatment facilities (11,45). The dead algae may cause short-term increases in the THM formation. Oliver and Lawrence (21) proposed that ammonia in wastewater effluents with high organic carbon concentrations inhibited THM formation by reacting with the chlorine to produce chloramines. Perhaps the formation of THMs is inhibited, in water from lakes that seasonally stratify and circulate, by the presence of ammonia compounds released from the hypolimnion.

A range of molecular weight and sizes for THM precursors has been reported. Schnoor et al. (22), using gel permeation chromatography to fractionate organic matter in the Iowa River, found that organics of molecular weight <3000 comprised 90 percent of the total pool and 75 percent of the THM precursor. More simply, the smaller molecular weight fractions had a high THMFP. Over 90 percent of the Iowa River watershed is in agricultural use and agricultural runoff is the major source of water pollution in the Iowa River. In a related study, Veenstra and Schnoor (27) found that an average of 88 percent of the TOC in Iowa River water was in the <3000 AMW group and that in chlorinated fractions, chloroform was detected in the greatest concentrations in the 2800-1000 AMW group. Joyce et al. (28), using gel permeation chromatography, characterized the chloroform yield of humic substances derived from pine forest soils and an adjacent pond. They found that the lowest AMW fraction, < 1000, had the lowest chloroform yield and the >10,000 AMW fraction had the highest yield.

Oliver and Visser (26) used ultrafiltration to characterize chloroform production in aquatic samples collected from lakes and streams in a forested, precambrian shield area of Quebec Province, Canada. Oliver and Visser found the highest chloroform yield to occur in the 20,000-30,000 MW range. Collins et al. (31) used ultrafiltration to characterize THMFP in Colorado River water and found that, in general, THM reactivity increased with increasing molecular weight.

These studies substantiate the belief that the reactivity of aquatic organic material in forming THMs varies as a function of molecular weight. Yet the variability in results also indicates that reactivity varies with the geochemical and environmental origins of the organic material.

CHAPTER III

METHODS

Overview

This chapter describes the methods used for the limnological survey and for the characterization of organics distributions in the Abel Lake Reservoir. The limnological survey was an investigation of conventional water quality characteristics in Abel Lake conducted over a period of six months. In addition, organics in water samples collected from the surface and bottom of the reservoir and from Potomac Creek were size fractionated by ultrafiltration. These size fractions were subsequently chlorinated and analyzed for THM-formation potential.

Experimental Design - Limnological Survey

Five sampling sites in Abel Lake were characterized according to physical and chemical characteristics six times during the study period from June to November 1985. Sampling was conducted approximately every three weeks from June through September with the final sampling date being in November during the fall circulation. The main inflow, Potomac Creek, and one secondary stream were sampled twice during the study period. A minor inflow of intermittent storm runoff was also sampled once.

Figure 1 shows the locations of the five sampling sites in Abel Lake and the locations of the streams. The depth of the lake progressively increases from the upper reaches toward the dam. Site No. 1, near the mouth of Potomac Creek, was shallow (5-6 feet). Site No. 2 was deeper (20-22 feet), and the depth of the lake increased toward the dam (32 feet at Site No. 3, 37-40 feet at Site No. 4, and 49-50 feet at Site No. 5).

Lake samples were collected at the surface by plunging the collection vessel below the water surface. Bottom samples were collected with a brass Kemmerer sampler with plastic end fittings (Wildlife Supply Company, Saginaw, Michigan). Grab samples were collected from moving water locations in the streams. All samples were preserved in the manner required and placed on ice for transport to the laboratory at Virginia Polytechnic Institute and State University for analysis. Samples were then stored in the refrigerator at 4°C before analysis.

Conventional water quality characteristics of all lake and stream samples were determined. These constituents included alkalinity, hardness, color, total phosphorus, orthophosphate phosphorus, nitrogen, sulfates, chlorides, iron, manganese, organic carbon and chlorophyll-a. At each lake site, dissolved oxygen and temperature profiles and Secchi disc transparency were determined. Conductivity and pH of lake and stream samples were also recorded in the field.

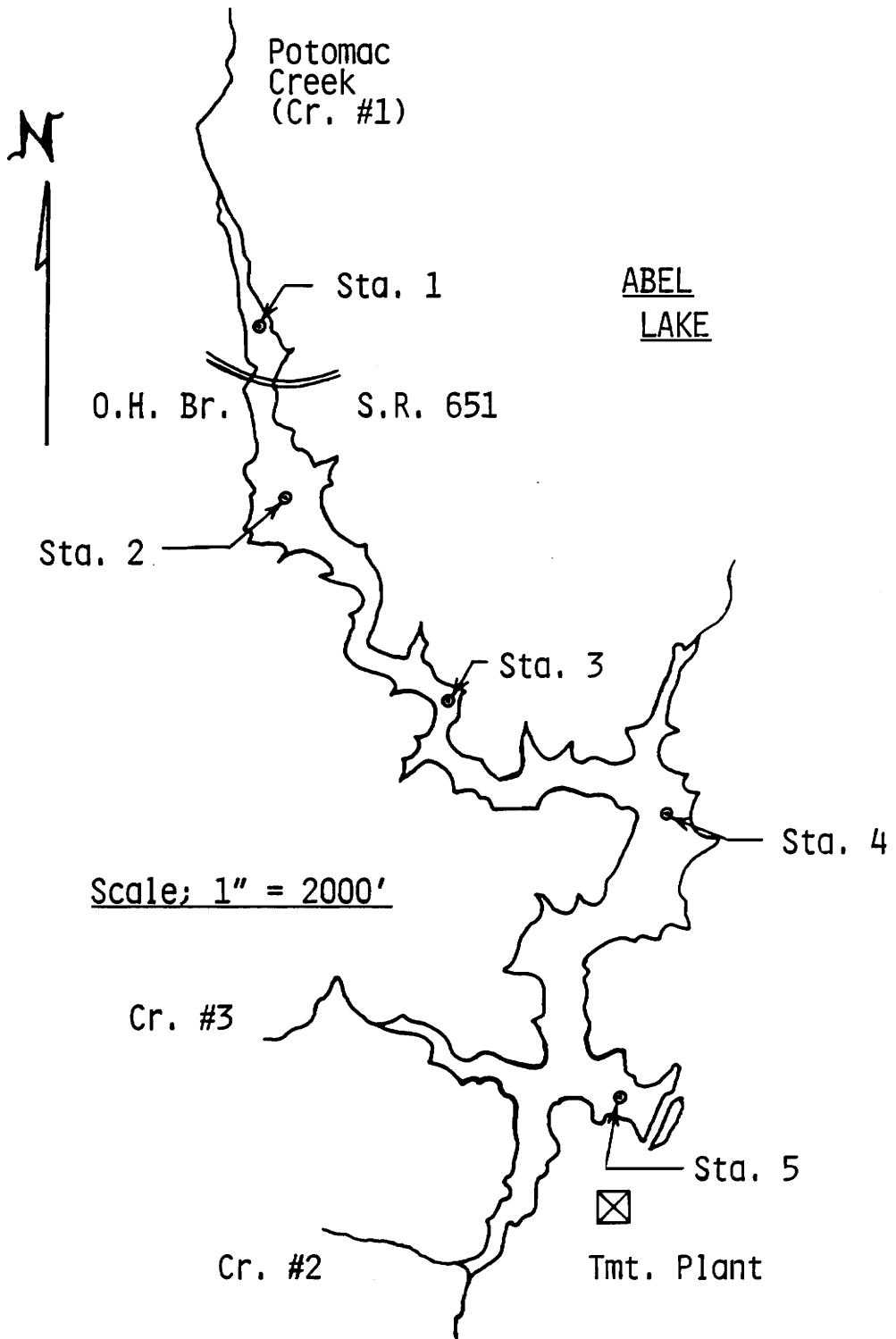


Figure 1 Able Lake

Experimental Design - Organics Distributions

Water samples were collected in October 1985 during stratification from one surface site and two bottom sites of Abel Lake and from Potomac Creek. The samples were iced and transported to the laboratory and refrigerated before analysis. All samples were fractionated according to molecular size within two weeks of the collection date. Bottom samples were fractionated first, then the surface and stream samples were fractionated.

Each size fraction and a raw sample were analyzed for total organic carbon (TOC) concentrations, then dosed with chlorine and analyzed for THM-formation potential. The methods for these analyses will be described in the Analytical Methods section.

A Typical Field Sampling Event

The equipment and the boat were launched between 9:00 and 10:00 a.m. of the sampling date near the water treatment plant (see Figure 1). The sampling equipment was always in order long before it came time to launch the boat. It was the anchor, extra gasoline, paddle, boat plug, and floatation devices that were always on the last minute check list.

Usually, the first stop was Site No. 5 on the way to Site No. 1. Because Secchi disc transparency should be evaluated between 9 a.m. and 3 p.m., the first stop at would be at Site No. 5 and the second

at Site No. 4 to collect this information -- suspecting that the day's sampling at the other sites would last beyond 3 p.m. After taking these two Secchi disc readings, sample and data collection would continue at Site No. 1 at the headwaters of the reservoir.

At each sampling location, the first data recorded were usually the dissolved oxygen and temperature profiles. One person operated the meter and the other recorded the data. In order to maintain continuity in the sampling, each person performed the same tasks on each sampling event.

Surface pH, conductivity, and Secchi disc transparency were recorded by one person, while the other collected surface samples in the prepared and pre-labeled sample bottles (bottle preparation described in the following section). Samples for metals analysis were filtered and acidified with nitric acid in the field. Samples to be analyzed for nitrogen were acidified with sulfuric acid in the field. Samples for TOC analysis were preserved with phosphoric acid. Samples for orthophosphate-phosphorus analysis were filtered in the field. Samples for alkalinity analysis were collected and analyzed upon return to the water treatment plant laboratory. All samples were placed on ice in ice chests.

After the surface samples were collected, bottom samples were retrieved with the Kemmerer sampler. The samples were evacuated from the Kemmerer directly into the sample bottles when appropriate. The samples for metals and orthophosphate phosphorus analyses were evacuated into a beaker first so that they could be filtered. An

additional bottom sample was evacuated into a beaker for pH and conductivity analyses. Before hauling in the anchor, an inventory was made to ensure that the collection was complete. The sampling procedures would then be repeated at the next site downstream.

With data and sample collection complete the boat and equipment were removed from the lake and transported to the water treatment plant. After returning the equipment to storage areas, the samples for total and orthophosphate phosphorus analysis were retrieved from the ice chest and placed in the freezer at the treatment plant where they remained frozen until they were analyzed. The alkalinity samples were also retrieved and allowed to return to room temperature before analysis. All other samples remained on ice for transport to the Virginia Tech Environmental Engineering Laboratories.

Analytical Methods - Limnological Survey

This section describes the analytical procedures followed for the limnological survey. The procedures have been summarized in Table 2.

The lake's stratification profiles were determined using a Model 57 Dissolved Oxygen and Temperature meter made by the Yellow Springs Instrument Company (Yellow Springs, Ohio). The instrument was calibrated according to the manufacturer's specifications. Dissolved oxygen concentration and temperature were recorded at intervals throughout the depth of the lake at each sampling site.

TABLE 2
METHODS AND MATERIALS FOR LIMNOLOGICAL INVESTIGATION

Analysis	Method/Standard Methods Part No. (Sixteenth Edition)	Instrument
Sample Collection	Field/105	Kemmerer Sampler
pH	Field/NA	Corning Model 3 pH meter
Alkalinity	Titrimetric/403	Corning Model 610
Hardness	AAS ¹ /314a	Perkin Elmer Model 703 AAS
Dissolved Oxygen Temperature	Field/NA	YSI ² Model 57 Oxygen and Conductivity meter
Conductivity	Field/NA	YSI Model 33 SCT Conductivity meter
Hydrogen Sulfide	Hach/NA	Hach kit
Color	Colorimetric/NA	KSPC ³ Model 900
Total-Phosphorus	Ascorbic Acid/424F	KSPC Model 900
Ortho-Phosphate	Ion Chromatography/ 429	Dionex Ion Chromatograph Model 2010i
Nitrogen	Kjeldahl/420a	Titration
Sulfates & Chlorides	Ion Chromatography/ 429	Dionex Ion Chromatograph Model 2010i
Organic Carbon	Persulfate & UV oxidation/505B	Dormann/Envirotech Model DC 54
Metals	AAS/314a	Perkin Elmer Model 703 AAS
Chlorophyll a	Spectrophotometric/ 1002G1	Beckman Spectrophotometer Model DU-6

¹Atomic Absorption Spectrophotometry

²Yellow Springs Instruments

³Klett Summerson Photoelectric Colorimeter

NA = Not Applicable

The Secchi disc transparency at each lake sample site was determined routinely. A standard, 20 cm diameter Secchi disc was used according to the technique described by Lind (8).

Conductivity and pH values were also recorded in the field. Surface samples were collected in a clean beaker for pH and conductivity analysis. Bottom samples were collected from the bottom of the lake using the Kemmerer sampler and poured into the beaker for analysis. The beaker was rinsed several times with the sample before pH and conductivity were measured. The pH was determined with a Corning Model 3 pH meter and conductivity was measured with a Yellow Springs Instrument Company Model 33 SCT conductivity meter.

Samples for alkalinity determinations were collected in pint Mason jars with Teflon lids previously washed with hydrochloric acid and rinsed with distilled water. These samples were iced and then analyzed in the laboratory at the Abel Lake Water Treatment Plant as soon as the day's sampling was complete. Alkalinity was determined titrimetrically according to Part 403 in Standard Methods, 16th Edition (9) using a Corning Model 610 pH meter.

Hardness determinations were calculated from the calcium and magnesium ion concentrations measured by Atomic Absorption Spectrophotometry (AAS) according to Part 314a, Standard Methods, 16th Edition (9). These samples were filtered through a 0.45 micron membrane, preserved with nitric acid to pH 2, and collected in vials that had been washed with nitric acid and rinsed with distilled water. Analyses were determined using a Perkin Elmer Model 703 AAS (Norwalk, Connecticut).

The calculation of the hardness created by each ion is as follows:

$$\text{Hardness mg/L (as CaCO}_3\text{)} = M^{++} \text{ (mg/L)} \times \frac{50}{\text{equivalent weight of } M^{++}}$$

where M^{++} represents the divalent metallic ion (10).

The hardness caused by the calcium and magnesium ions were calculated individually and added together to obtain a total hardness value in mg/L as CaCO_3 .

Color evaluations were made using the sample remaining after the alkalinity analyses were made. Measurements were made with a Klett-Summerson Photoelectric Colorimeter (New York, New York) according to the manufacturer's specifications. Raw water color was designated as "apparent color". Each sample was passed through a Gelman type A/E glass fiber filter to remove the particulate matter contributing to the apparent color value. "True color" was determined by analyzing a filtered sample (5).

Samples collected for both total and orthophosphate-phosphorus were collected in bottles washed with hydrochloric acid and rinsed with distilled water. The samples were placed on ice in the field and then frozen upon returning to the water treatment plant laboratory. The samples remained frozen until the time of analyses. Total phosphorus was determined by the Ascorbic Acid method in Part 424F of Standard Methods, 16th Edition (9). Orthophosphate-phosphorus samples were filtered in the field through a 0.45 micrometer membrane. Orthophosphate-phosphorus analysis was conducted using a

Dionex Ion Chromatograph (Sunnyvale, California) model 2010i. These values were consistently below the detection limit of the instrument which was one tenth of a part per million. On one occasion, (August 25) the frozen total and orthophosphate phosphorus samples were transported to the Occoquan Watershed Monitoring laboratory for analysis with a Technicon Autoanalyzer II.

Samples for nitrogen analysis were collected in pint Mason jars with Teflon lids previously washed with sulfuric acid and rinsed with distilled water and iced upon collection for transport to the lab. These samples were preserved with concentrated sulfuric acid. Total Kjeldahl nitrogen was determined by the method in part 420a of Standard Methods, 16 Edition (9). Nitrogen, ammonia nitrogen, and nitrate values for August 25 were also determined at the Occoquan Watershed Monitoring Laboratory with the Technicon Autoanalyzer II. This was the only occasion when ammonia nitrogen and nitrate-N concentrations were determined because these levels were usually below the detection limits of instruments available in the Virginia Tech laboratories.

Sulfate and chloride determinations were made with the samples remaining after alkalinity and color analyses were complete. Sulfate and chloride analyses were performed on the Dionex Ion Chromatograph Model 2010i.

Samples for organic carbon analyzes were collected in dark-amber bottles with Teflon seals that had been washed with chromic acid and rinsed with carbon-free water. The samples were preserved with

concentrated phosphoric acid and iced for transport to the laboratory. Analyzes were determined by the Persulfate and UV Oxidation method described in Part 505B Standard Methods 16th Edition (9) with a Dohrmann/Envirotech Model DC 54 Ultralow Level Total Organic Carbon Analyzer (Santa Clara, California) (Now Xertex) with replicates within 2 percent.

Iron and manganese concentrations were also monitored. These samples were collected and analyzed together with the calcium and magnesium samples. Nitric acid washed vials were used to collect the samples. The samples were filtered in the field through a 0.45 micron membrane and preserved with nitric acid. Analyzes were determined according to Part 314a Standard Methods, 16th Edition (9) with a Perkin Elmer Model 703 Atomic Absorption Spectrophotometer.

Chlorophyll-a was determined by the spectrophotometric method described in Part 1002G1 Standard Methods, 16th Edition (9) with a Beckman Spectrophotometer Model DU-6 (Fullerton, California). These samples were collected in dark (coated with duck tape), one-quart Mason jars with Teflon lids and iced for transport to the labs.

Analytical Methods - Organic Distributions

Sample Collection

Samples for organics characterization were collected in October 1985 from the surface and bottom of Abel Lake and from Potomac Creek. These samples were collected in one-gallon containers that had been

washed with sulfuric acid and rinsed with carbon-free water, placed on ice, and transported to the laboratory at Virginia Tech. The samples were refrigerated before analyses. Bottom samples, expected to contain organic matter that would coagulate rapidly, were analyzed first. All samples were fractionated within two weeks of the collection date.

Size Fractionation

Organics in the water samples were segregated into size categories by first excluding the particulate organic carbon (POC) with pre-combusted Gelman type A/E glass-fiber filters. Filtrate from this step was then filtered through four Amicon (Lexington, Massachusetts) series YM and one series YC ultrafilters. Table 3 summarizes the ultrafilter specification data.

Table 3. Pore Size and Nominal Molecular Weight Exclusion Limit of Ultrafilters*.

Membrane	Approximate Pore Size (nm)	Nominal molecular weight Exclusion limit (daltons)
YC05	1.1	500
YM2	1.2	1,000
YM5	1.5	5,000
YM10	1.6	10,000
YM30	2.1	30,000

*Data from Amicon Company, Lexington, MA

Before use, the ultrafilters were preserved in 10 percent ethanol at 4°C to prevent bacterial growth on the membranes. In order to use the membranes, the ethanol was first removed using a two step process. The membranes were placed in beakers filled with organic free water on the lab bench. The water was changed several times over a 24-hour period. After sufficient leaching, the filters were mounted on the ultrafiltration units and flushed several times with carbon-free water. Flushing continued until the organic carbon concentration of the filtered, organic-free water was equal to its original value. Each ultracell was then rinsed twice with the water sample to be filtered.

Ultrafiltration of the water samples was performed in stirred, 200 ml Amicon ultracells under pressure of 2.8 kg/cm² nitrogen at 25°C. Each fractionated sample was collected in dark-amber bottles with Teflon seals that had been washed with chromic acid and rinsed with carbon free water for organic carbon analysis. The samples were preserved with phosphoric acid and refrigerated at 4°C for subsequent analysis with the Dohrmann/Envirotech Model DC-54 Ultralow Level Organic Carbon Analyzer (replicates within 2 percent). Duplicate samples were also collected in clean 30-mL vials for subsequent THMFP analysis.

THMFP Determinations

Duplicate, 30-mL water samples, including raw water samples, were chlorinated at a chlorine:DOC weight ratio of 3:1. The samples

were buffered to pH 7.0 with pH 7 phosphate buffer (9). All samples were incubated in the dark at 22°C for seven days before the THMFPS were determined. If the analysis was not conducted immediately after the seven-day period, the THM-formation reactions were halted by adding sodium sulfite to quench the chlorine. In addition, the prevention of hydrolysis of THMs from organic halide intermediates was achieved by depressing the pH to pH 2 with nitric acid. These quenched samples were refrigerated until analyzed.

THM analysis was performed by the purge-and-trap method according to Part 514 Standard Methods, 15th Edition. A Tracor (Austin, Texas) Model 560 gas chromatograph with Tracor LSC-2 purge-and-trap module and a Hall electronic conductivity detector was used to determine THM concentrations.

CHAPTER IV
RESULTS AND DISCUSSION
Limnological Survey

The limnological survey of Abel Lake Reservoir has produced a data base of water-quality information. The discussion of these data will be limited here those that are pertinent to water-supply maintenance and operations at the Abel Lake WTP. The data that will not be discussed directly are included in the appendices in both graphical (Appendices A and B) and tabular (Appendices C and D) form. Data found in the appendices include pH, alkalinity, conductivity, phosphorus, nitrogen, chlorophyll-a, sulfate and chlorides. The stream inflow data are included in Appendix D.

The stratification patterns and chemical quality of Abel Lake are described by the data presented in this chapter with emphasis on the features that impact on WTP operations. Sampling station locations were shown in Figure 1.

Dissolved Oxygen and Temperature

Station No. 1: At the head of the reservoir, Station No. 1 was the most shallow sampling location, and the lake there was never thermally stratified. The oxygen concentrations from surface to bottom were high and nearly uniform on each sampling event. Figure 2 illustrates a typical dissolved oxygen and temperature profile at

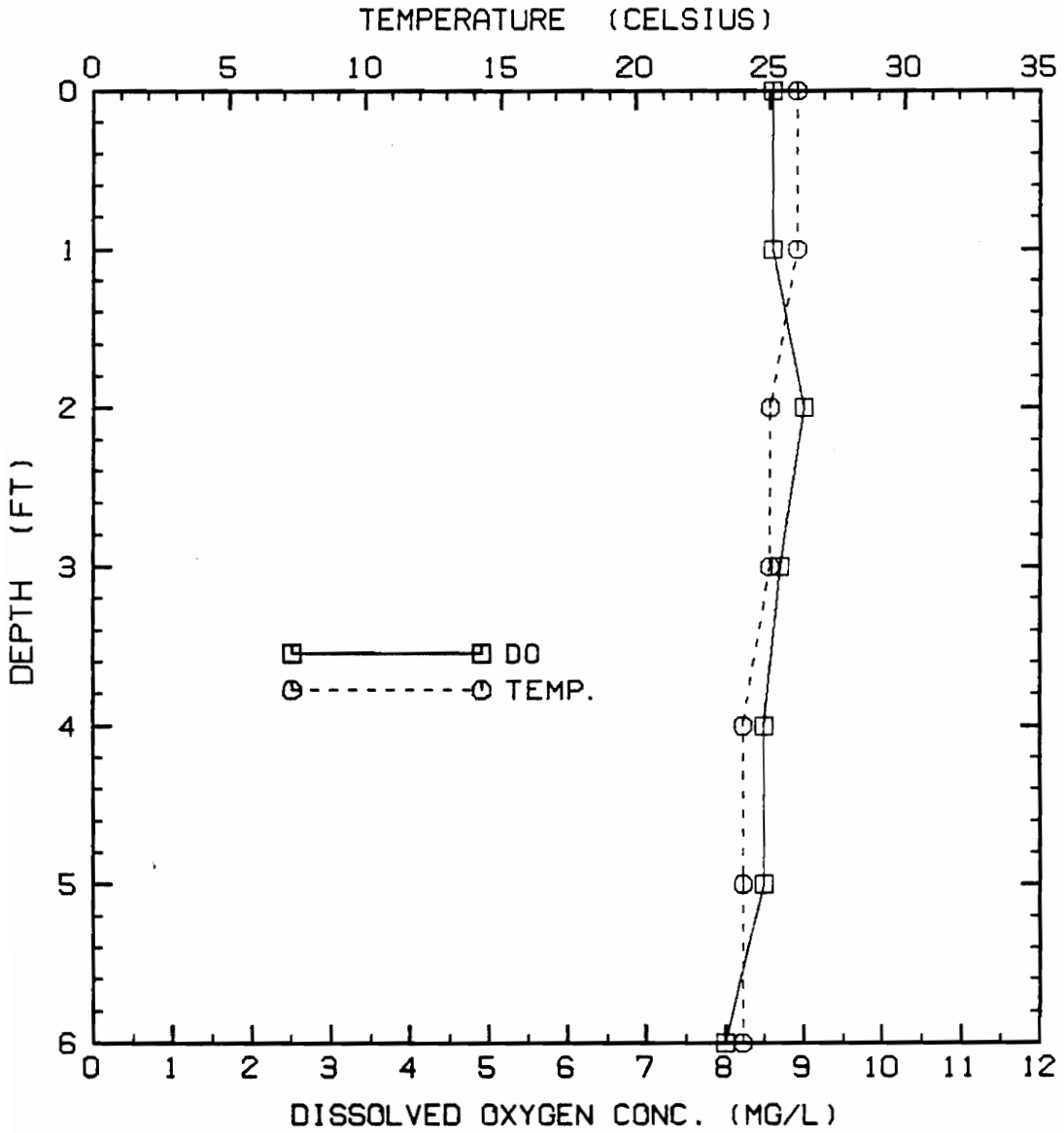


Figure 2 Dissolved Oxygen and Temperature Profile
Able Lake Sta. 1, June 19, 1985

Station 1. An exception to this pattern was observed on July 30 (Figure 3). The oxygen concentration decreased from surface to bottom. From the surface to a depth of four feet, the oxygen concentration exceeded that of the saturation value -- an indication of algal productivity. At the surface, the oxygen saturation concentration was exceeded by 50 percent or equal to 1.5 times the saturation concentration. The supersaturation of oxygen at the surface indicates extensive algal growth. Because this oxygen supersaturation phenomena was observed only once (out of six samplings), it appears that the algal proliferation was a short-term event.

Station No. 2: Depths of the lake at Station No. 2 varied from 18.5 to 21.5 feet. The temperature decreased from surface to bottom, yet the lake never stratified thermally into the well-differentiated layers of a temperate-zone lake, most likely because the relatively shallow depth and morphology of this area of the lake subjects it to wind- induced mixing. Conversely, the dissolved oxygen profiles (Figure 4) (Appendix A, Figures A5-A7) characterize a typical temperature-zone, enriched lake; the epilimnion was near 100 percent oxygen saturation and below depths of about 10 feet the dissolved oxygen concentration decreased rapidly.

The lake at Station 2 was virtually devoid of oxygen below a depth ranging from 10.5 to 14 feet on the sampling dates in June, July, and August (Figures 4, A5-A7). Water samples collected from the bottom as early as June 19 smelled of sulfide and were grey in

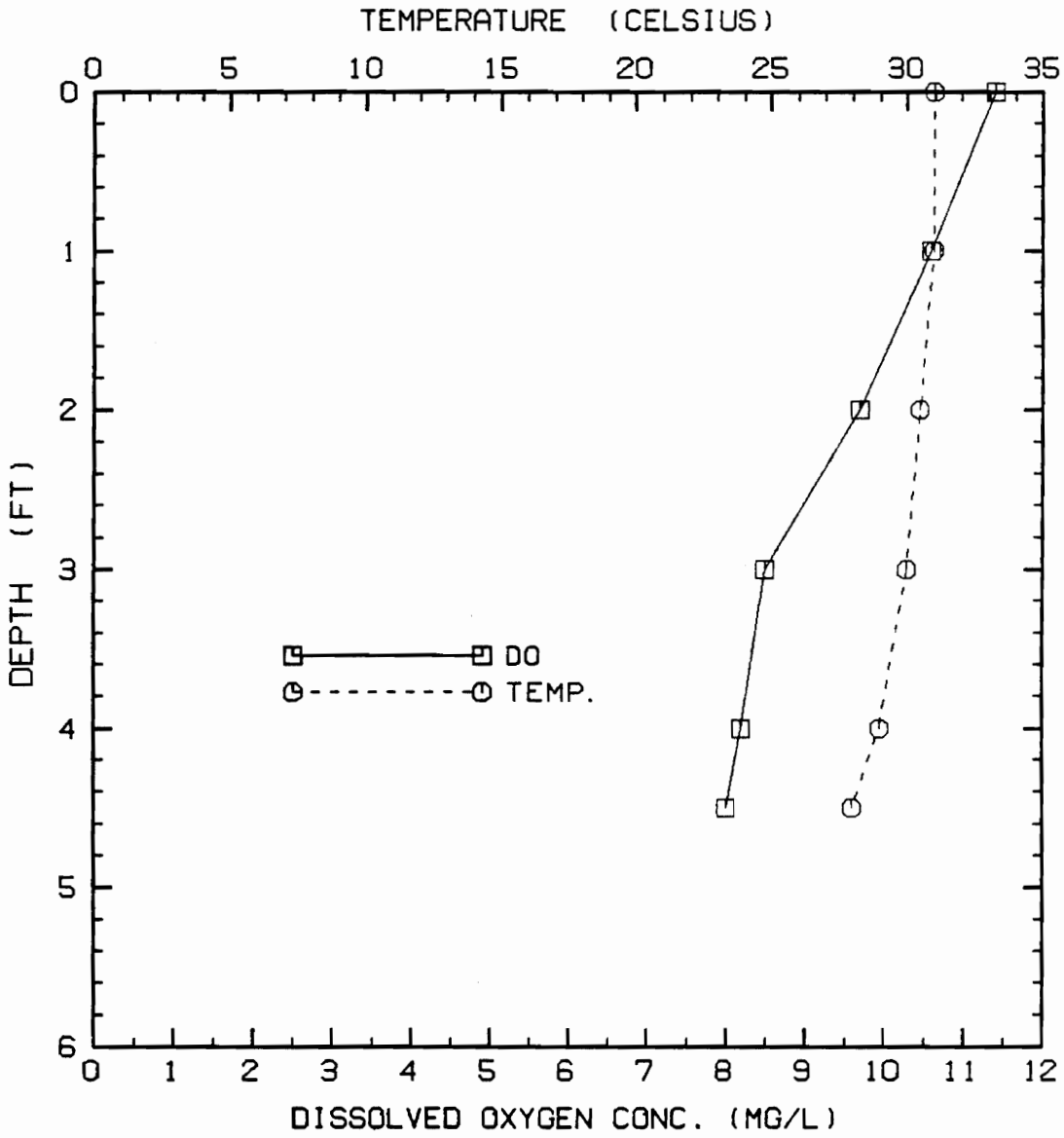


Figure 3 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 1, July 30, 1985

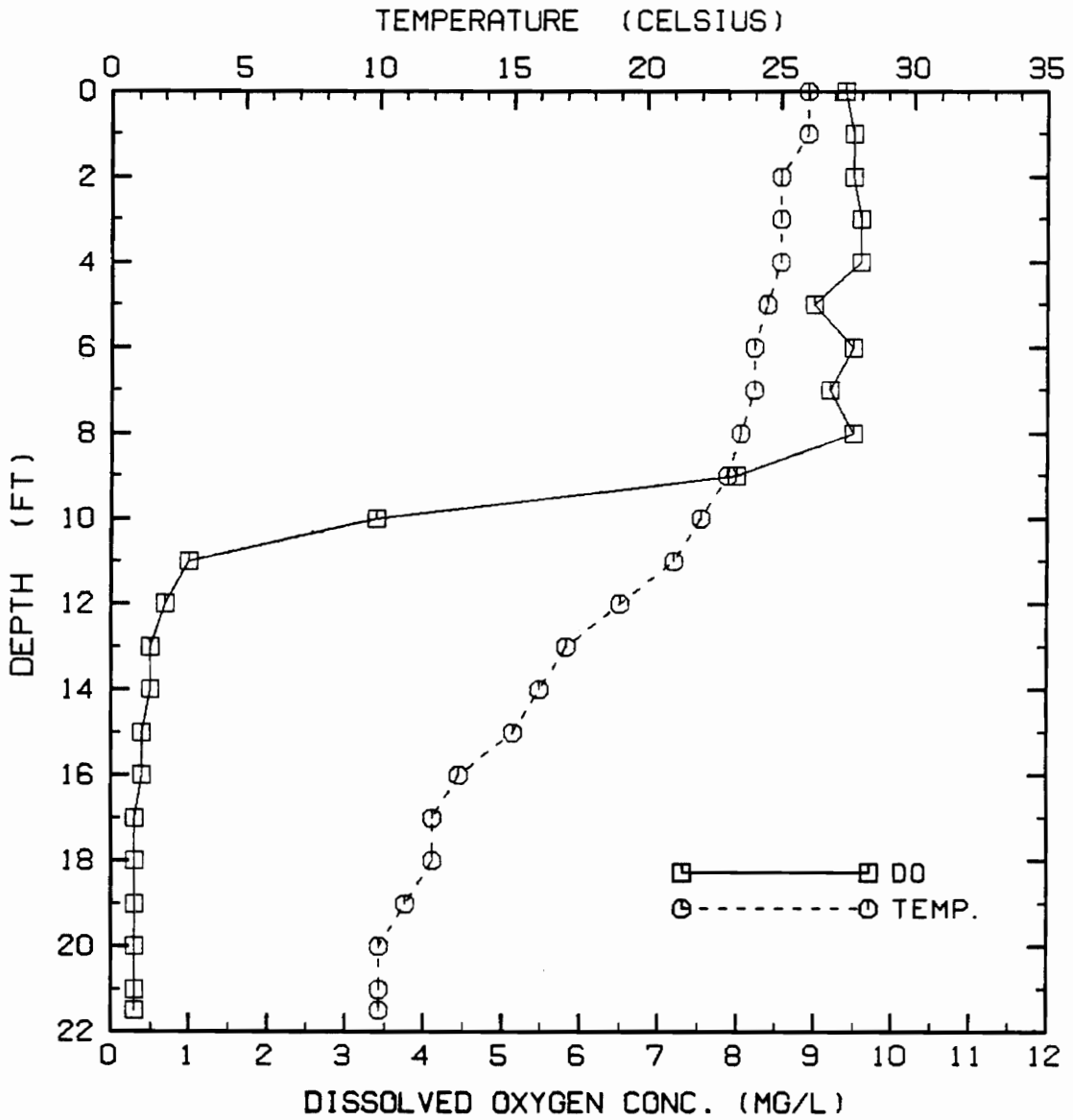


Figure 4 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 2, June 19, 1985

color -- qualities that intensified through the summer -- indicating increasing rates of reduction in the bottom waters. Sulfate concentrations decreased progressively in the interstitial waters at Station 2 through the summer (Appendix B, Figure B6) as reducing conditions prevailed. On September 20, dissolved oxygen was found to a depth of 16 feet (Figure 5), indicating that some mixing had occurred. By November 7 (Figure 6), oxygen was present throughout the lake's depth at this site and thus completely mixed.

Station 3: The depth of the lake at Station 3 was from 30.5 to 32 feet. The lake at this site was observed to weakly stratify thermally. Stratification with respect to dissolved oxygen concentrations was typical of a temperate-zone lake (Figure 7) (Appendix A, Figures A8-A11). On one sampling date (July 30, Figure A9) the surface oxygen concentration exceeded the saturation value, indicating some algal activity. The lake at Station 3 was still stratified on September 18 (Figure A11). Even with the on-set of fall overturn in the upper reaches of the lake, oxygen was not yet well-mixed throughout the depth at this site on November 7 (Figure 8).

Station No. 4: The observed depth of the lake at Station 4 varied from 36 to 40 feet. Stratification was evident by both the temperature and dissolved oxygen distributions. The surface dissolved-oxygen concentrations were less than than the saturation values on all but one sampling event. On July 30, the surface dissolved oxygen concentration was 1.1 times the saturation value -- suggesting some algal activity. Depths below 16-18 feet

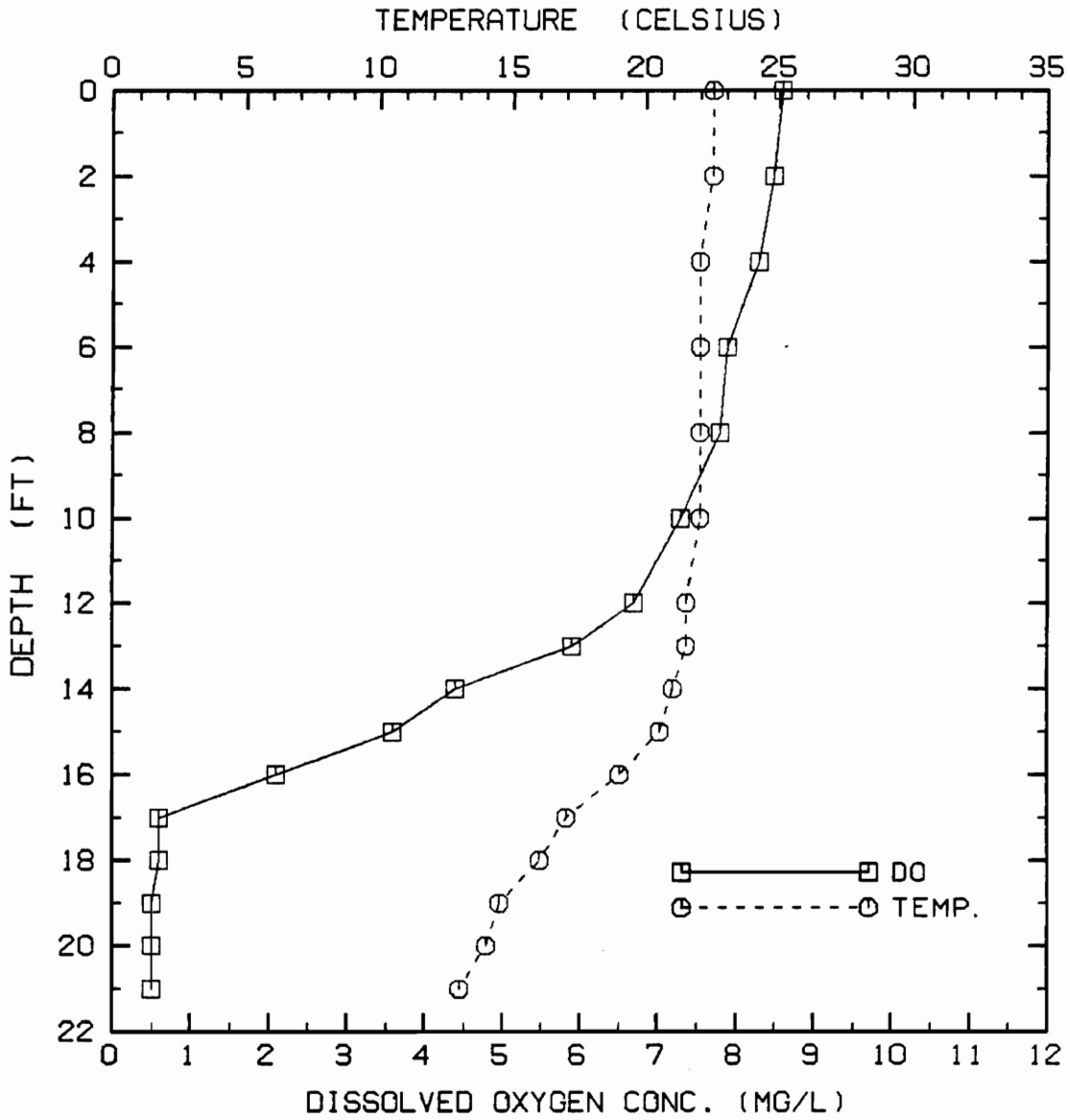


Figure 5 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 2, September 20, 1985

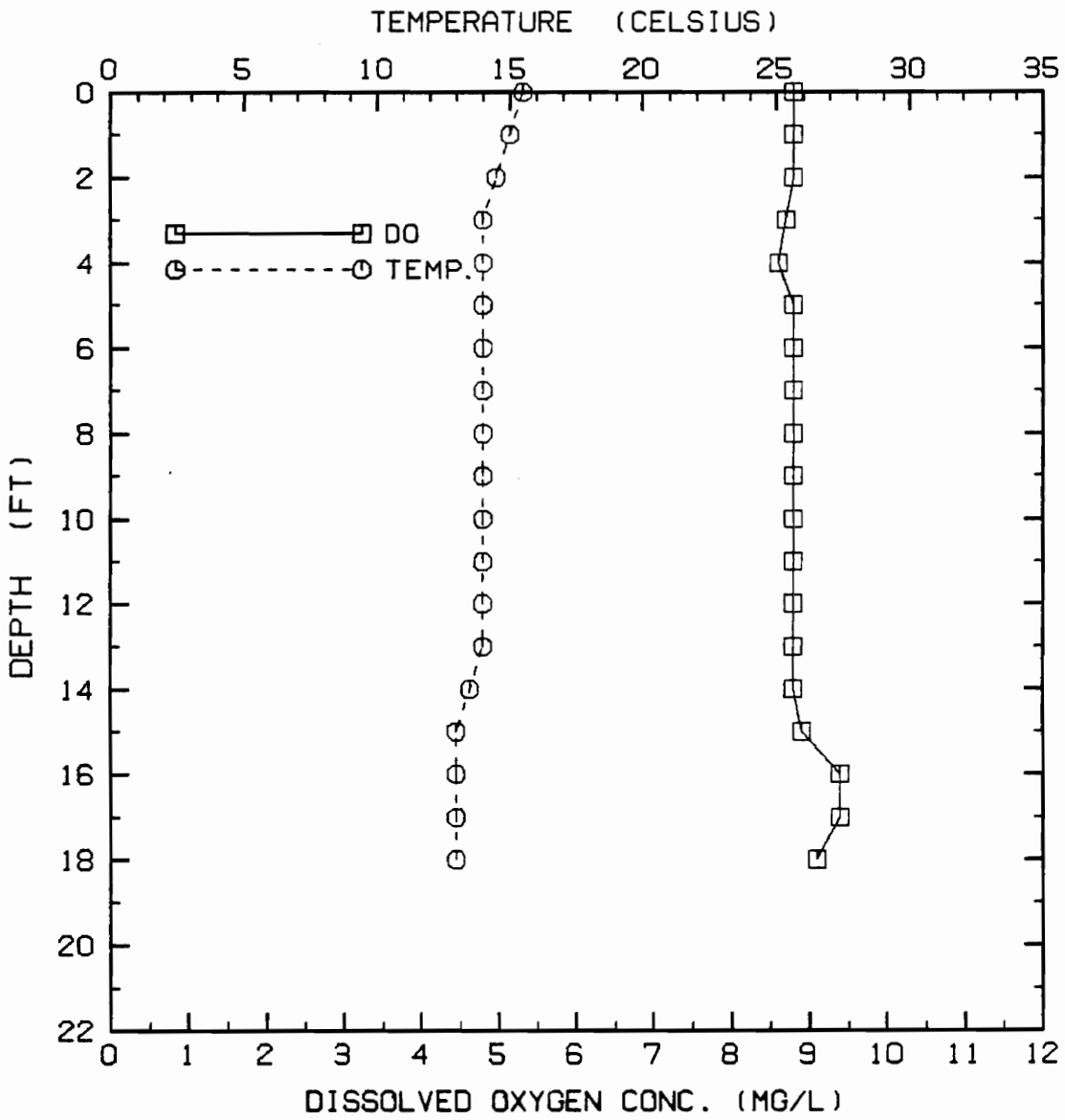


Figure 6 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 2, November 7, 1985

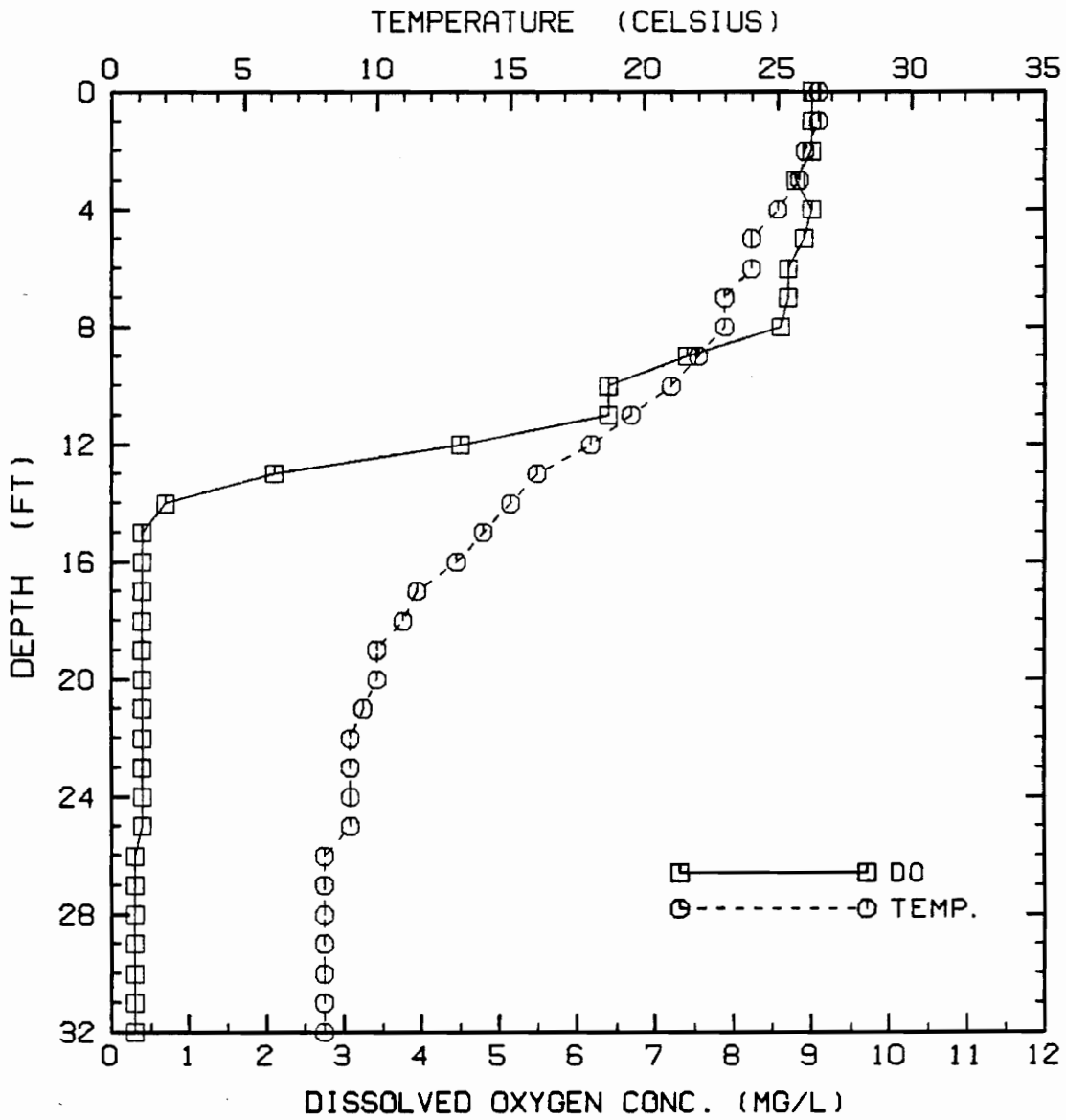


Figure 7 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 3, June 19, 1985

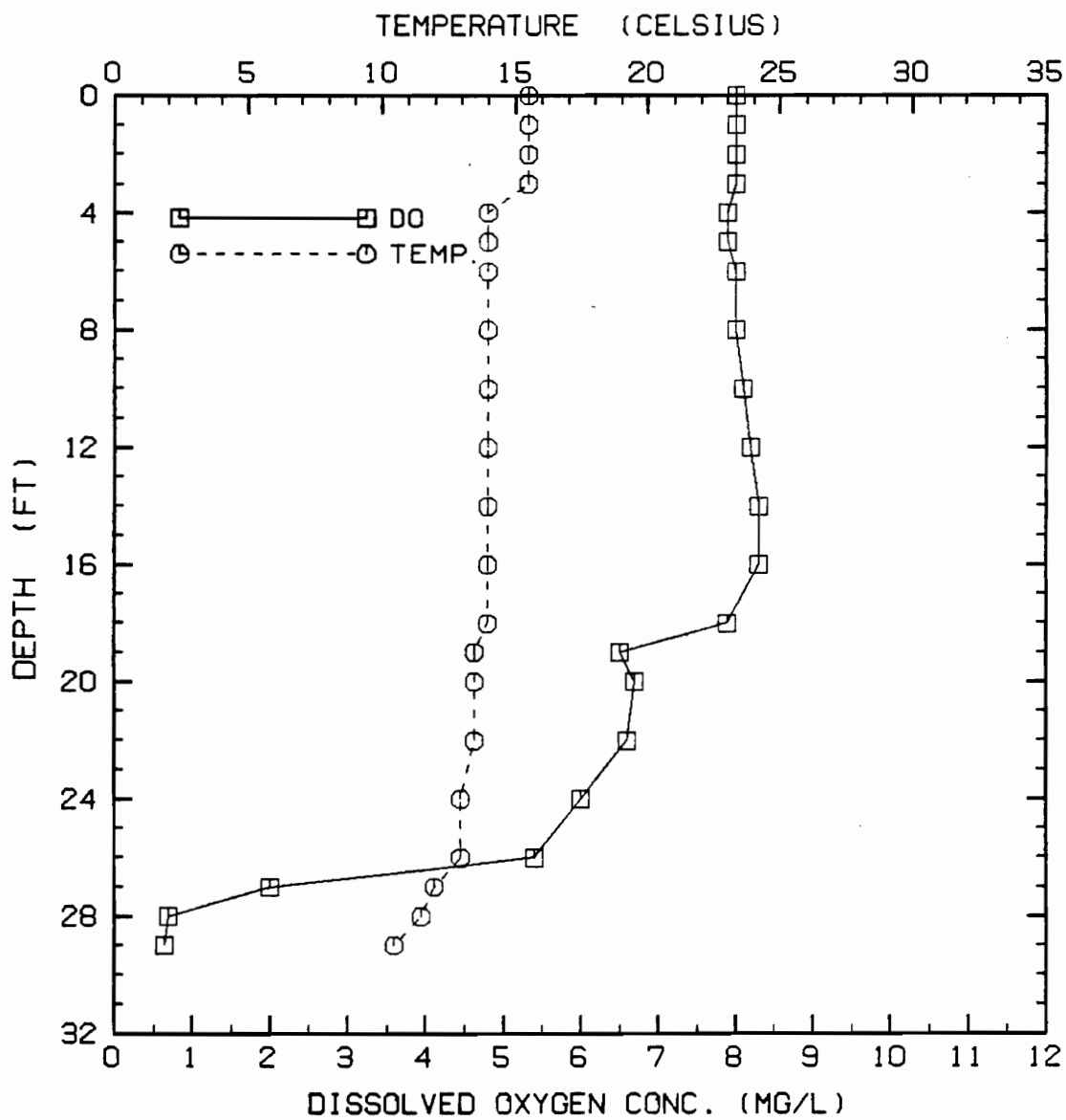


Figure 8 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 3, November 7, 1985

were devoid of oxygen throughout the summer (Appendix A, Figures A12-A16). By November 7, the circulation process had extended the presence of oxygen to a depth of 28 feet (Figure 9). This site was only partially mixed on November 7 as indicated by the varying temperature and dissolved oxygen profiles in Figure 9.

Station No. 5: Station 5, located near the intake for the WTP and also near the dam at the end of the reservoir, was approximately 50 feet deep. The lake at this site was thermally stratified throughout the summer. Some oxygen profiles unique to this site in the reservoir were observed. On June 19 (Figure 10) and July 9 (Figure 11), the surface dissolved oxygen concentrations were near saturation and oxygen concentration increased markedly between depths of 10 and 15 feet. This phenomenon is known as a metalimnetic oxygen maximum as described in the Literature Review (Chapter II).

The dissolved oxygen concentration in the hypolimnion at Station 5 was low as it was in other parts of the lake. Even after the fall circulation process had begun in the upper reaches of the lake, this site remained oxygen-stratified on November 7 (Figure 12) indicating that mixing was incomplete. With respect to the proximity of this site to the WTP intake, it is significant that this area of the lake had not circulated as late as November.

Transparency and Color

Figure 13 illustrates the transparency of Abel Lake throughout this study. At Station No. 1, the most shallow sampling site,

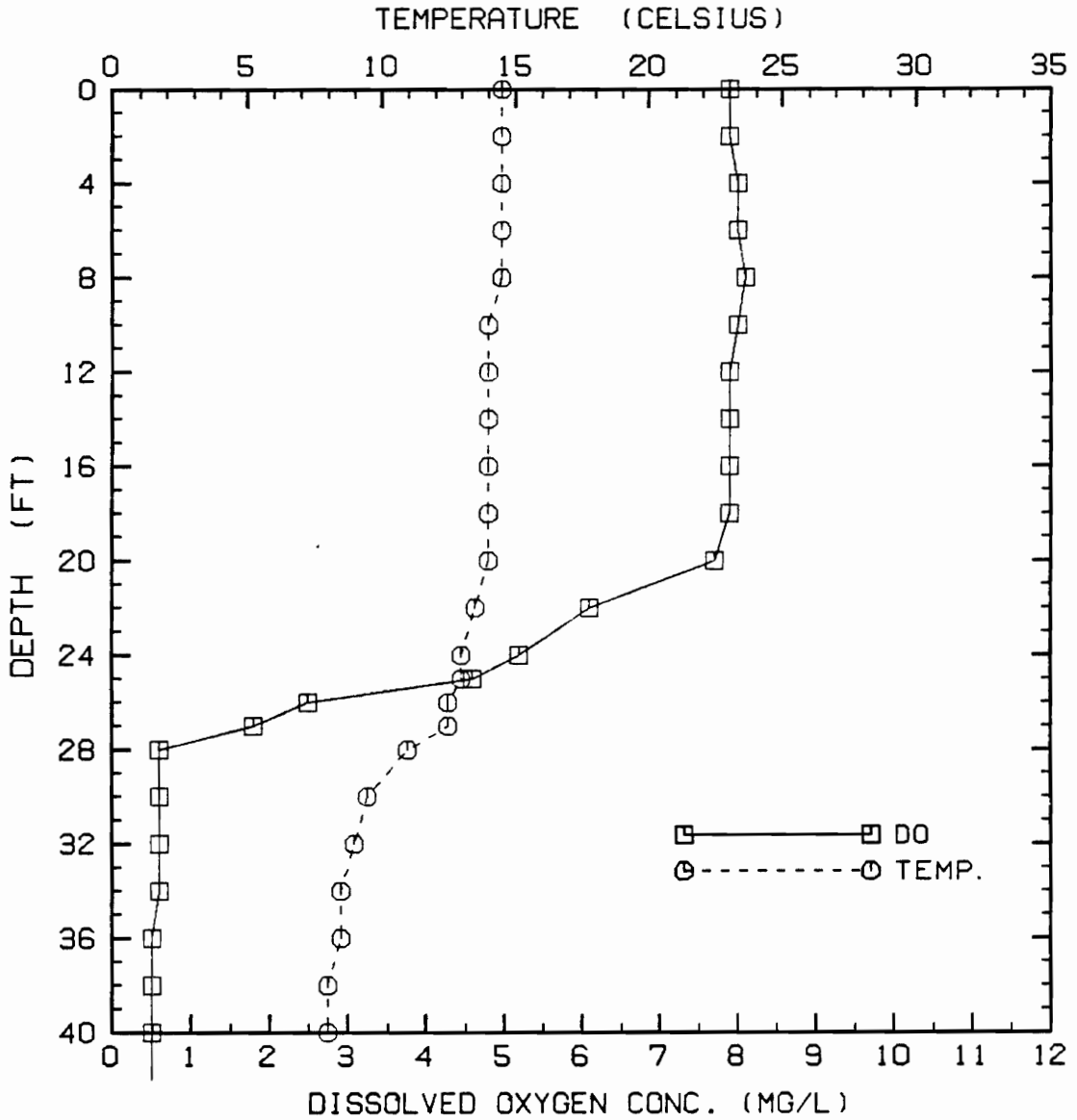


Figure 9 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 4, November 7, 1985

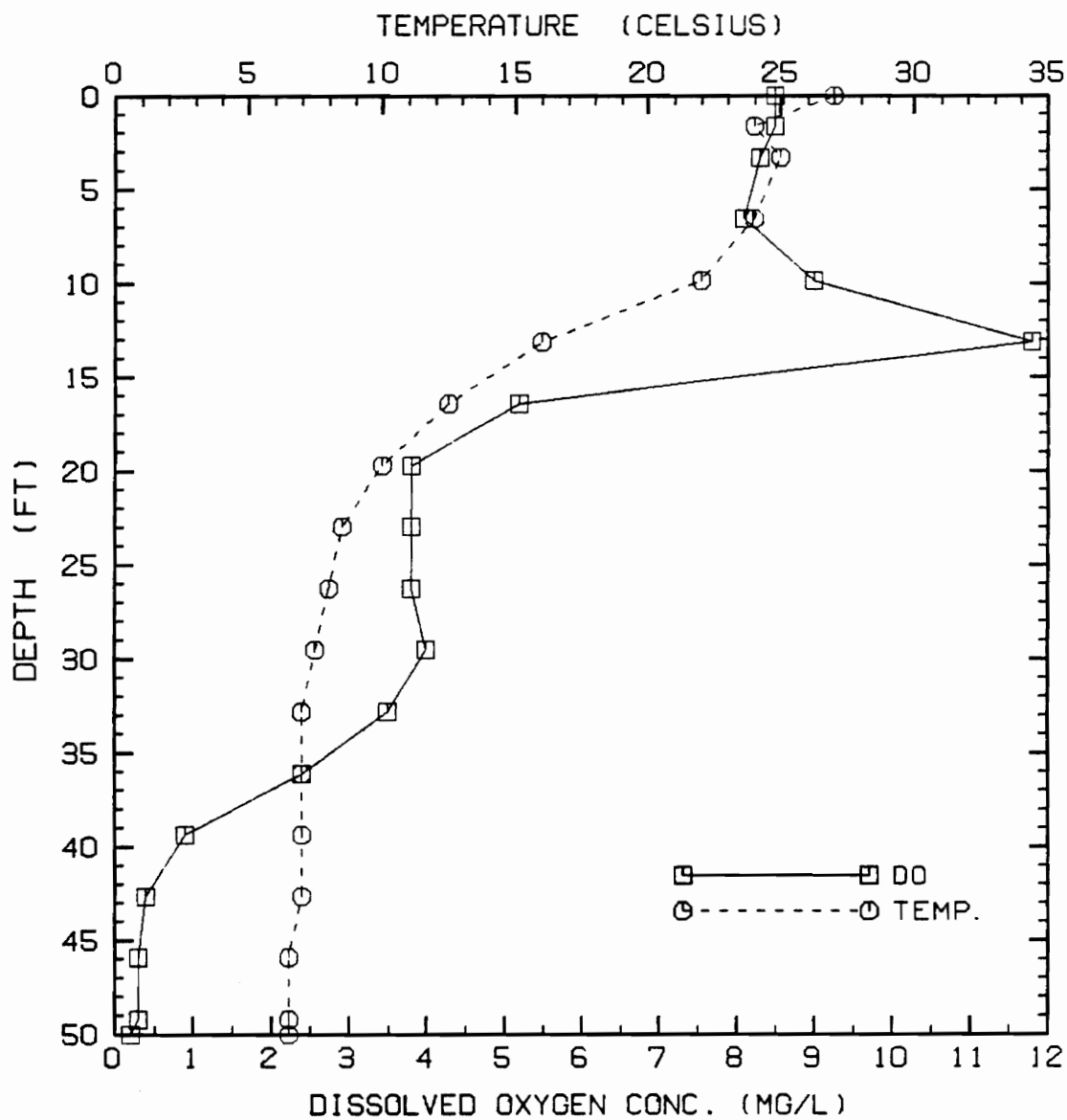


Figure 10 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 5, June 19, 1985

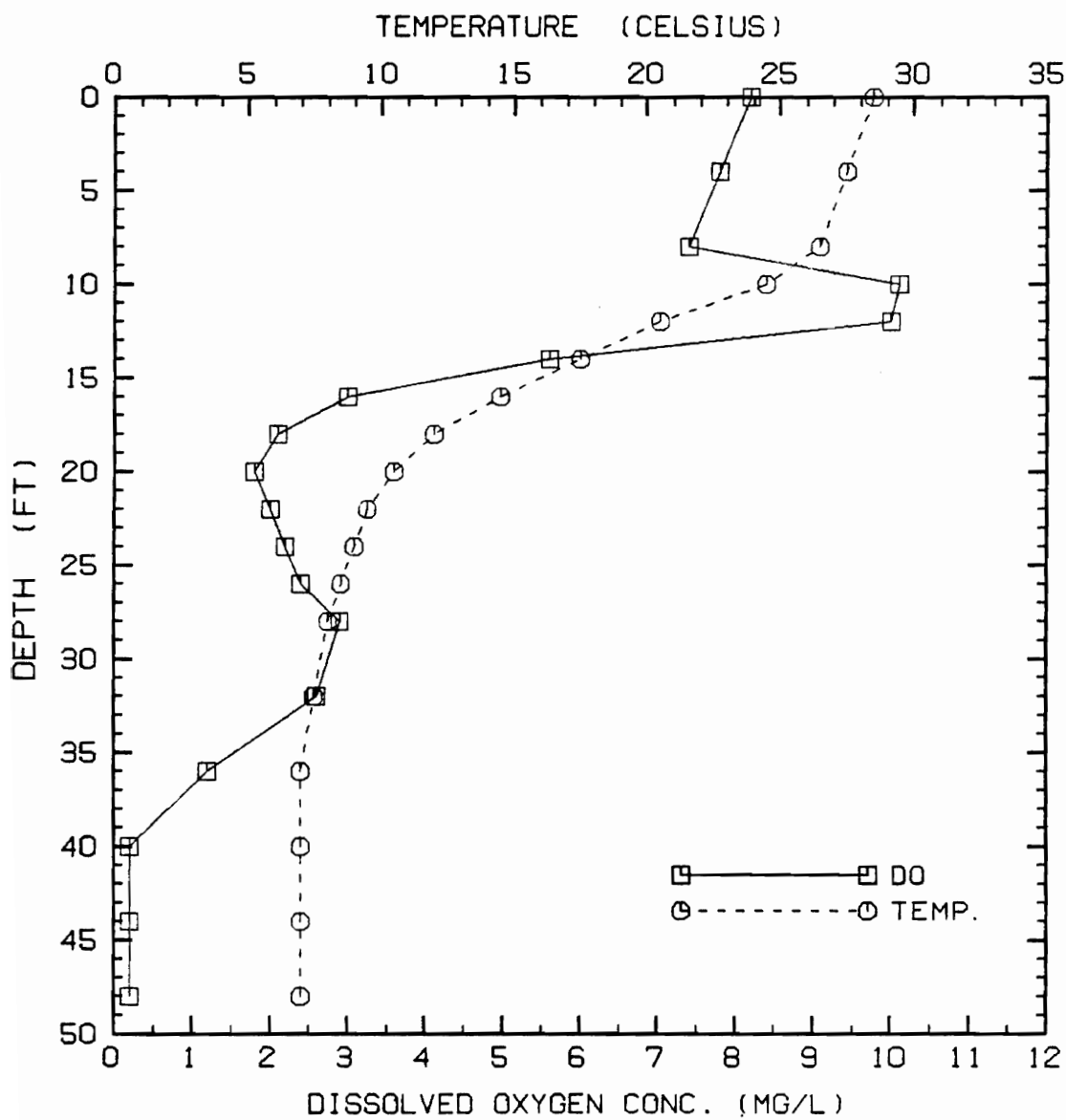


Figure 11 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 5, July 9, 1985

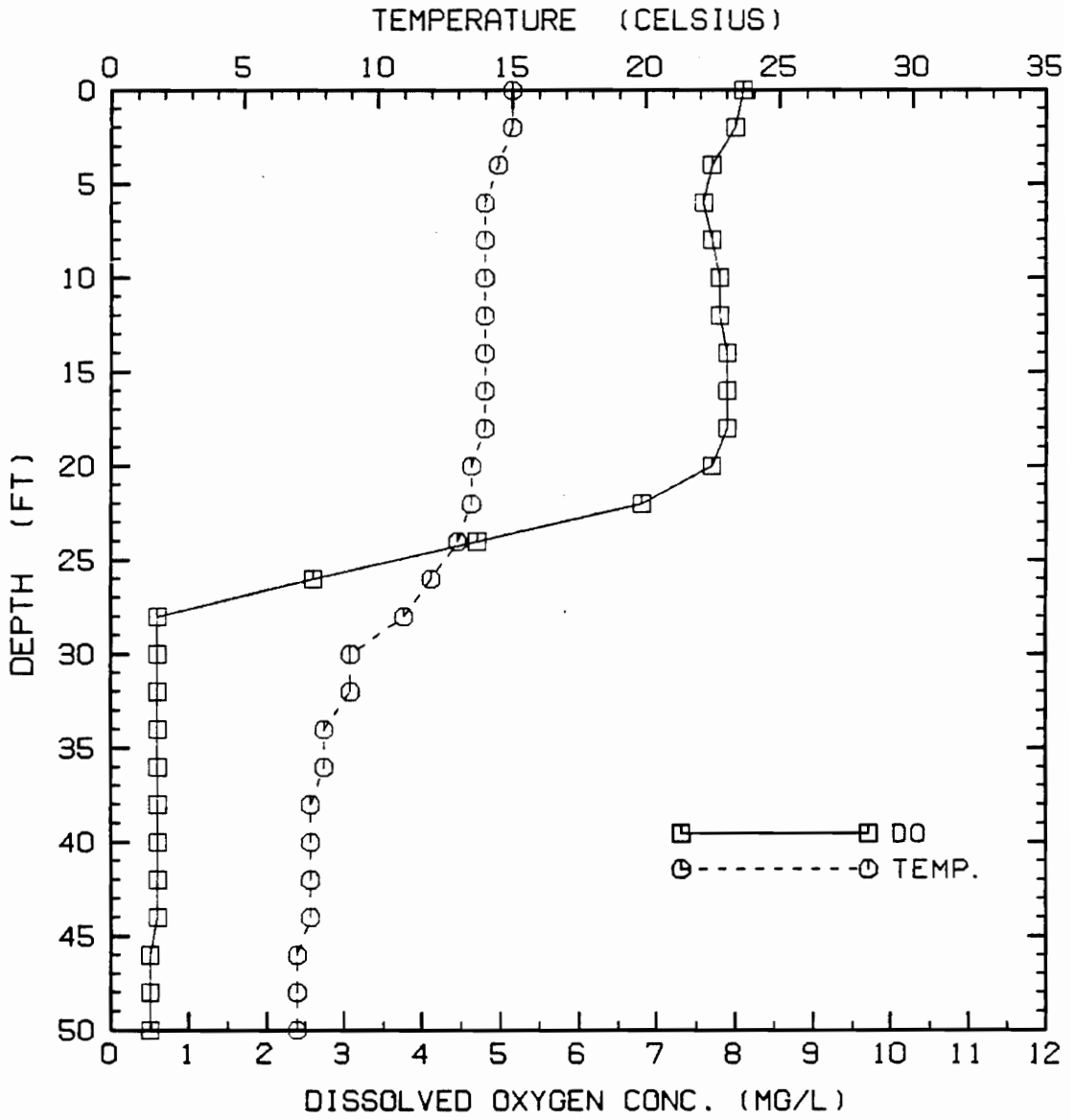


Figure 12 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 5, November 7, 1985

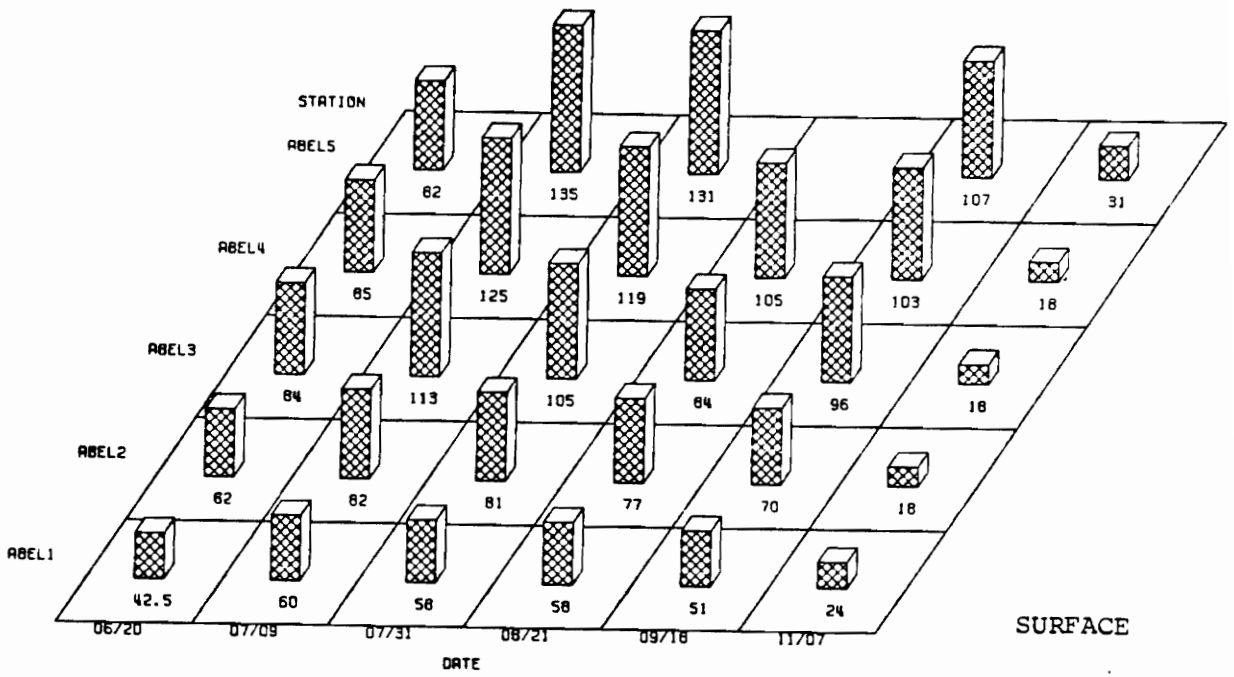


Figure 13 Variations in Secchi Disc Depth (inches) on Six Sampling Dates at Five Stations

sunlight penetrated the water column nearly to the bottom on all except the final sampling date. Transparency was also good at all other sites throughout the sampling period except on November 7 when circulation had begun. The surface of the entire reservoir was highly turbid on November 7. Note from the dissolved oxygen and temperature profiles in Figures 6, 8, 9 and 12 that circulation was not complete beyond Station 2 and that the water quality with respect to transparency was degraded throughout the reservoir. This was most likely the result of both circulation effects and the increased runoff created by a recent rain storm.

The true color of the surface water was usually quite low (Figure 14). The high surface-water color observed on November 7 is another effect of the runoff and circulation processes. The color values of the water collected near the bottom of the lake reveal a trend. Note the increasing trend in bottom-water color values from June to November at Stations 2 and 5. In September, the bottom-water color values at these sites were extremely high. This trend indicates a deterioration of hypolimnetic water quality during stratification. On November 7, circulation and oxidation processes had decreased the bottom-water color values at Station 2 and 3. Stations 4 and 5, remaining stratified, showed a further increase in color.

Further discussion of the visual quality of the bottom-water samples is appropriate here in interpreting the significance of color variations. As was previously mentioned, some bottom-water samples were grey and smelled of sulfides, an indication of anaerobic

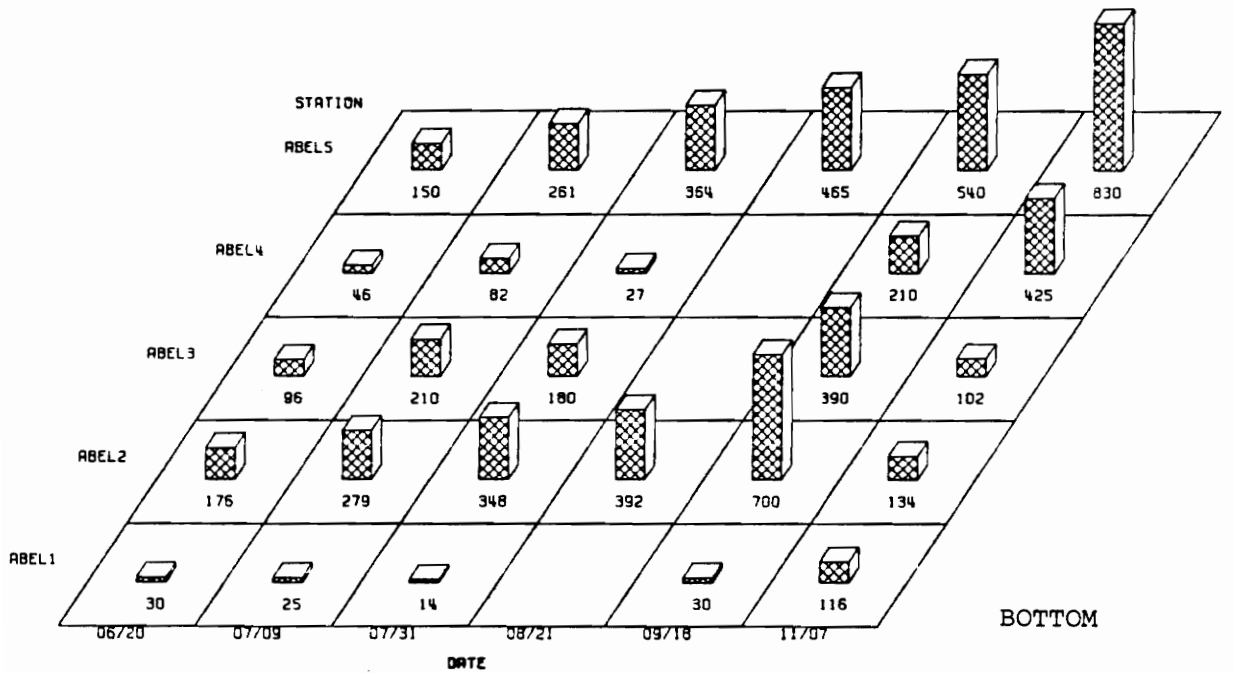
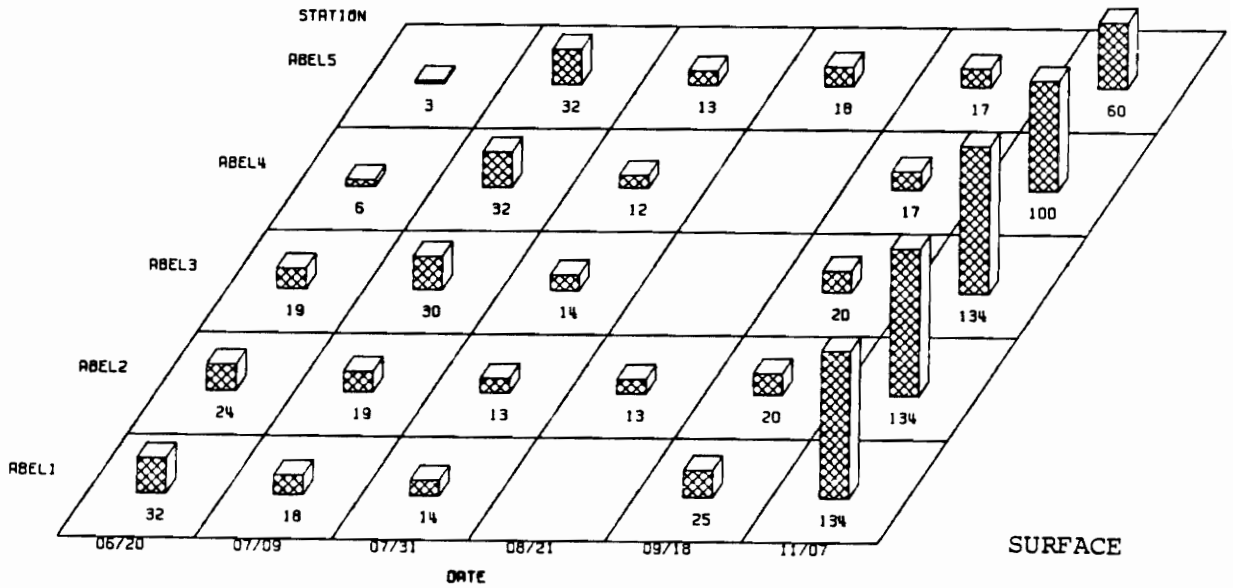


Figure 14 Variations in Abel Lake True Color (color units) on Six Sampling Dates at Five Stations

decomposition. When these samples were exposed to the atmosphere, the color changed to a deep yellow-orange color, indicating that the soluble, colorless iron and manganese were being oxidized. These inorganic constituents contributed to the water's intense color, which is usually created by naturally occurring humic materials.

Total Organic Carbon (TOC)

The surface TOC concentrations in the reservoir were low, typically less than 5 mg/L, throughout the stratification period (Figure 15). On November 7, however, TOC concentrations had increased to values ranging from greater than 7 mg/L at Station 5 to more than 13 mg/L at Station 3. An increasing trend in bottom TOC concentrations throughout the summer is another indication of the deterioration of hypolimnetic water quality.

Profiles of both TOC and dissolved oxygen concentrations at Station 5 on July 9 are shown in Figure 16. A curious feature of the TOC profile is the increase of about 1.5 mg/L between the depths of 15 and 18 feet, just below the depth of the metalimnetic oxygen maximum. This increase was most likely created by the accumulation of algae in the metalimnion, and specifically, the release of algal extracellular products and lysis of dead algae. In addition, Figure 16 clearly reveals the relationship between the absence of dissolved oxygen and the increase in TOC concentrations from a depth of 39 feet to the bottom.

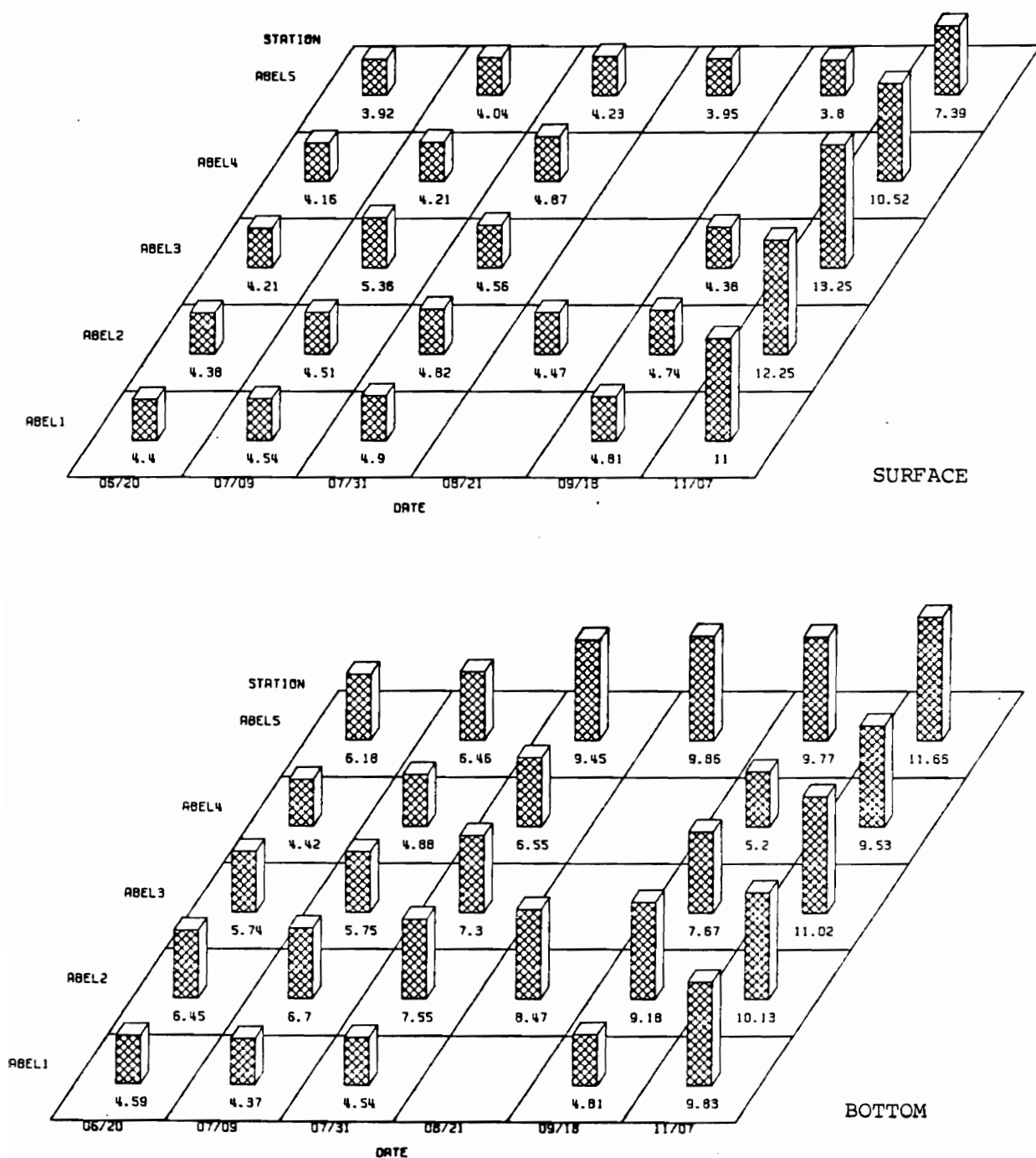


Figure 15 Variations in Abel Lake Total Organic Carbon Concentrations (mg/L) on Six Sampling Dates at Five Stations

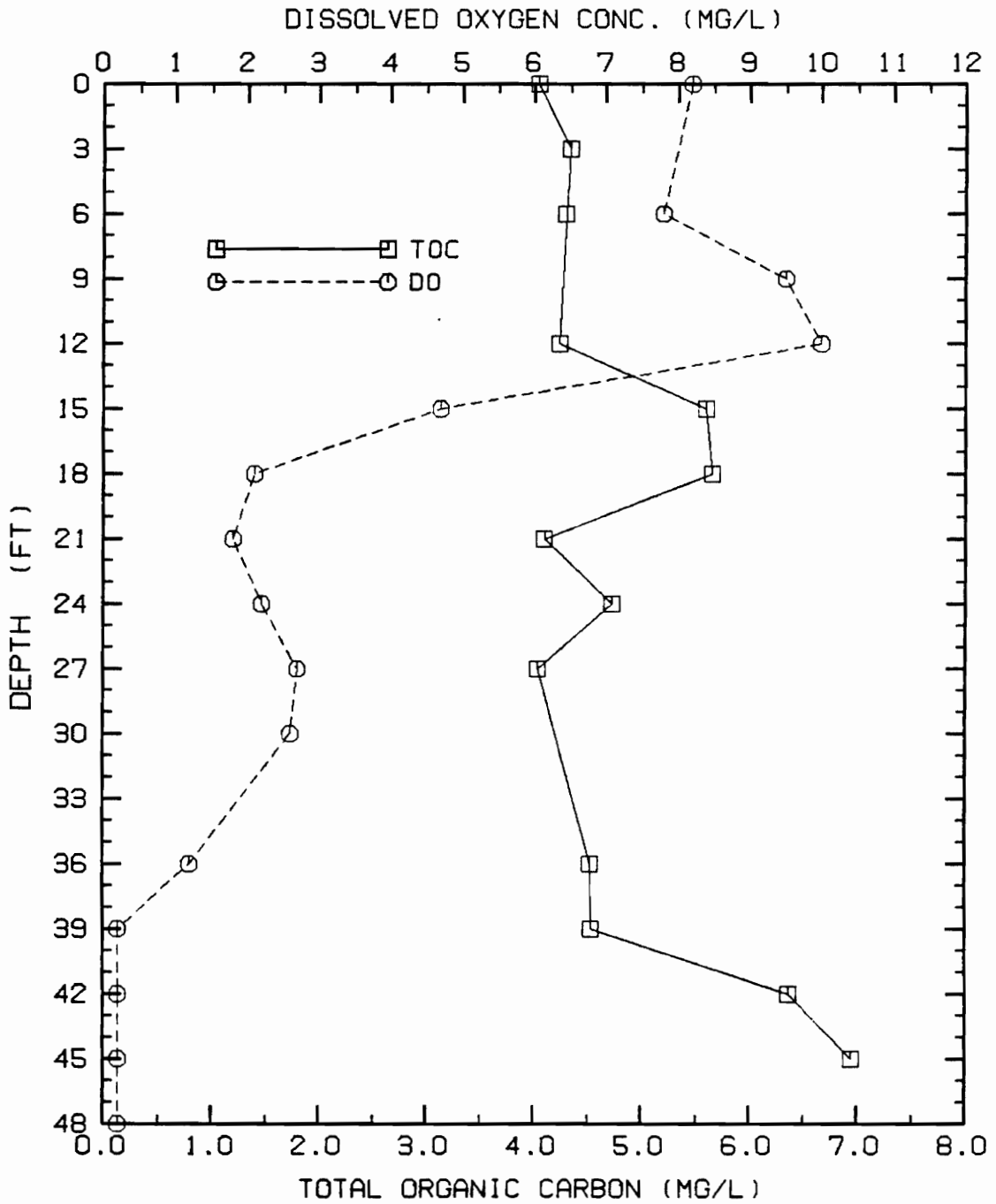


Figure 16 Dissolved Oxygen and TOC Profile
 Abel Lake Sta. 5, July 9, 1985

Iron and Manganese

Figures 17 and 18 illustrate the iron and manganese concentrations in Abel Lake. As was previously explained, these two metals were of particular interest because SMCL's exist for these and because their removal, especially manganese, poses difficult treatment problems. As shown in the figures, the surface iron and manganese concentrations were low throughout the summer and thus did not create any treatment problems. With the fall circulation in progress, however, the surface iron and manganese concentrations had increased markedly on November 7.

At the bottom of the lake, iron and manganese concentrations increased during summer stratification in the reducing environment created by low dissolved oxygen concentrations at the sediment-water interface. The relationship between dissolved oxygen and these metals is clearly illustrated in Figure 19.

With the circulation of the lake in progress, the impact of destratification and bottom water quality on surface iron and manganese concentrations is revealed by Figures 17 and 18. The manganese concentration at Station 5 near the raw water intake for the WTP on November 7 was 0.222 mg/L (more than four times the finished water standard) and the iron concentration was 0.6 mg/L or double the SMCL for finished water. Although surface iron and manganese concentrations along the entire length of the lake had increased by November 7, bottom concentrations had not diminished at Stations 4 and 5 as they had at Stations 1, 2, and 3. Even though

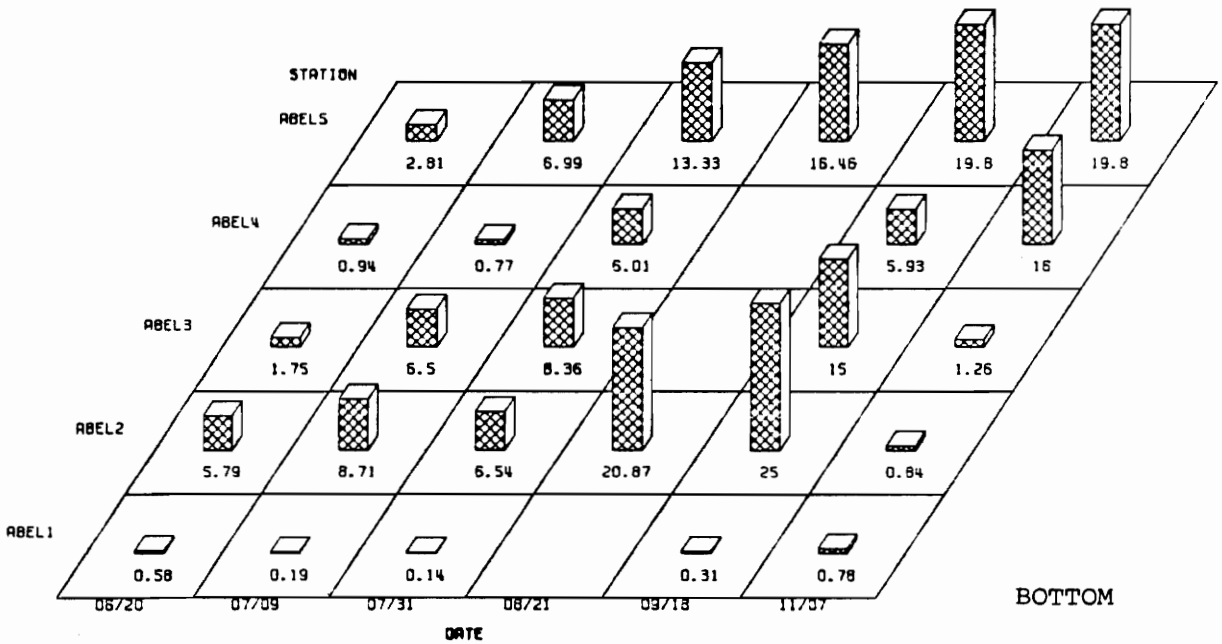
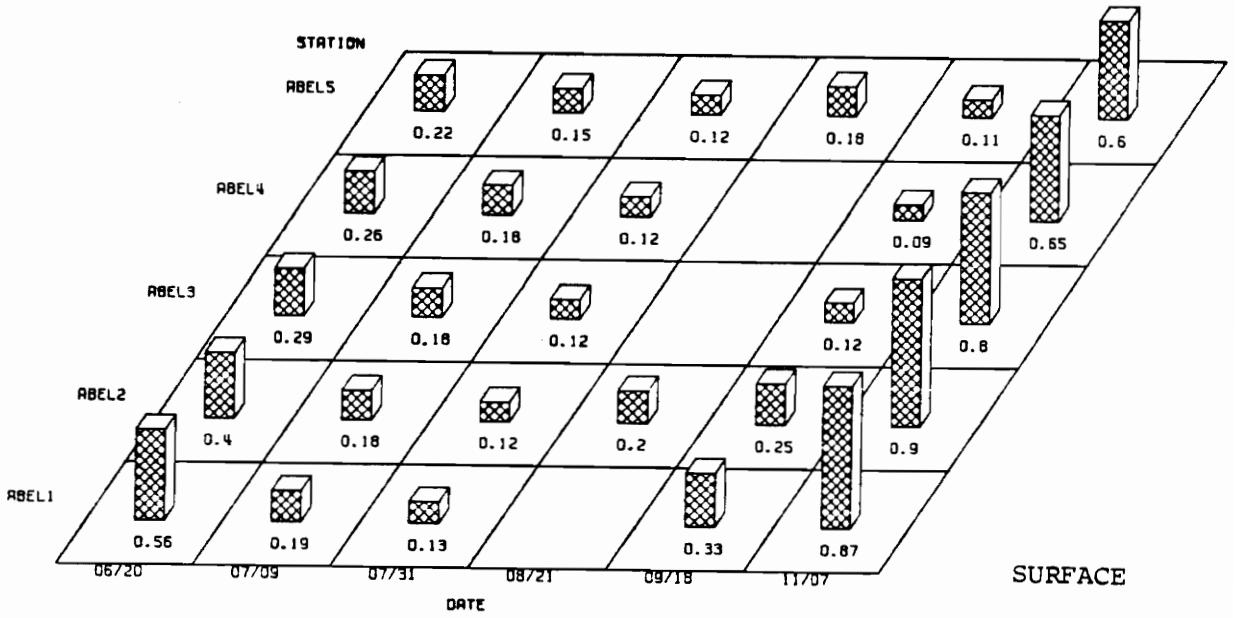


Figure 17 Variations in Abel Lake Iron Concentrations (mg/L) on Six Sampling Dates at Five Stations

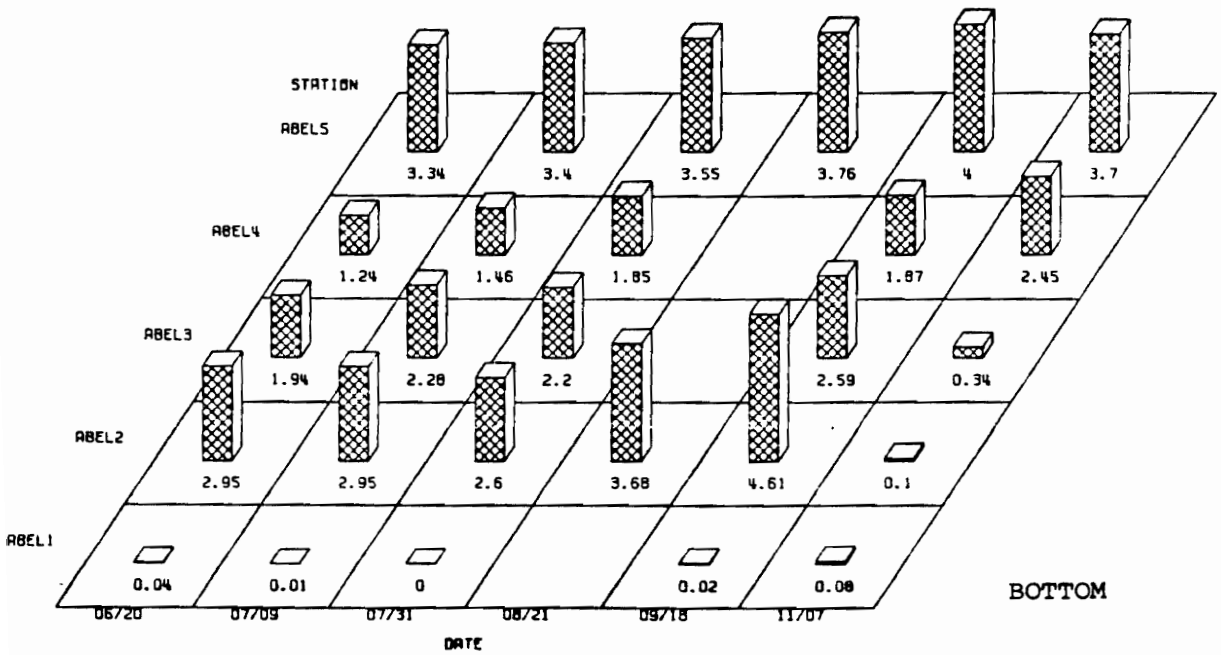
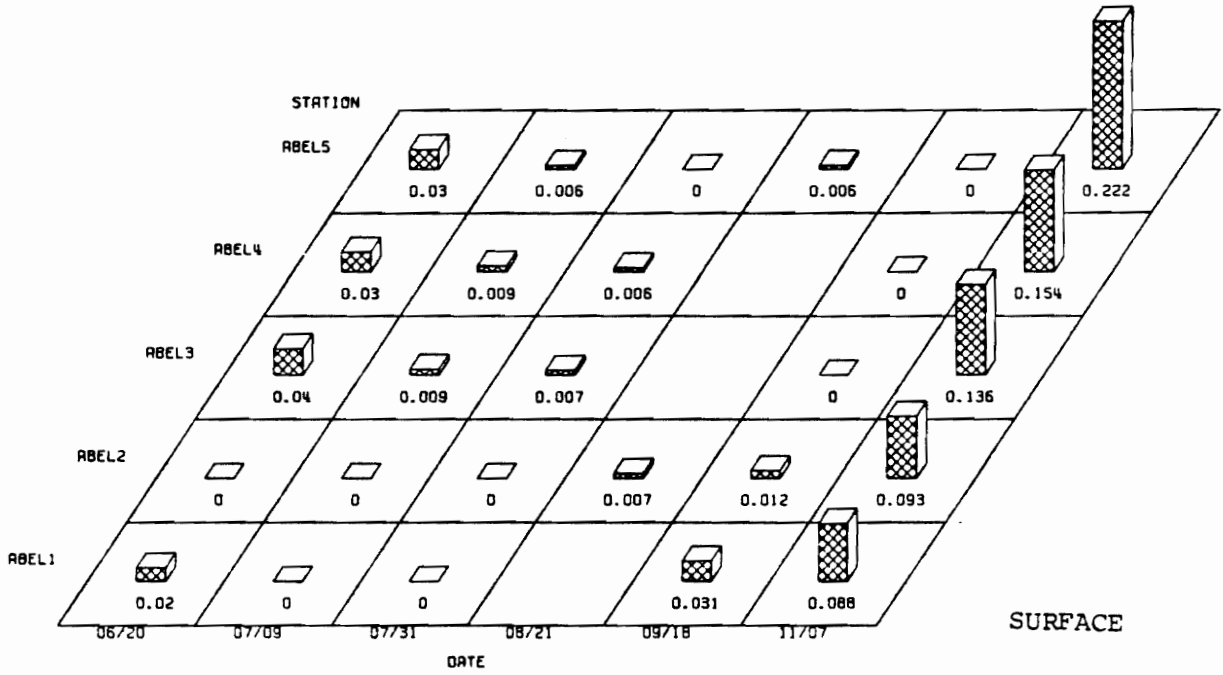


Figure 18 Variations in Abel Lake Manganese Concentrations (mg/L) on Six Sampling Dates at Five Stations

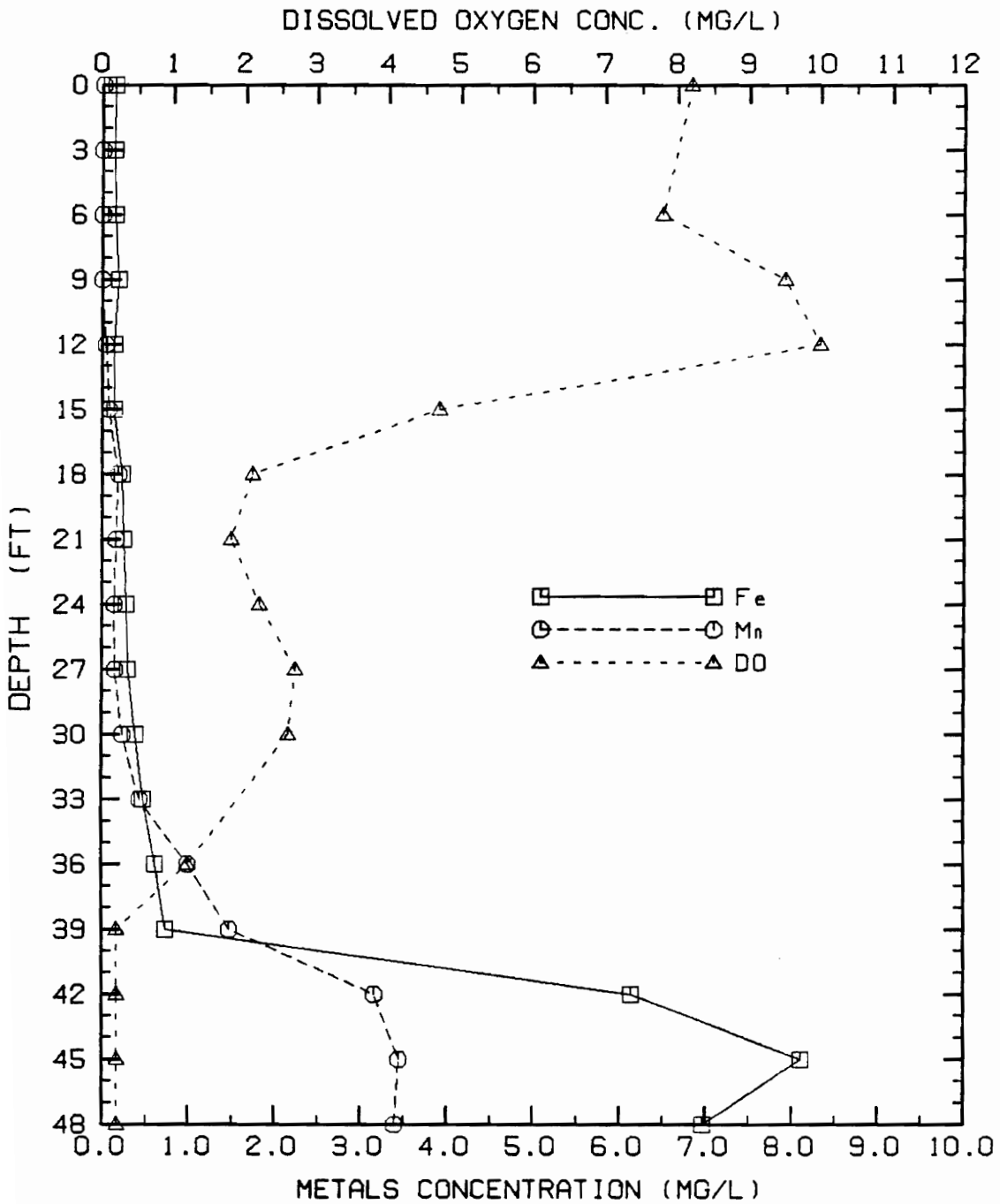


Figure 19 Dissolved Oxygen and Metals Profile
Able Lake Sta. 5, July 9, 1985

this indicates that the lake was not circulating at Stations 4 and 5, poor quality water from the upper reaches of the lake could be expected to appear at the WTP intake.

Nutrients and Algae

Nitrogen, phosphorus, and chlorophyll-a concentrations were monitored infrequently during the limnological study. The supplies of nitrogen and phosphorus can limit algal growth and, thus, their concentration can indicate the health and trophic state of a lake. Because the WTP personnel treated portions of the reservoir with copper sulfate to limit algal growth, nutrient supply and chlorophyll-a concentrations were important in evaluating the copper sulfate program. In addition, information about nutrient supply and algal abundance may be useful in future attempts to manage and protect the watershed from potential increases in nutrient supplies that can result from development.

The results of the nutrient and chlorophyll-a studies are included in Appendix B, Figures B7-B9. In general, the data reveal that nitrogen and phosphorus were available in sufficient amounts to support algal growth. Negligible orthophosphate-phosphorus concentrations may indicate that the readily available orthophosphate is being consumed spontaneously by the biota as it becomes available.

Another hypothesis to explain the negligible amounts of orthophosphate detected in the lake comes from a study by Stewart and

Wetzel (11). They proposed that in systems of low alkalinity and high iron concentrations, orthophosphate availability is limited by the tendency for orthophosphate to bind with dissolved humic material. The preconditions for this process to occur in Abel Lake do exist: low alkalinity, high iron concentrations, and high concentrations of organic matter. A relationship among calcium carbonate, iron, dissolved humic material, and orthophosphate may be limiting the availability of orthophosphate to the system and thus the productivity as indicated by moderate chlorophyll-a values. The chlorophyll-a data reveal that algal populations are moderately low and never reached the 30 ug/L value currently associated with nuisance or problem conditions (12). It appears from these data that the copper sulfate program was suppressing some algal growth.

It is of interest to add here a comment on the nutrient loading potential for the Abel Lake Reservoir. A current index for this potential is the watershed to lake surface area (WA:SA) ratio. The WA:SA ratio of Abel Lake is 105:1. This value exceeds the 20:1 ratio that indicates that nonpoint source pollution can contribute significant nutrient sediment loads to a lake. The ratio for Abel Lake also exceeds the 100:1 ratio that indicates that the lake would be less likely to respond to protection measures and would be difficult to restore due to the high levels of sediments and nutrients that are associated with runoff. Although the nutrient load and productivity in Abel Lake appeared moderate at the time of the study, caution should be exercised in planning for development

in the Abel Lake watershed. The potential for water-quality degradation from runoff indicates that the preservation of water quality in Abel Lake will require vigilant watershed management.

Reservoir Water Quality

From these data, the water quality in Abel Lake can be summarized as follows.

Abel Lake is an attractive and desirable water-supply reservoir with good water quality: nutrient levels are moderately low, transparency is good with minimum depths of several feet, and attempts to control algal growth with copper sulfate have been successful. Abel Lake is a typical temperate-zone lake that stratifies in the summer and the bottom-water quality degrades with the depletion of oxygen by microbial activity. As the lake warms in the spring and summer, the warmer upper layers effectively isolate the colder layers from the atmosphere and prevent the lake from mixing. Because there is no circulation, oxygen from the atmosphere no longer reaches the bottom waters. As the microbes in the hypolimnion consume the available oxygen, the bottom waters become colored and odorous with the release of manganese, iron, sulfides, and ammonia from the lake sediments. This process occurs at Station 2 and throughout the remaining downstream portion of the reservoir.

During the summer, the deteriorating water quality in the hypolimnion is not an issue for the WTP operations because the

surface layers remain aerobic to depths of 14 - 18 feet and are isolated from the hypolimnion. However, reservoir quality and WTP difficulties develop through the fall and winter as the decreasing temperatures, cold rains, and high winds activate the circulation process. As surface waters cool, the colder water sinks and displaces the bottom waters causing the surfacing of the undesirable materials previously trapped in the hypolimnion. With the surfacing of the degraded water, the WTP begins to experience problems treating the water.

This limnological survey revealed that the lake begins to circulate in the shallower, upper reaches and progresses, as depth increases, toward the dam. As surface waters degrade with circulation, the poor quality water flows toward the dam causing the water quality near the WTP intake to be poor. In early November, the water near the WTP intake had not completely mixed and the materials in the hypolimnion were still trapped. However, the surface water quality was very poor because the upstream waters that had circulated were being transported downstream and had reached the WTP intake. It is assumed that the fall overturn was not complete until December or January. Treatment difficulties, persisting well into 1986, included an increase in the oxidant demand and other difficulties with the oxidation and coagulation processes.

Results and Discussion of Organic Materials Distribution

Characterization

The data described here were collected during stratification of the Abel Lake reservoir. A surface sample, two bottom water samples, and an inlet stream sample were characterized according to molecular size and THM formation potential in order to relate organic compound source to THM yield.

Figure 20 illustrates the TOC data for all samples. For each fractionation range, <500, 500-1K, 1K-5K, 5K-10K, 10K-30K, and >30,000, the percent of the whole sample TOC within each range is represented by a vertical bar. In the surface sample, less than 20 percent of the TOC was in the AMW range >30K. Most of the organics were less than 10K with the greatest percentage in the 1K-5K AMW range. In the bottom samples, however, the largest fractions were in the AMW >30K portions. These results follow those of Ogura (15) who predicted that the distribution of AMW of DOM changes with the state of decomposition of the organic material and found more high-molecular-weight DOM in bottom waters than in surface waters. However, Chost and Faust (20), in a study using ultrafiltration of algal extracellular products, found that the AMW < 1000 and the 10K-30K fractions represented the greatest percentage of TOC in an algal-laden surface water. Little TOC in the 10K-30K AMW range was found in the surface sample from Abel Lake. Comparison of these results suggest that either there was very little phytoplankton activity in Able Lake or the primary consumers were consuming the

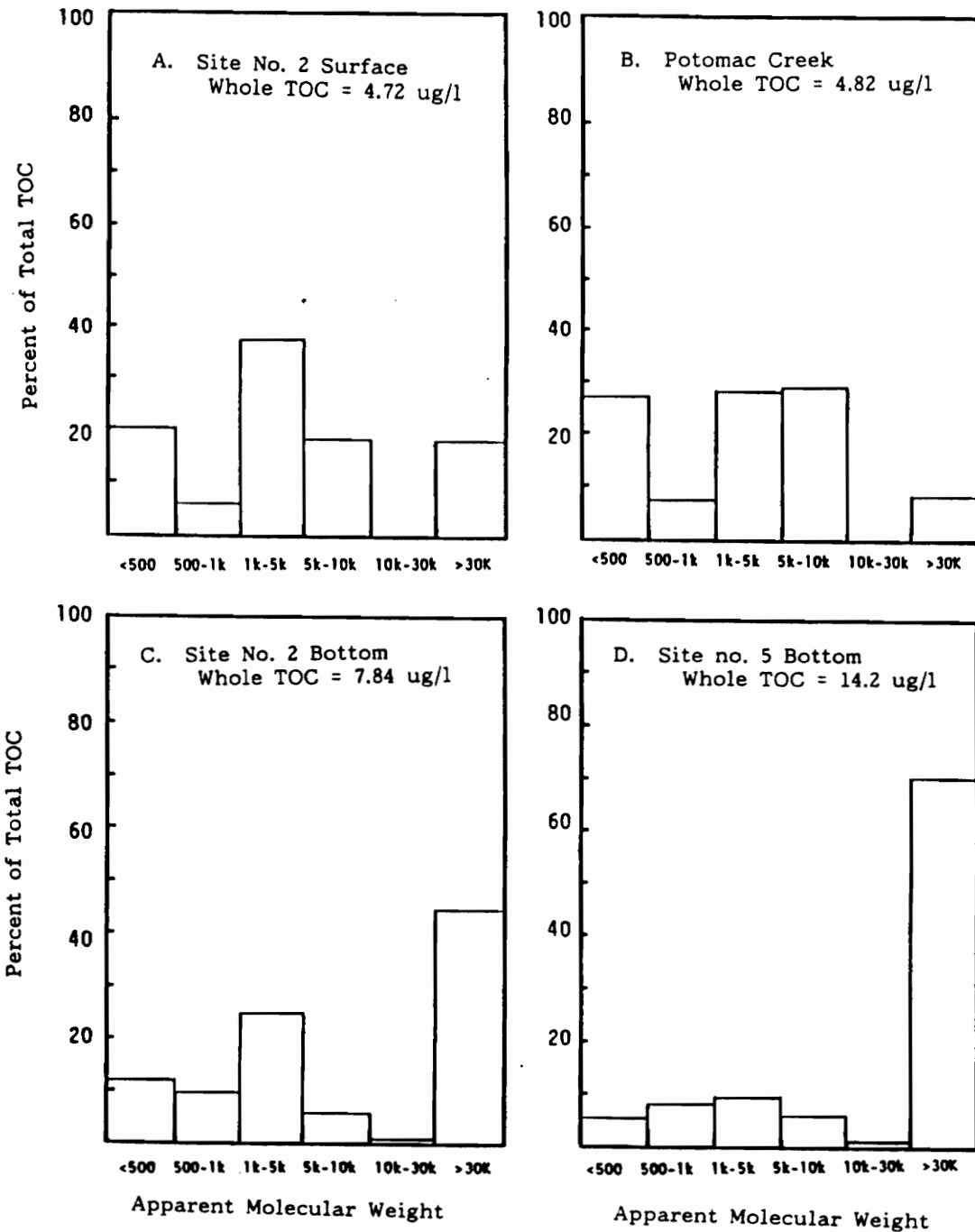


Figure 20 TOC Comparison by % Total - Abel Lake Reservoir

phytoplankton rapidly. These results are corroborated by the reservoir data (discussed previously) that revealed low chlorophyll-a concentrations in the reservoir.

The creek sample had less than 10 percent of the TOC in the AMW size range >30K and most of the organic material was less than 10K.

Figure 21 illustrates the THM-formation potential (THMFP) for the corresponding samples and fractionation ranges in Figure 20. The THMFP of the unfractionated surface sample was less than the THMFP values of the unfractionated bottom and creek samples. The THMFP values in the >30K AMW portions of both the bottom and creek samples were greater than any other fraction and were also greater than those in the >30K AMW fraction of the surface sample. The <10K AMW fractions of the surface sample had greater THMFP than the >30K fraction.

Figure 22 illustrates the THM yield data for the corresponding molecular-size fractionated samples in Figures 20-21. The unfractionated creek sample produced a higher THM yield than the unfractionated surface and bottom samples. The organic material with AMW >30K produced the highest yield in the creek sample. Although more than 90 percent of the organic material in the stream sample was <10 AMW, the small percentage of organic material that was >30 AMW contributed most significantly to the THM yield. The AMW size fractions of the surface sample contributed to THM yield nearly uniformly. The AMW >30K fraction of the bottom waters also produced a large THM yield.

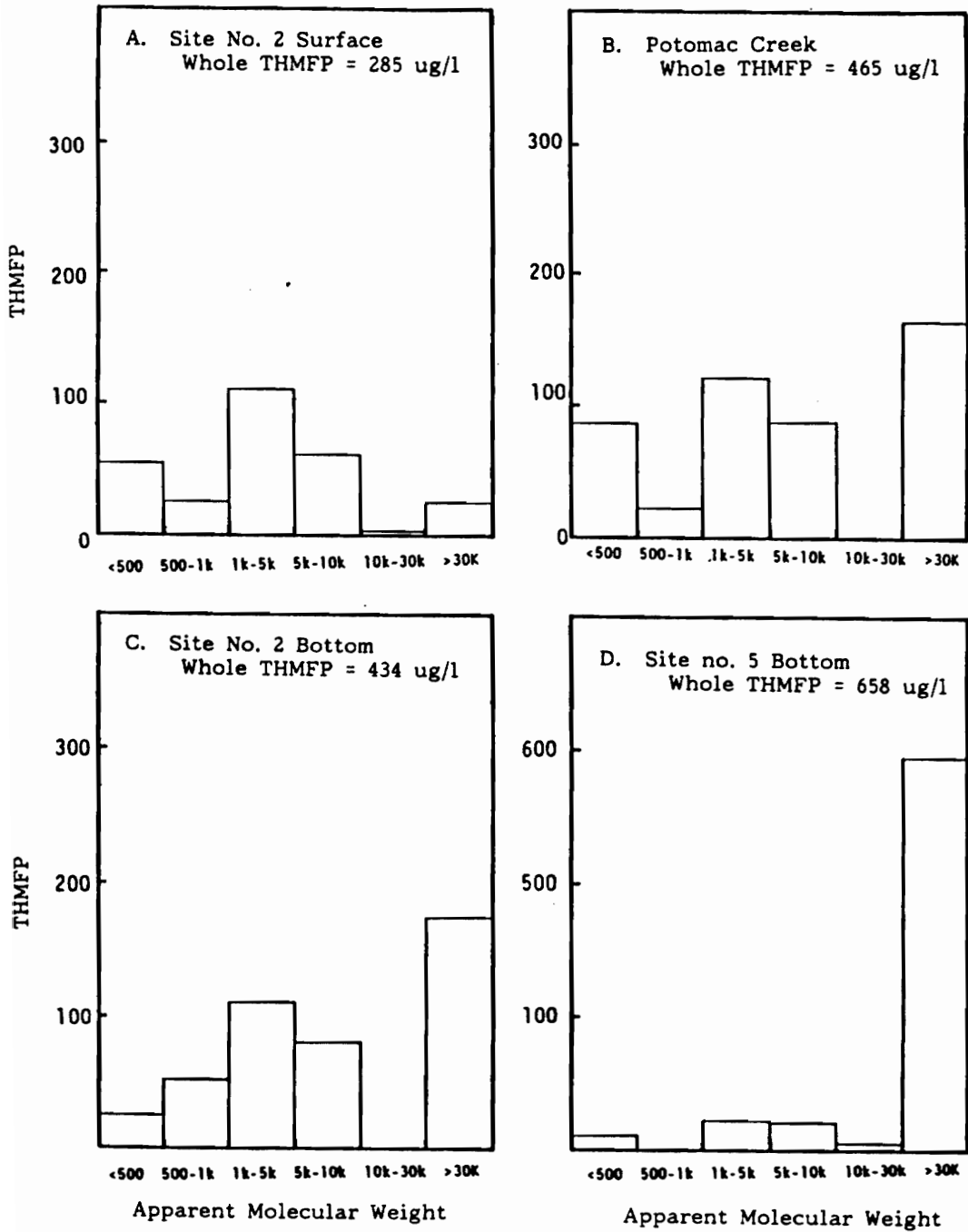


Figure 21 THMFP (ug/l) - Abel Lake Reservoir

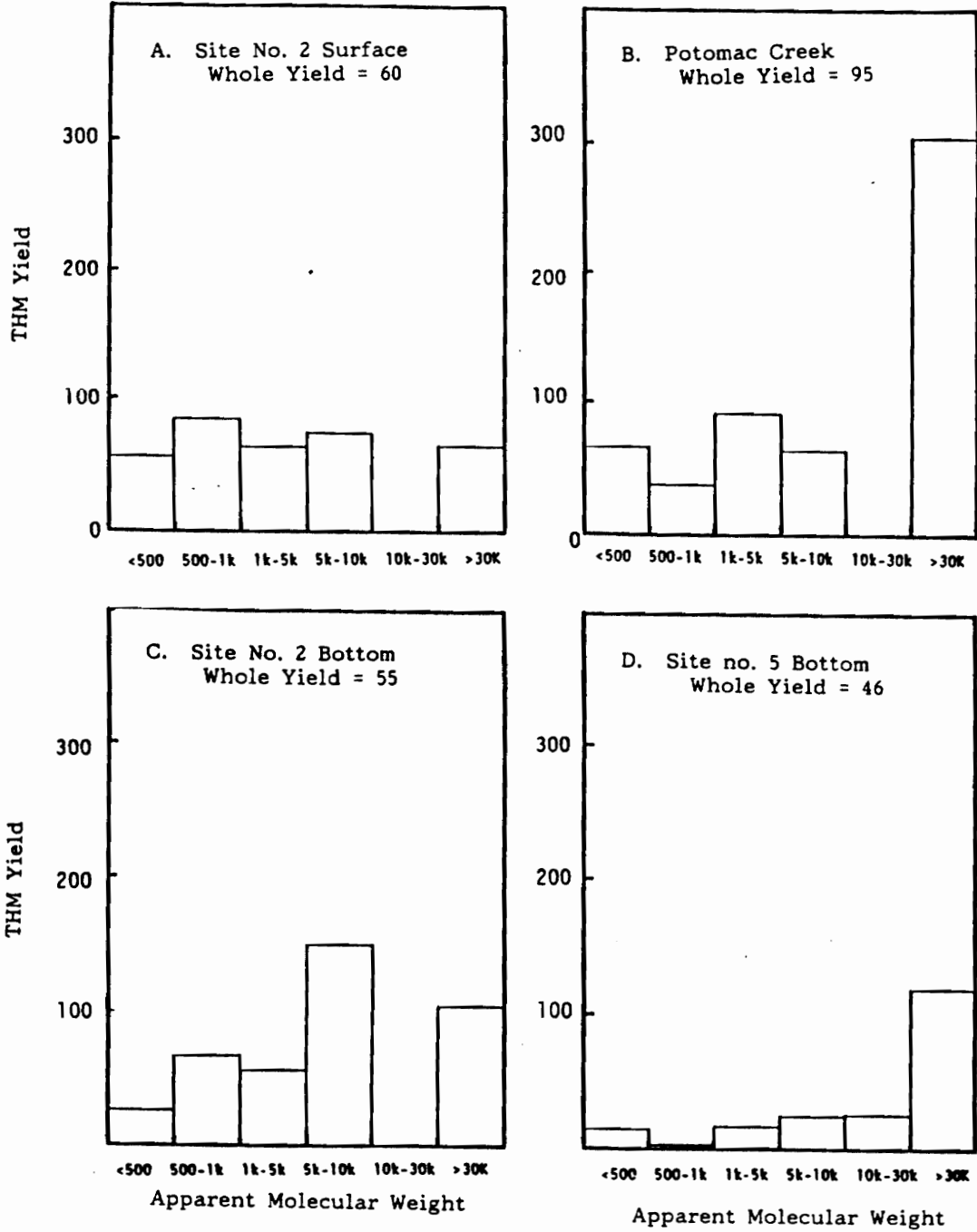


Figure 22 THM Yield Abel Lake Reservoir

It appears that the allocthonous material flowing into the reservoir from the Potomac Creek watershed (primarily forested with hardwoods) could contribute greatly to the THM precursor pool in the surface waters. Organic material of AMW >30K contributes greatly to the THM yield in the creek flow (allocthonous material) and in the degraded bottom waters (degradation products and autochthonous material).

It cannot be known from these data how stratification and circulation affect the organic materials distributions in Abel Lake. It is suspected that during circulation, the lake water would be too turbid to accurately fractionate organic material by the ultrafiltration process. The effects of stratification on the organics distributions may have to be determined by monitoring the distributions throughout the period of stratification. Concentrations and distributions of organic material have been observed to oscillate over short periods of time. In a study of a lake reported by Aiken et al. (15), great fluctuations in the distributions of molecular weight fractions of organics occurred with depth and from one sampling date to the next (a twelve day period). DeHaan (46) found proportional differences between the fulvic acid fractions of lake water samples collected in summer and in winter. In summer, 50 percent of the fulvic acid had an apparent molecular weight exceeding 5000 daltons, whereas in winter, the portion increased to 70 percent. These studies are an indication of the dynamic nature of aquatic humic substances.

CHAPTER V

SUMMARY AND CONCLUSIONS

This study evaluated the water quality of the Abel Lake Reservoir in Stafford County, Virginia. Problems in the water treatment plant including iron, manganese, and THM-precursor removal prompted the study.

The first objective of this study was to develop a data base for the reservoir and with this information to describe the hydrodynamics of the reservoir. The second objective was to characterize and differentiate the lake organic matter according to source (inflow, surface, bottom) in Abel Lake with respect to molecular size distribution and THM formation potential.

Limnological Survey

Abel Lake is a typical temperate-zone lake that stratifies thermally in the summer, and the bottom water quality degrades with the depletion of oxygen by microbial activity. Anoxic conditions in the hypolimnion release manganese, iron, sulfides, phosphorus, and ammonia from the lake sediments creating a highly colored and odorous hypolimnion. With the decreasing temperatures and high winds of autumn, the lake begins to circulate and bring poor quality water to the surface. The more shallow, upper-reaches of the lake circulate

first. The circulation process gradually progresses toward the deeper, downstream areas of the lake. However, the poor-quality water that results from mixing in the shallow head of the reservoir is transported downstream as surface water. Thus, poor-quality water is established in the surface waters of the deep, downstream portions of the lake before these portions have circulated.

This progressive translocation of poor quality water toward the treatment plant intake creates treatment problems that begin in November and can last until the following February. Oxidant demand in the treatment plant is inflated during this period because hypolimnetic materials, particularly ammonia, have been introduced to the surface waters. Manganese removal is difficult throughout this period because it does not oxidize and precipitate readily once it is introduced to the upper strata with the circulation process.

The survey also revealed that algal growth was moderate in 1985 and that lake productivity is phosphorus-limited.

Improvement and protection of the water quality of Abel Lake may require efforts to control both external nutrient loading from the watershed and internal nutrient loading and recycling. The potential for nutrient loading from the Abel Lake watershed needs to be considered in future watershed development strategies. A watershed development strategy should review and include the Best Management Practices that apply to the Abel Lake watershed characteristics.

In order to control internal recycling, treatment plant personnel may want to explore the possibility of utilizing a state-of-the-art

hypolimnetic aeration device near the WTP intake to suppress the release of iron, manganese, and nutrients into the water system.

Finally, a lake management strategy should include a continual lake-water quality monitoring program. A modest program to monitor the major water-quality characteristics at critical locations in the reservoir and the monitoring of inlet stream nutrient loads would provide the data necessary to evaluate long-term trends and predict potential pollution problems in the reservoir. The reservoir monitoring program should include Secchi disc transparency, dissolved oxygen and temperature profiles, total phosphorus, chlorophyll-a, iron and manganese concentrations and should be collected at least twice monthly from May through November and once each month in the winter. Samples should be collected from two depths -- one foot below the surface and two feet above the lake bottom -- at a site near the water treatment plant intake and at least one other location in the reservoir.

Organic Material Distributions

With respect to the organic material molecular-size fractionation and THMFP characterization, the following conclusions can be made:

- Most organic material in the surface waters are <10K AMW. All fractions in the surface water sample contribute nearly uniformly to the THM yield. The THMFP of unfractionated surface water was less than that of the unfractionated bottom and creek samples.

- Most organic material in the creek is <10K AMW. However, the AMW >30K fraction produced the highest THM yield.
- In the bottom waters, the greatest percentage of the TOC was in the >30K AMW fraction. This fraction also produced a high THM yield.
- Allocthonous material entering the reservoir from the forested watershed appears to contribute greatly to the THM yield in the surface waters.
- Organic material in the >30K AMW fraction contributes greatly to THM yield in the creek flow and in the degraded bottom waters of the reservoir.

BIBLIOGRAPHY

1. Carlson, M.A. "Oxidation of Trihalomethane precursors and manganese by chlorine dioxide and permanganate." Unpublished Doctoral dissertation, Virginia Polytechnic Institute and State University, (1988).
2. Carlson, M.A., R.C. Hoehn, T.L. Belinsky, D.W. Bruzzone, D.H. Hair, W.R. Knocke, "An Investigation of Water Quality in Stafford County's Water-Supply Reservoirs and Treatment Procedures at the Abel Lake Water Treatment Plant." Final Report prepared for the Director of Public Utilities, Stafford, VA, 138 pp. (1986).
3. Carlson, M.A., R.C. Hoehn, W.R. Knocke, D.H. Hair, "Experience with the Use of Chlorine Dioxide and Potassium Permanganate as Preoxidants for Trihalomethane and Manganese Control," AWWA Annual Conference Proceedings, pp. 319-346 (1986).
4. Wetzel, R.G., Limnology. W.B. Saunders Company (1975).
5. Cole, G.A., Textbook of Limnology, Third Edition. C.V. Mosby Company, St. Louis, Missouri (1983).
6. Hutchison, G.E., A Treatise on Limnology I. Geography, Physics and Chemistry. John Wiley and Sons, Inc., New York (1957).
7. Rebhun, M., D. Ronen, and J. Eren, "Monitoring and study program of an interregional wastewater reclamation system for agriculture." Journal WPCF 59(5):242 (1987).
8. Lind, O. T., Handbook of Common Methods in Limnology, Second Edition. C.V. Mosby Company, St. Louis, Missouri (1979).
9. Standard Methods for the Examination of Water and Wastewater, Sixteenth Edition. American Public Health Association, Washington, D.C. (1985).
10. Sawyer, C.N. and P.L. McCarty, Chemistry for Environmental Engineers, 3rd Edition. McGraw-Hill, Inc. (1978).
11. The Lake and Reservoir Restoration and Guidance Manual, First Edition. United States Environmental Protection Agency (February 1988).
12. Stewart, A.J. and R.G. Wetzel, "Dissolved Humic Materials: Photodegradation, sediment effects, and reactivity with phosphate and calcium carbonate precipitation." Arch. Hydrobiol., 92(3): 265-286 (1981).

13. Phosphorus: A Summary of Information Regarding Lake Water Quality. Illinois Environmental Protection Agency, Springfield, Illinois (August 1986).
14. Thurman, E.M., Organic Geochemistry of Natural Waters. Nijhoff and Junk Publishers (1985).
15. Aiken, G.R., D.M. McKnight, R.L. Wershaw and P. McCarthy, Humic Substances in Soil, Sediment, and Water. Geochemistry, Isolation, and Characterization. Wiley and Sons, New York (1985).
16. Seki, H., Organic Materials in Aquatic Ecosystems. CRC Press, Inc., Boca Raton, Florida (1982).
17. Rook, J.J. "Formation of haloforms during chlorination of Natural Waters." Water Treatment and Examination, Vol. 22-3:234 (1974).
18. Ogura, N., "Molecular weight fractionation of dissolved organic matter in coastal seawater by ultrafiltration." Marine Biology, 24:305-312 (1974).
19. Allen, H.L., "Experimental studies of dissolved organic matter in a soft-water lake." Aquatic Microbial Communities. Garland Publishing, Inc., New York and London (1977).
20. Macko, C., W.J. Maier, S.J. Eisenreich, and M.R. Hoffman, "Ultrafiltration characterization of Aquatic Organisms." AI Che Symposium Series, No. 190, 75:162 (1979).
21. Oliver, B.G. and J. Lawrence, "Haloforms in drinking water: A study of precursors and precursor removal." JAWWA 71(3): 161 (1979).
22. Schnoor, J.L., J.L. Nitschke, R.D. Lucas, and J.N. Veenstra, "Trihalomethane yields as a function of precursor molecular weight." Environ. Sci. Technol. 13(9): 1134 (1979).
23. Chrost, R.J., and M.A. Faust, "Molecular weight fractionation of dissolved organic matter (DOM) released by phytoplankton." Acta Microbiologica Polonica 29(2): 79-88 (1980).
24. Hama, T., and N. Handa, "Molecular weight distribution and characterization of dissolved organic matter from lake waters." Arch. Hydrobiol. 90(1): 106-120 (1980).

25. Hoehn, R.C., D.B. Barnes, B.C. Thompson, C.W. Randall, T.J. Grizzard, and P.T.B. Shaffer, "Algae as sources of trihalomethane precursors." JAWWA 72(6):344 (1980).
26. Oliver, B.G., and S.A. Visser, "Chloroform production from the chlorination of aquatic humic material: The effect of molecular weight, environment, and season." Water Research 14:1137 (1980).
27. Veenstra, J.N. and J.L. Schnoor, "Seasonal variations in trihalomethane levels in an Iowa river water supply." JAWWA 72(10): 583 (1980).
28. Joyce, W.S., F. DiGiano, and P.C. Uden, "THM precursors in the environment." JAWWA 76(6):102 (1984).
29. Ward, A.K., and R.G. Wetzel, "Molecular weight fractionation of dissolved organic nitrogen and carbon compounds from two lakes of differing trophic status." Arch. Hydrobiol. 101(4): 481-488 (1984).
30. Wachter, J.K., and J.B. Andelman, "Organohalide formation on chlorination of algal extracellular products." Envir. Sci. Technol. 18(11):811 (1984).
31. Collins, M.R., G.L. Amy, Members, ASCE, and Paul H. King, ASCE, "Removal of organic matter in water treatment." Journal of Environmental Engineering, 111(6): 850 (1985).
32. DeHaan, H., and T. DeBoer, "Geochemical aspects of aqueous iron, phosphorus, and dissolved organic carbon in the humic Lake Tjeukemeer, The Netherlands." Freshwater Biology, 16:661-672 (1986).
33. Reinhard, M., "Molecular weight distribution of dissolved organic carbon and dissolved organic halogen in advanced treated wastewaters." Environ. Sci. Technol. 18(6): 410 (1984).
34. Malcom, R.L., and P. MacCarthy, "Limitations in the use of commercial humic acids in water and soil research." Environ. Sci. Technol. 20(9): 904 (1986).
35. Buffle, J., P. Deladoey, and W. Haerdi, "The use of ultrafiltration for the separation and fractionation of organic ligands in freshwaters." Analytica Chimica Acta 101:339-357 (1978).
36. Amy, G.L., M.R. Collins, C.J. Kuo, and P.H. King, "Comparing gel permeation chromatography and ultrafiltration for the molecular weight characterization of aquatic organic matter." JAWWA 79(1): 43-(1987).

37. Bellar, T., J. Lichtenberg, and R. Kroner, "The occurrence of organohalides in chlorinated drinking waters." JAWWA 66(12): 703 (1974).
38. Trussel, R.R., and M.D. Umphres, "The formation of trihalomethanes." JAWWA 70(11): 604 (1978).
39. United States Environmental Protection Agency, "National interim primary drinking water regulations: Control of trihalomethanes in drinking water, final rule." Federal Register 40 CFR, 44(231): 68624-707 (1979).
40. Rook, J.J., "Haloforms in drinking water." JAWWA 68(3):168 (1976).
41. Johnson, J.D., and J.N. Jensen, "THM and TOX formation: routes, rates, and precursors." JAWWA 78(4):156 (1986).
42. Shorten, C., "Algal and bacterial interactions in producing precursors of trihalomethanes and other halogenated organics." Unpublished Master's degree thesis, Virginia Polytechnic Institute and State University (1983).
43. Hoehn, R.C., K.L. Dixon, J.K. Malone, J.T. Novak, and C.W. Randall, "Biologically induced variations in the nature and removability of THM precursors by alum treatment." JAWWA 76(4):134 (1984).
44. Hoehn, R.C., C.W. Randall, F.A. Bell, P.T.B. Shaffer, "Trihalomethanes and viruses in a water supply." Journal Environ. Eng. Division, 103:803-814 (1977).
45. Randke, S.J., F. deNoyelles, Jr., J.E. Denne, L.R. Hathaway, R.E. Miller, A.S. Melia, and C.E. Burkehead, "Source control of THM precursors." AWWA Annual Conference Proceedings Part 2, p. 1545 (1987).
46. DeHaan, H. "Molecule-size distribution of soluble humic compounds from different natural water." Freshwater Biol. 2, 235-241 (1972).

APPENDIX A. Additional Oxygen and Temperature Profiles
of Abel Lake at Stations 1-5, Summer 1985.

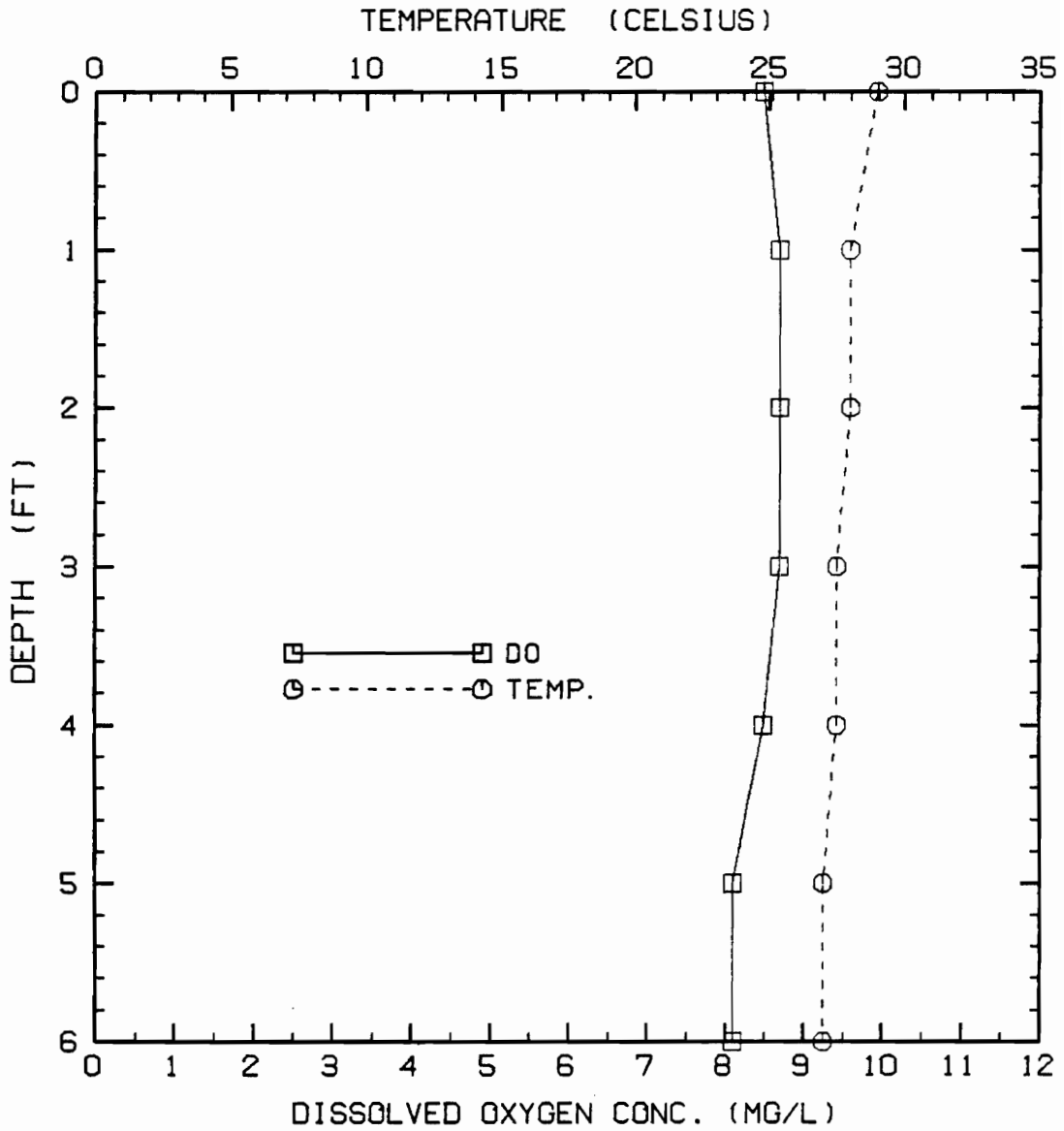


Figure A1 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 1, July 9, 1985

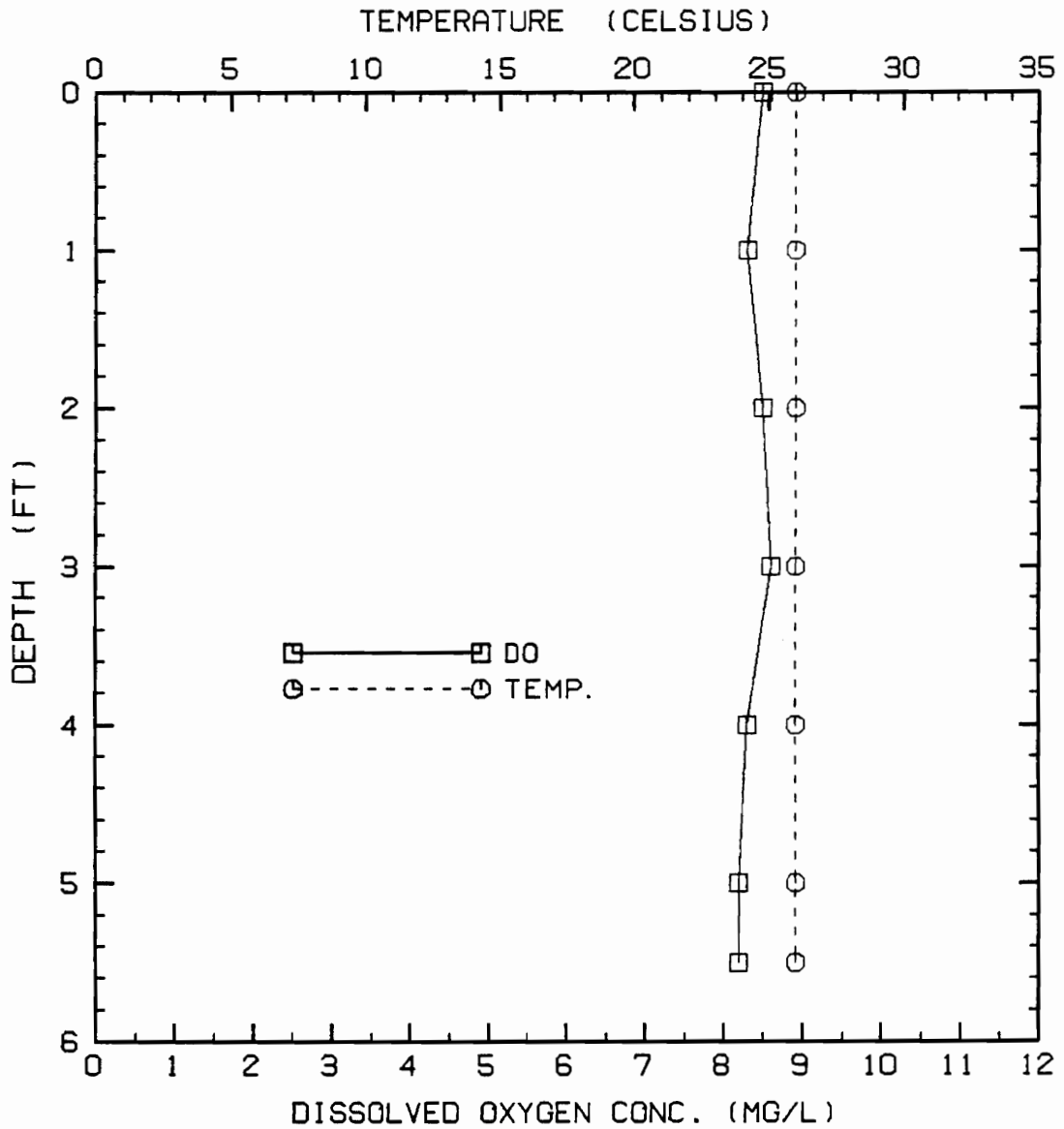


Figure A2 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 1, August 20, 1985

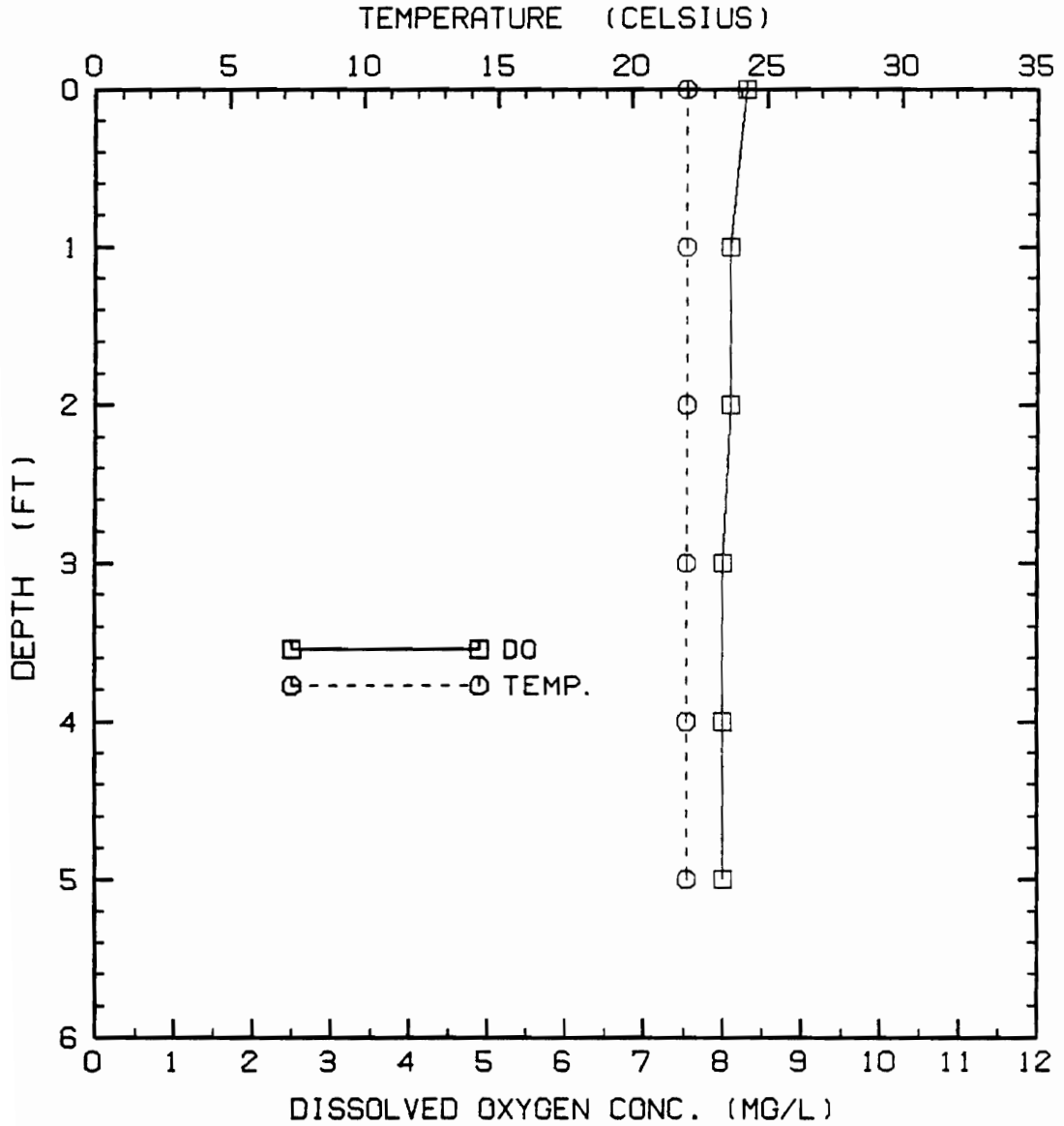


Figure A3 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 1, September 18, 1985

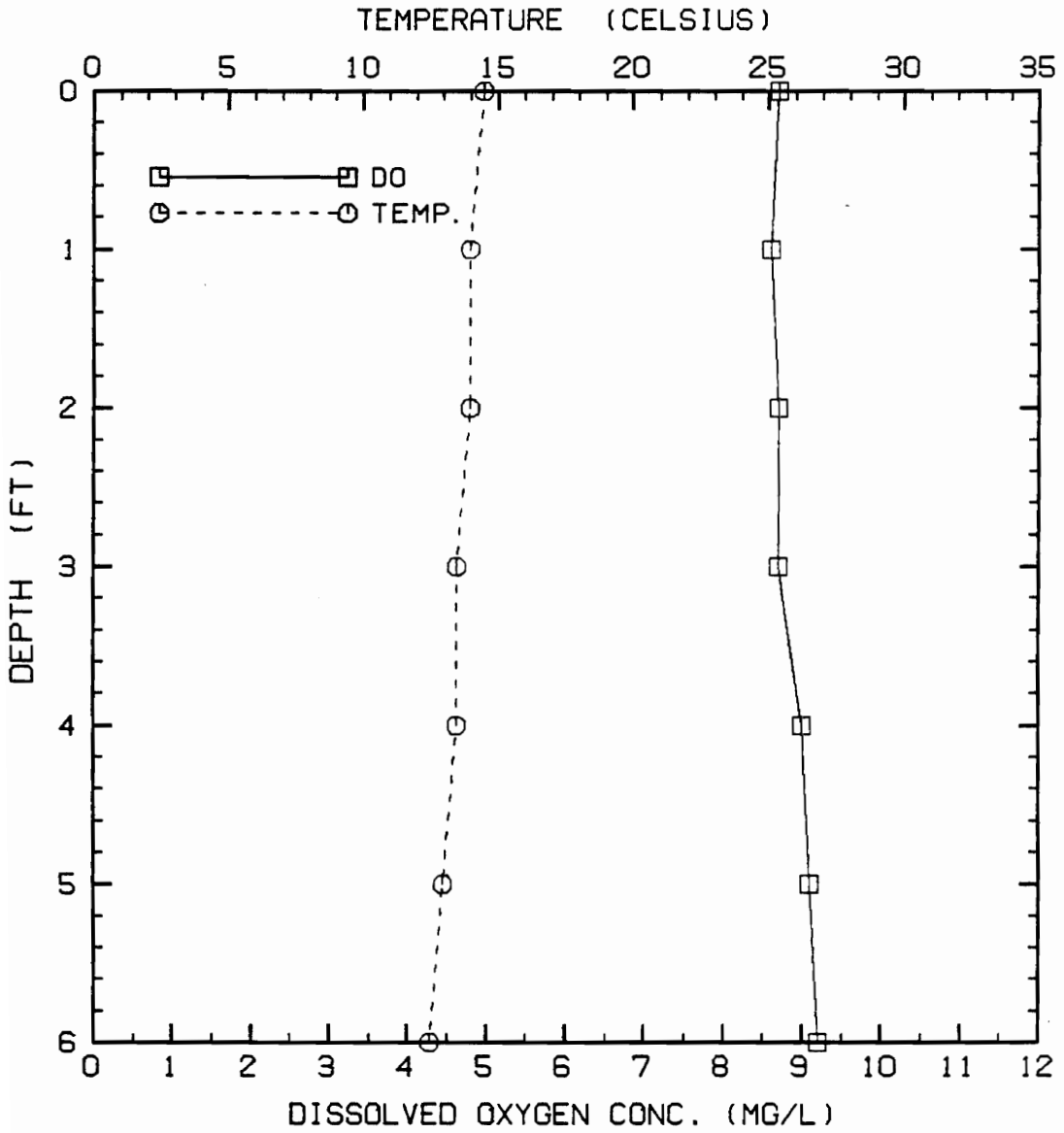


Figure A4 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 1, November 7, 1985

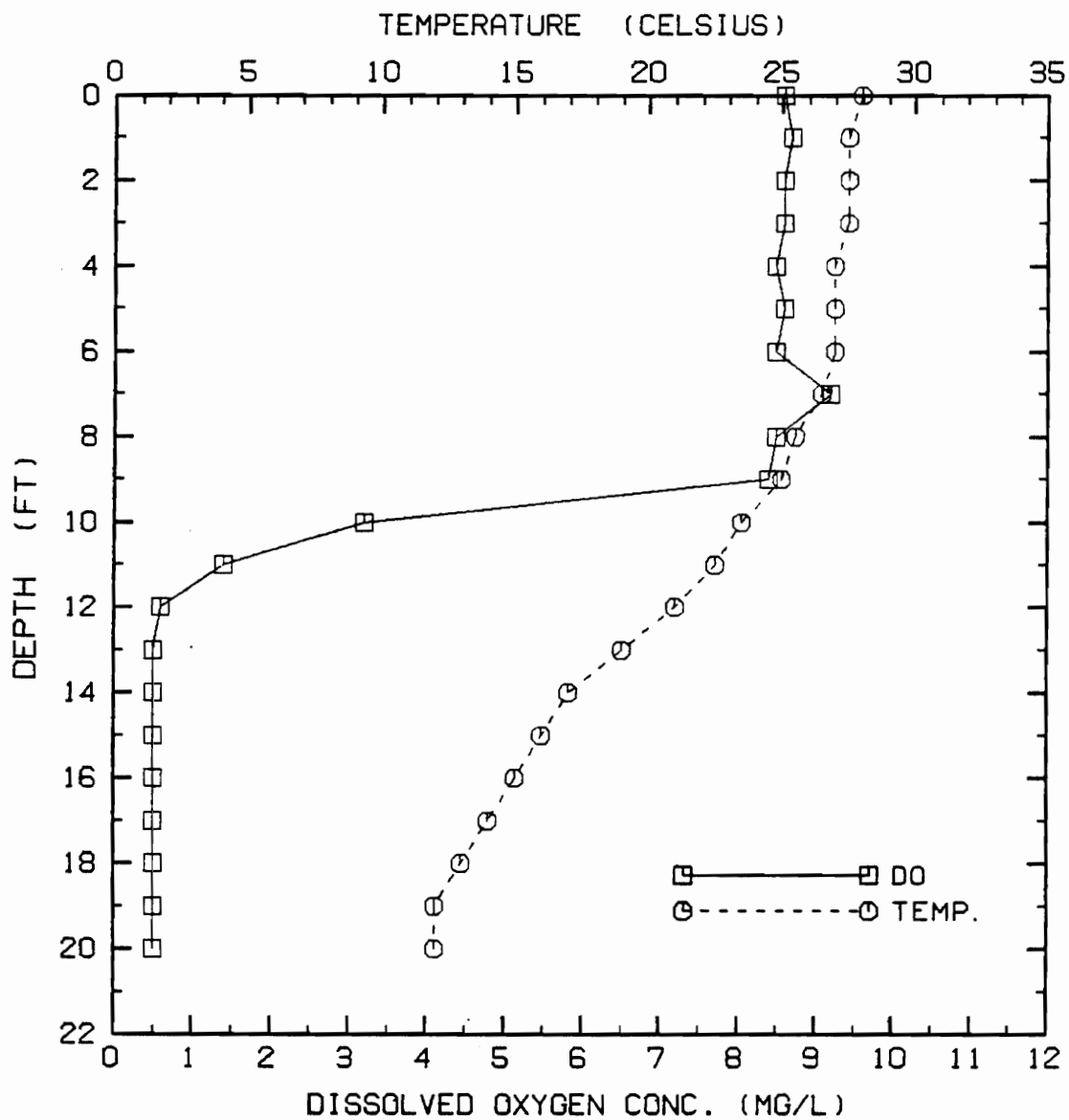


Figure A5 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 2, July 9, 1985

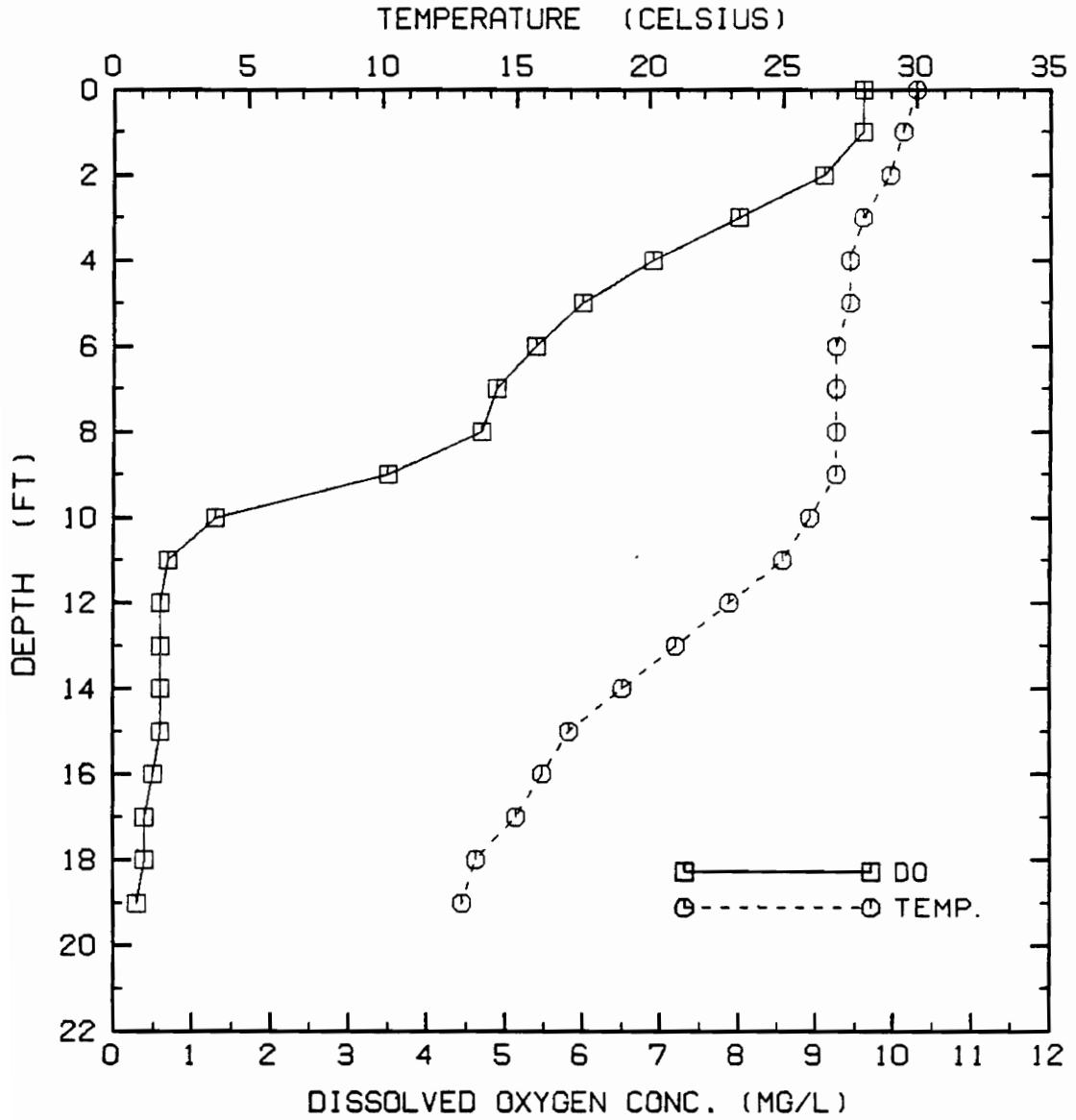


Figure A6 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 2, July 30, 1985

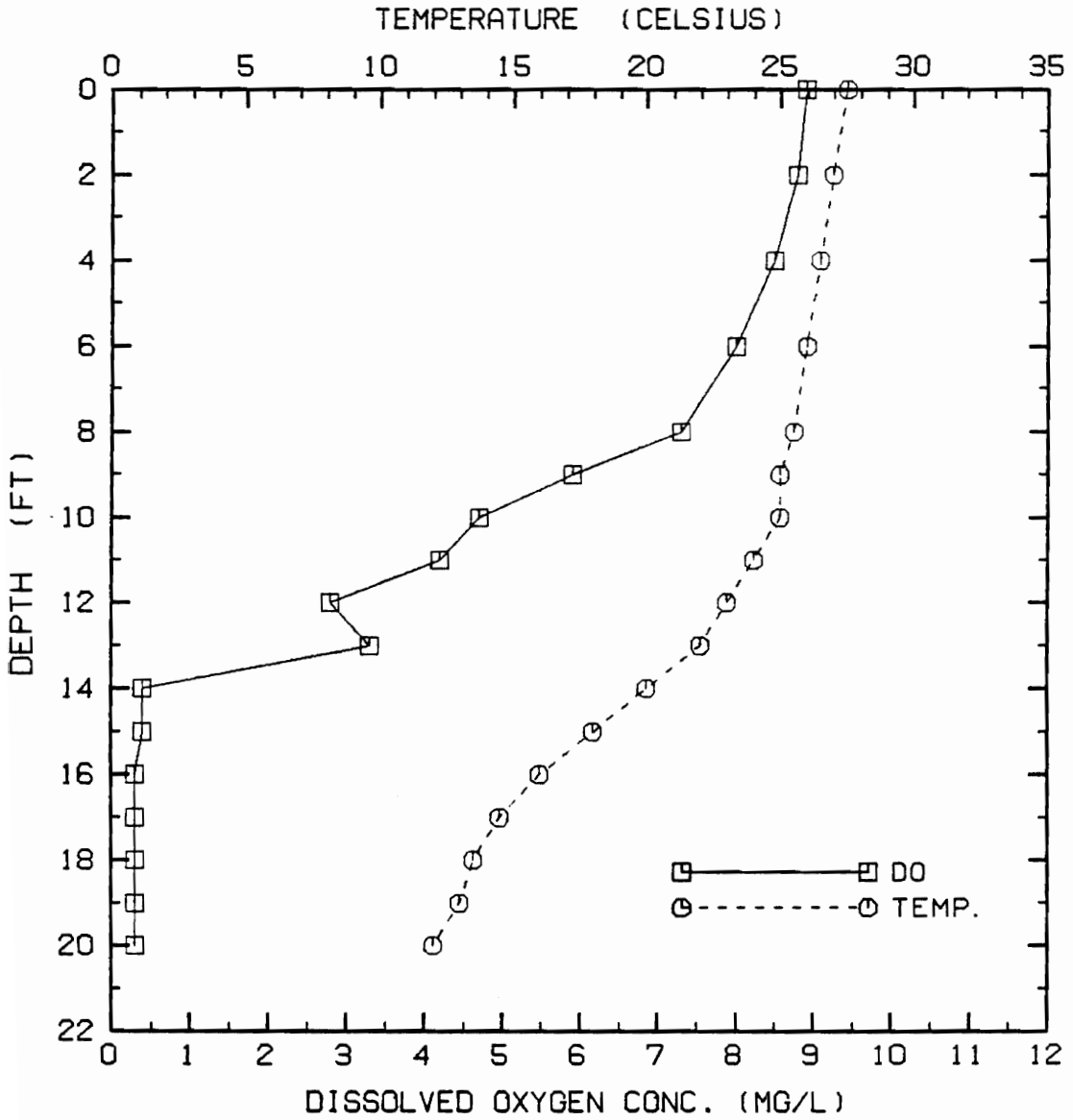


Figure A7 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 2, August 20, 1985

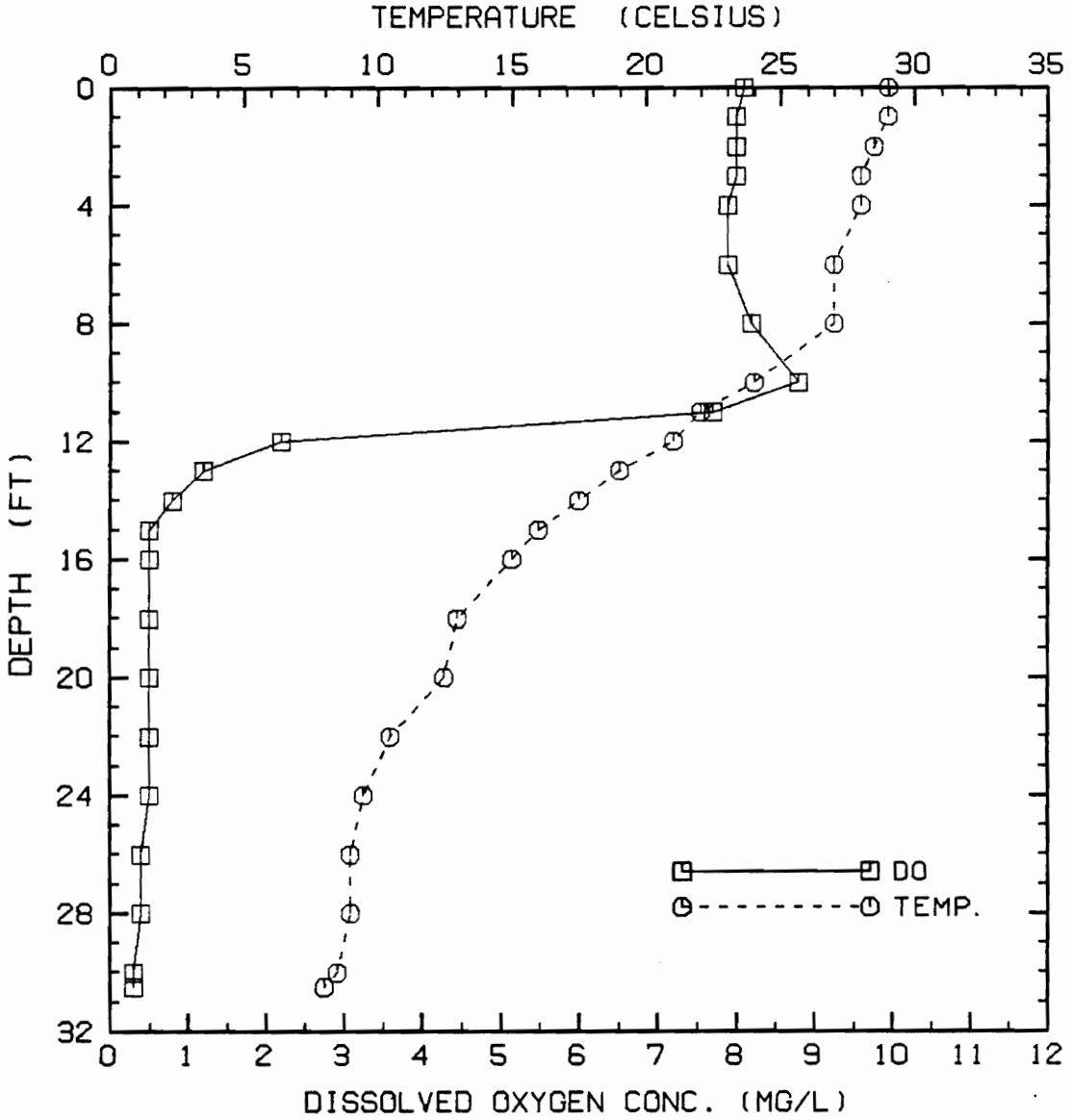


Figure A8 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 3, July 9, 1985

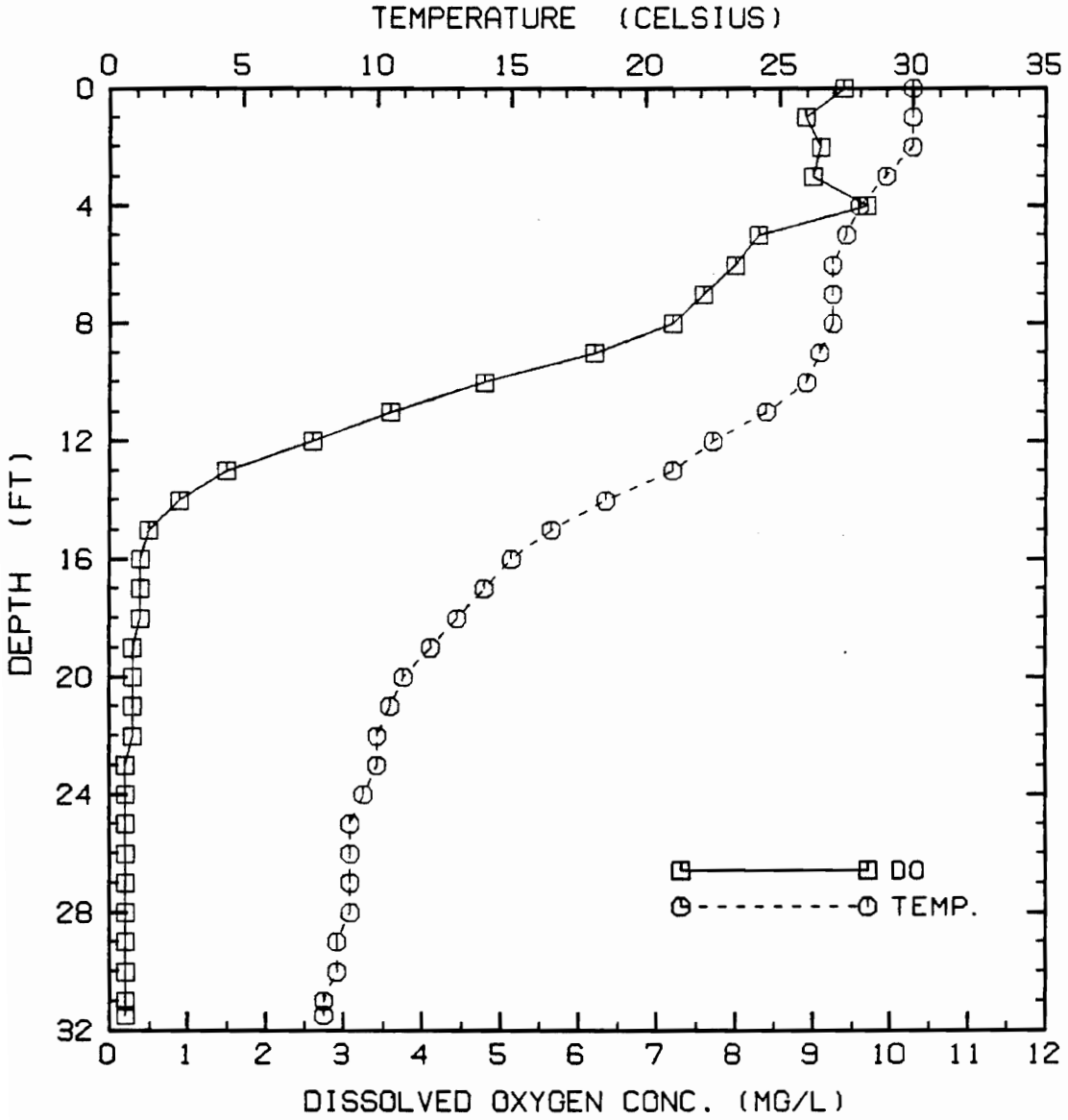


Figure A9 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 3, July 30, 1985

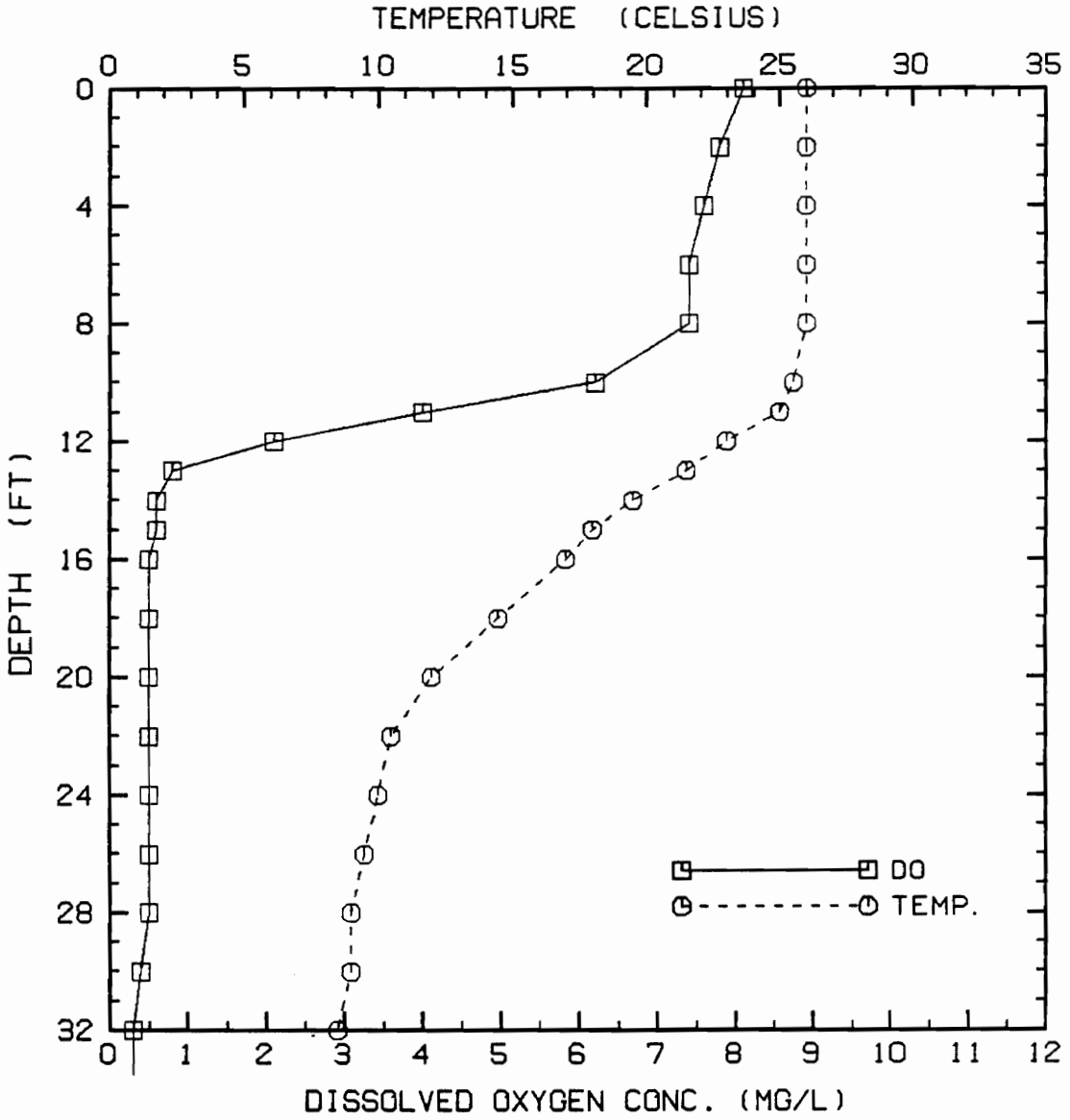


Figure A10 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 3, August 20, 1985

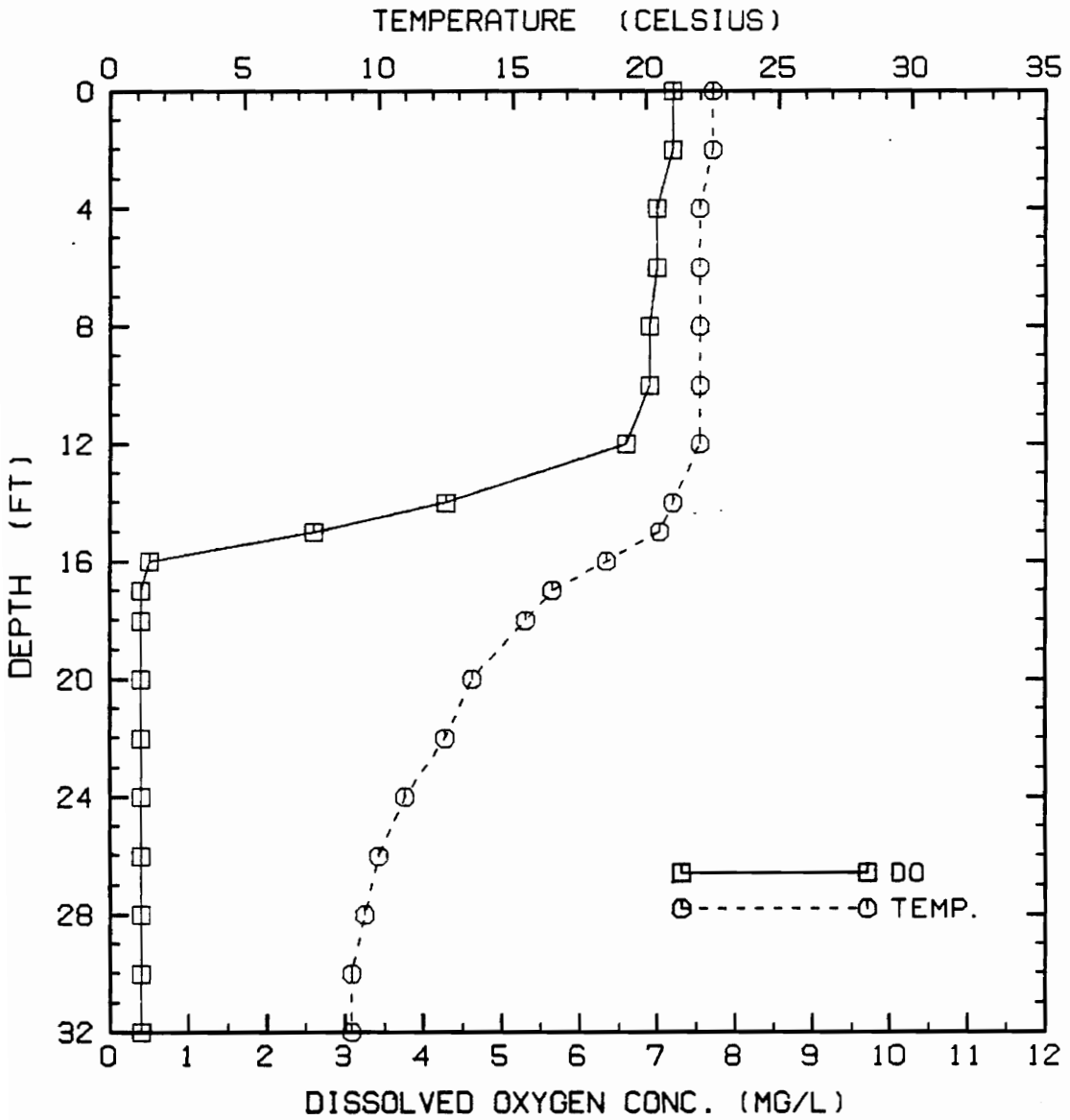


Figure A11 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 3, September 18, 1985

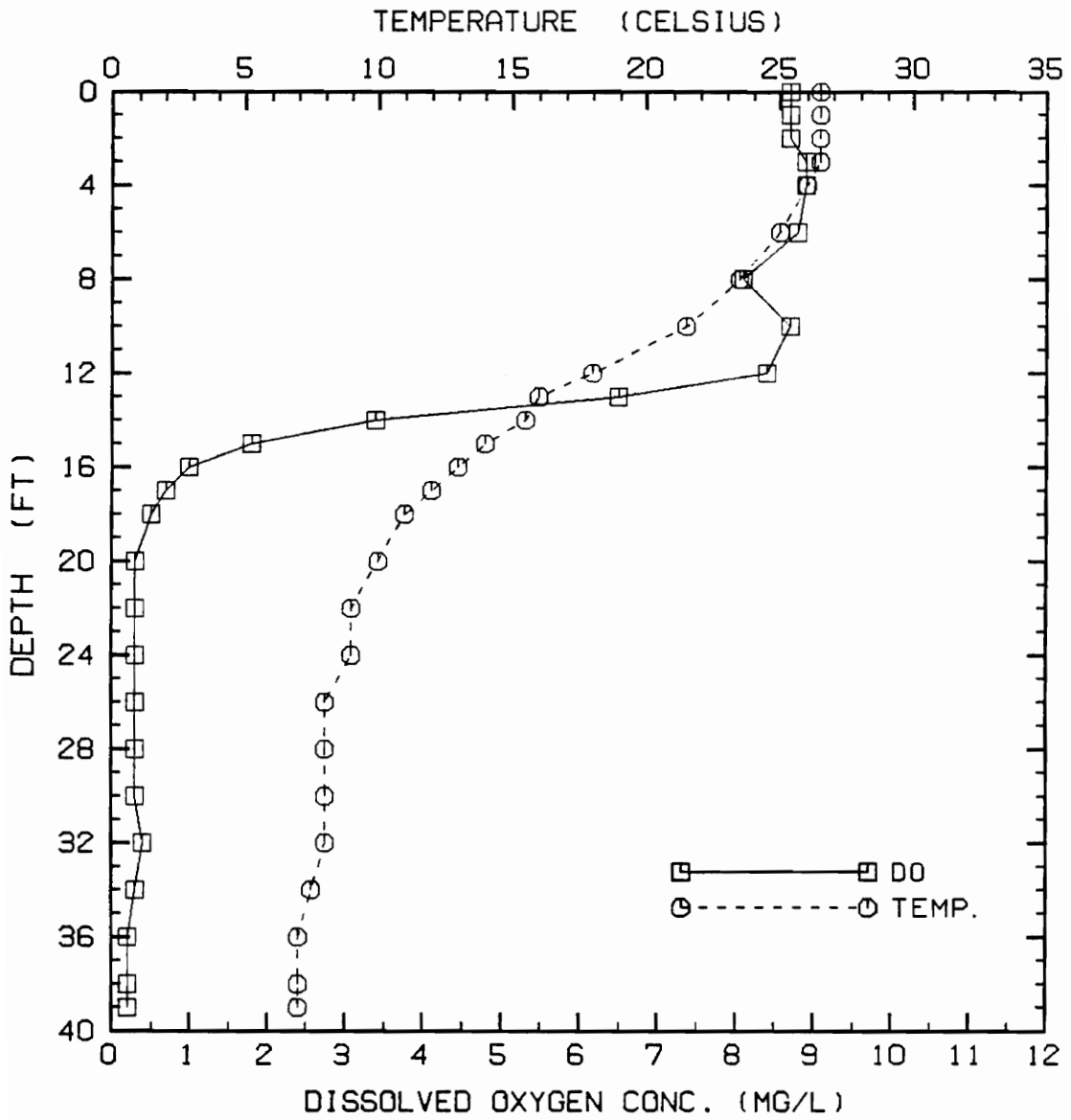


Figure A12 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 4, June 19, 1985

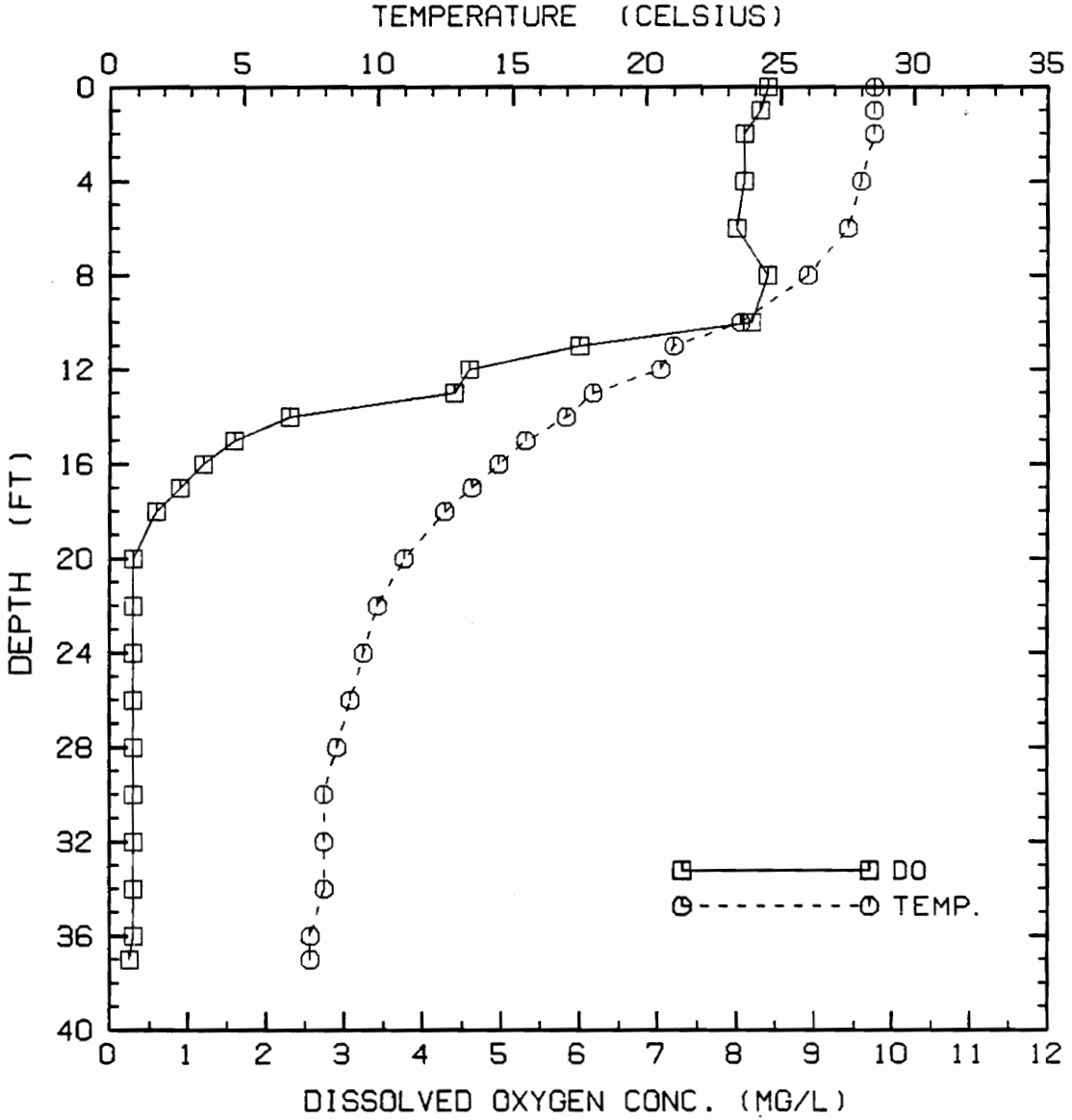


Figure A13 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 4, July 9, 1985

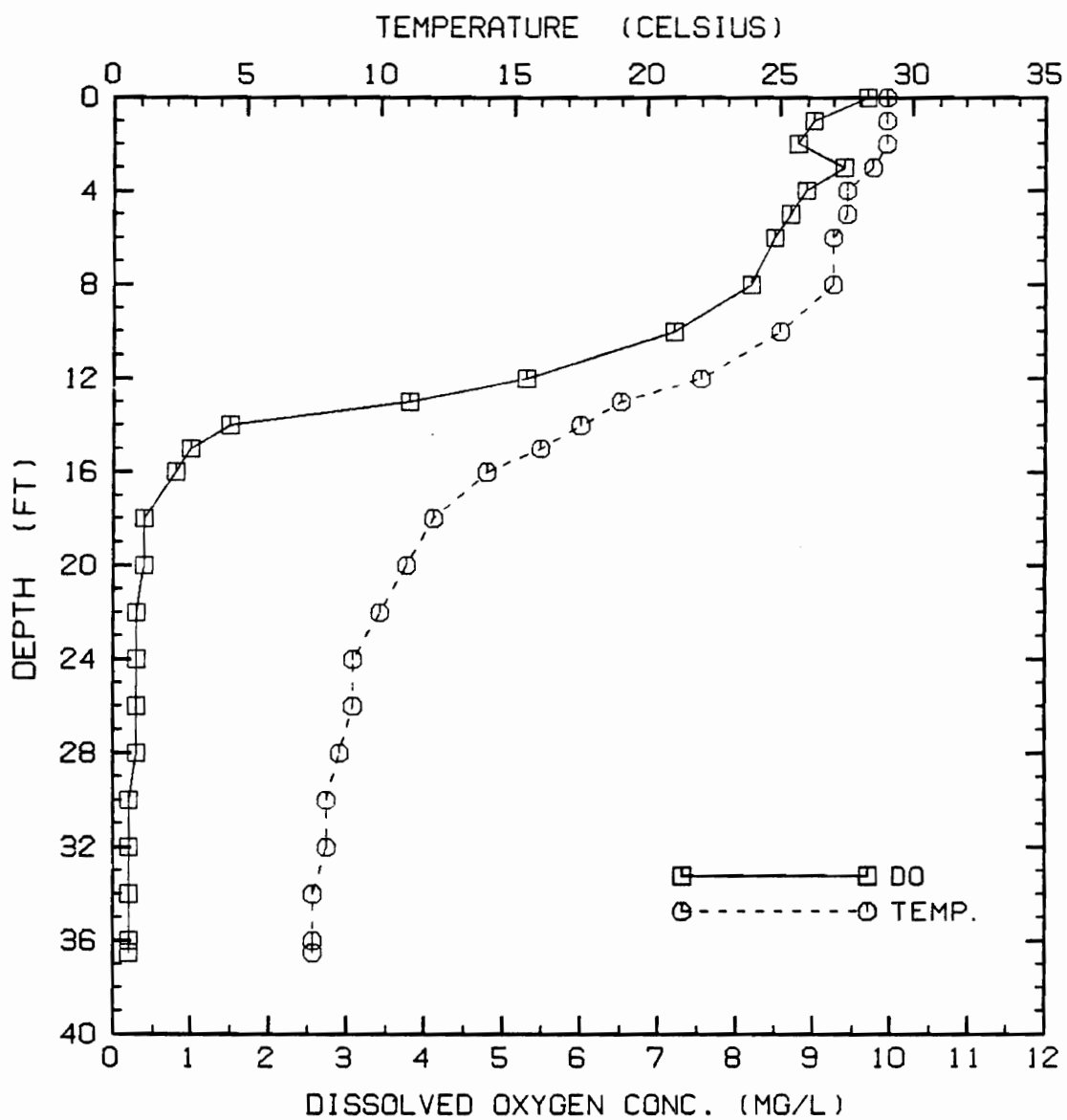


Figure A14 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 4, July 30, 1985

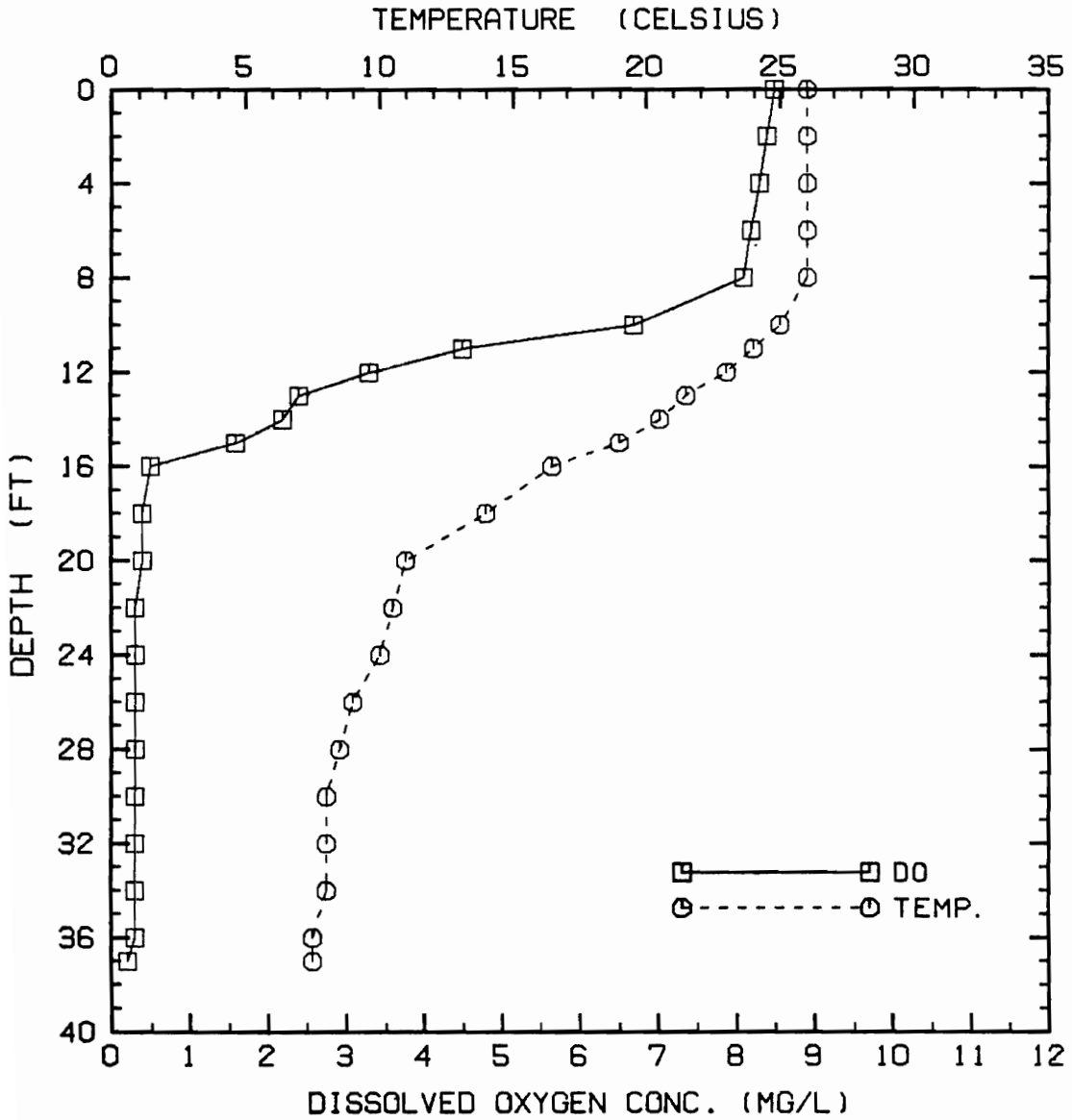


Figure A 15 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 4, August 20, 1985

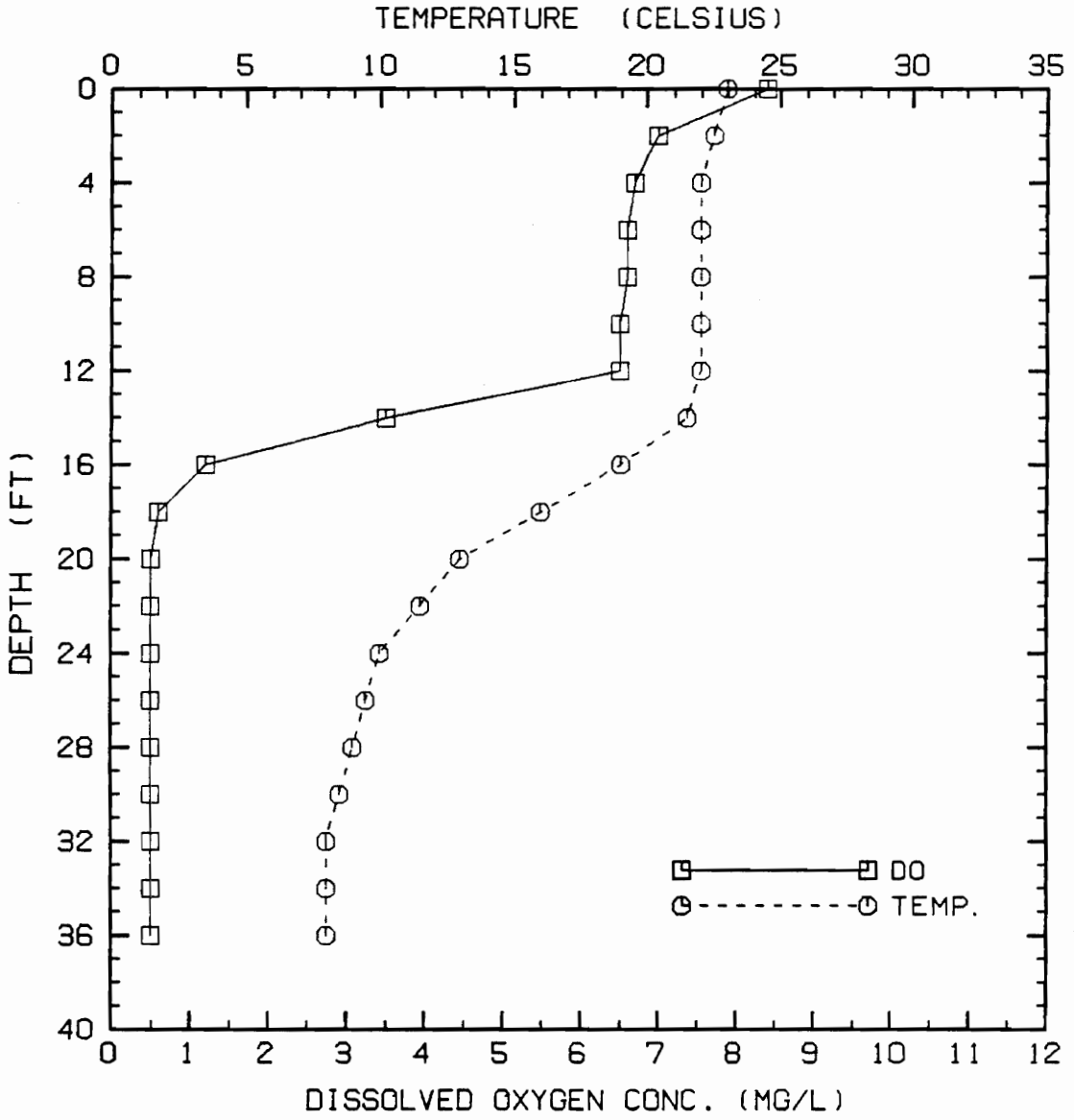


Figure A 16 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 4, September 18, 1985

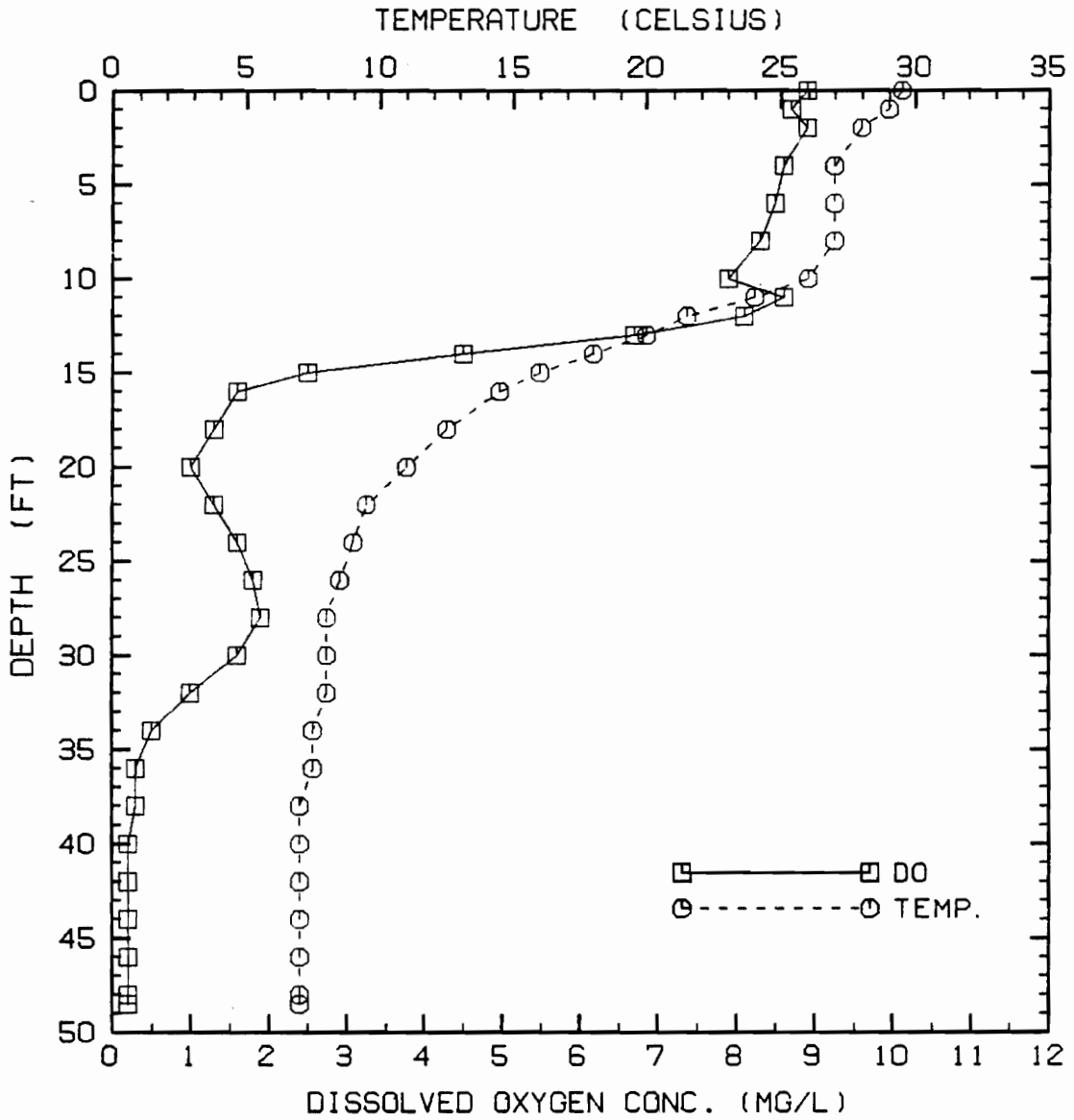


Figure A17 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 5, July 30, 1985

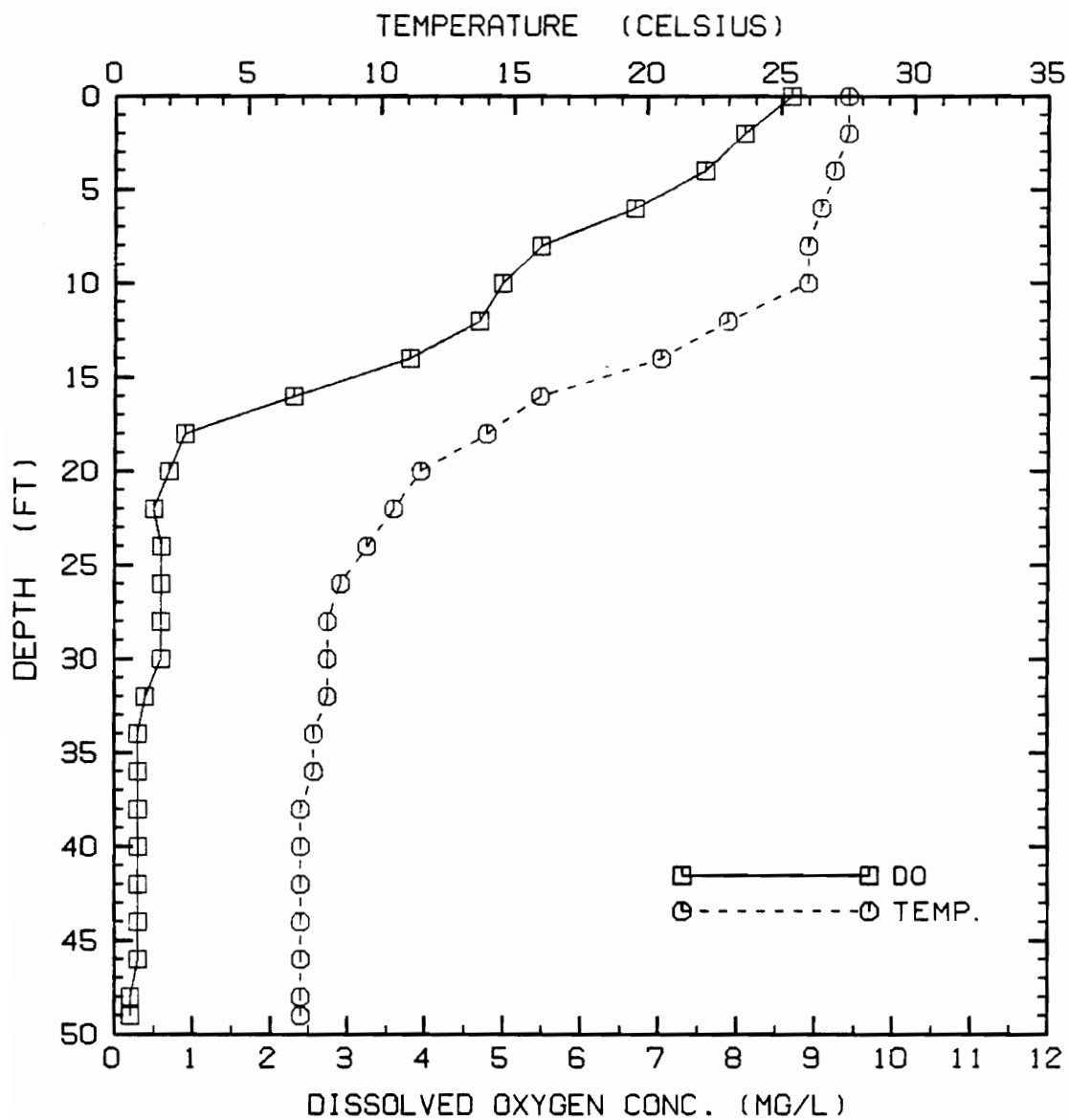


Figure A18 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 5, August 20, 1985

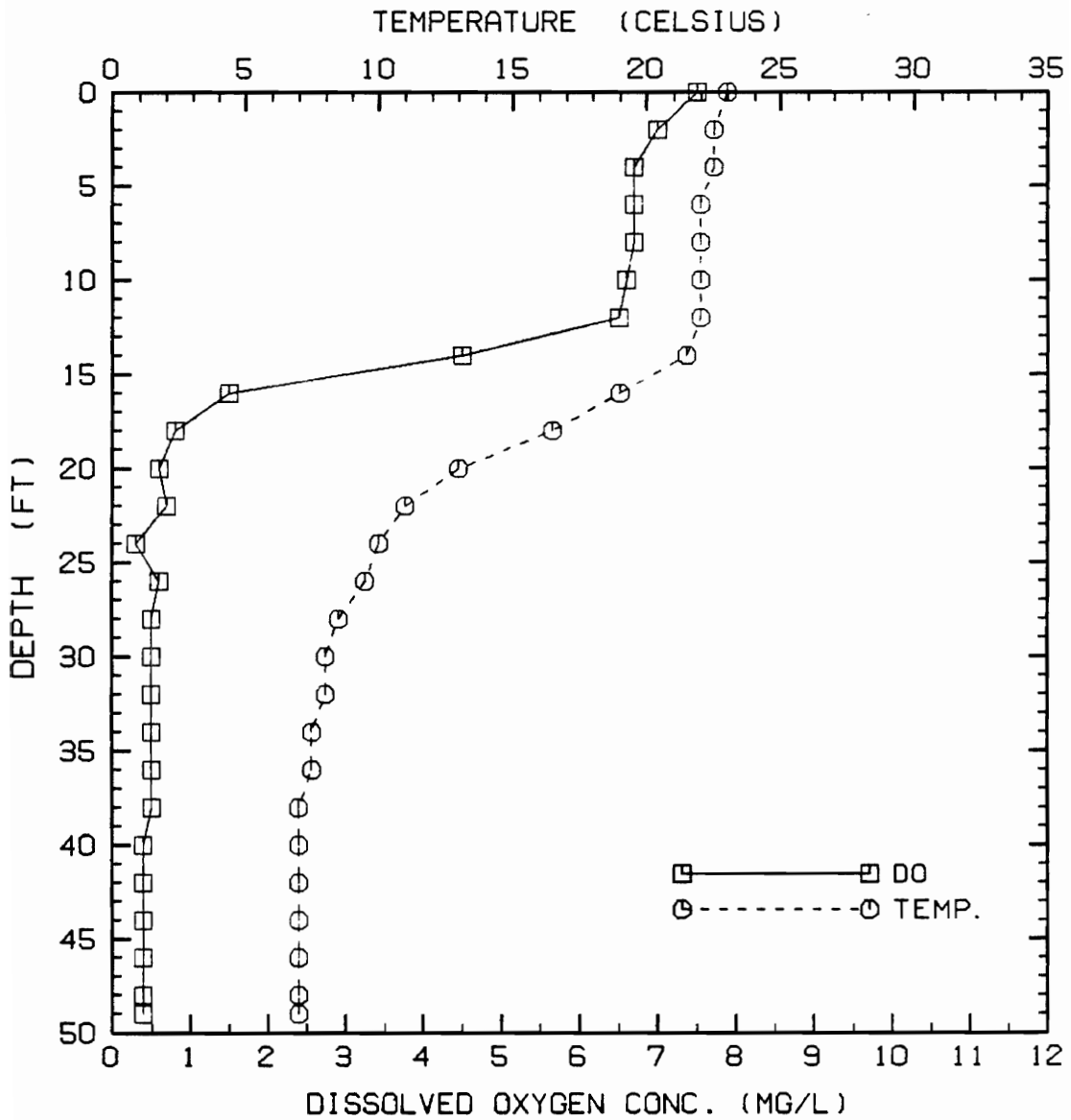


Figure A19 Dissolved Oxygen and Temperature Profile
Abel Lake Sta. 5, September 18, 1985

APPENDIX B Additional Water Quality Characteristics of
Abel Lake Stations 1-5, 1985, Graphs

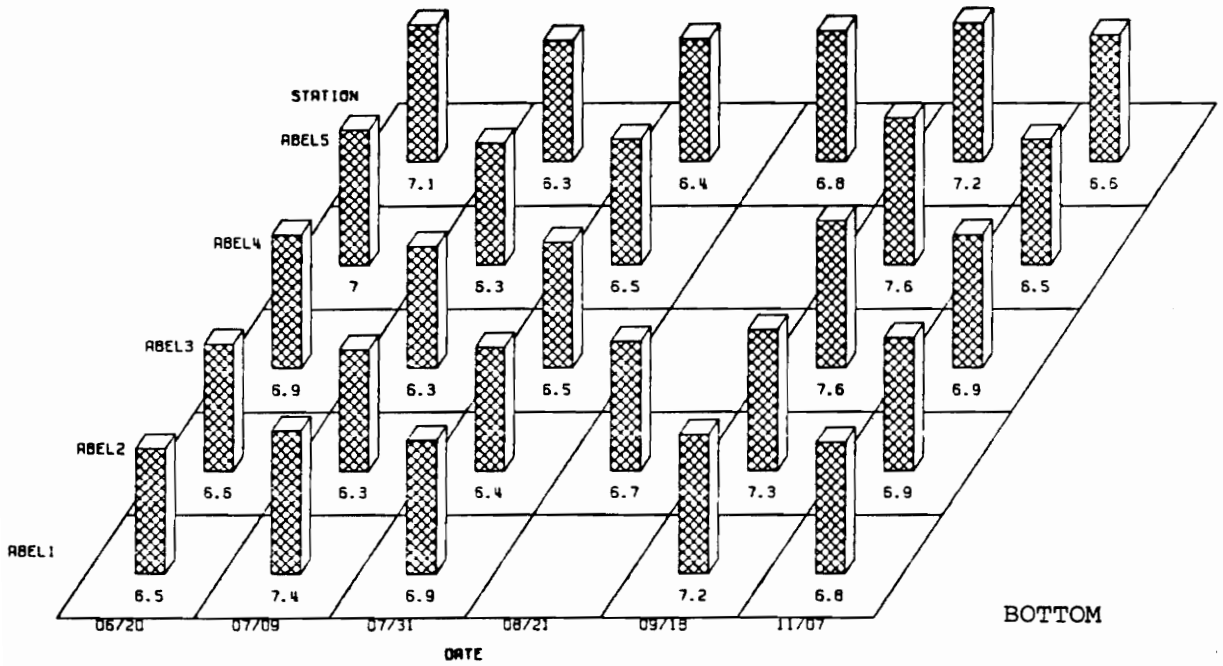
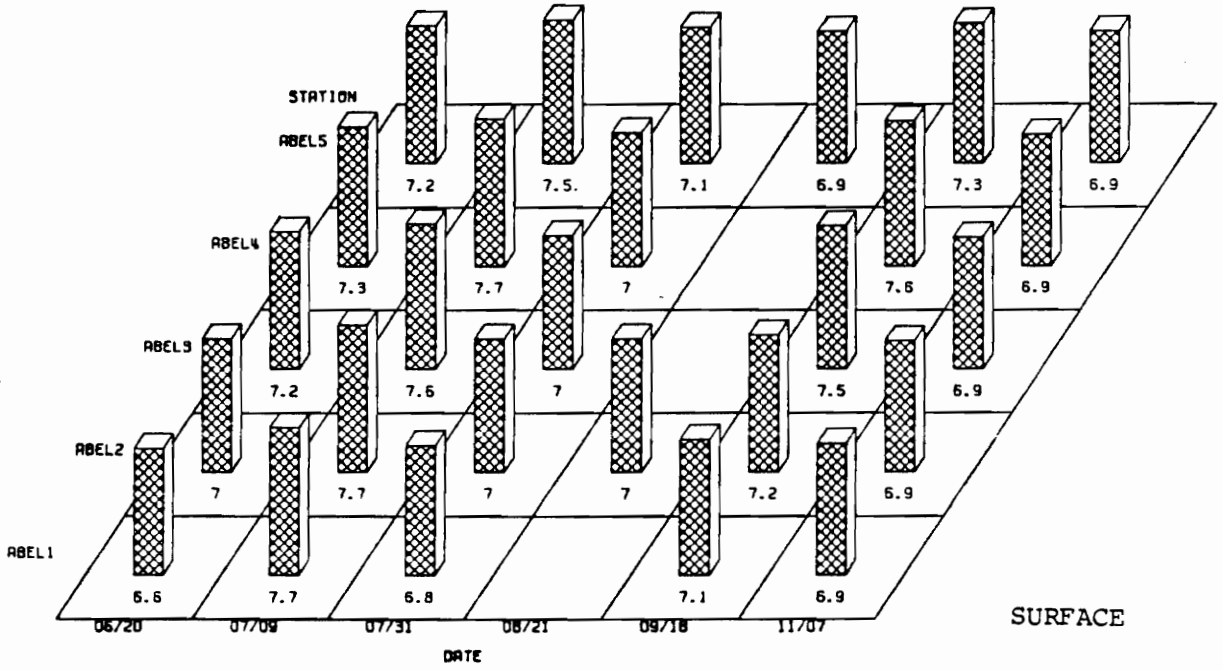


Figure B1 Variations in Abel Lake pH on six Sampling Dates at Five Stations

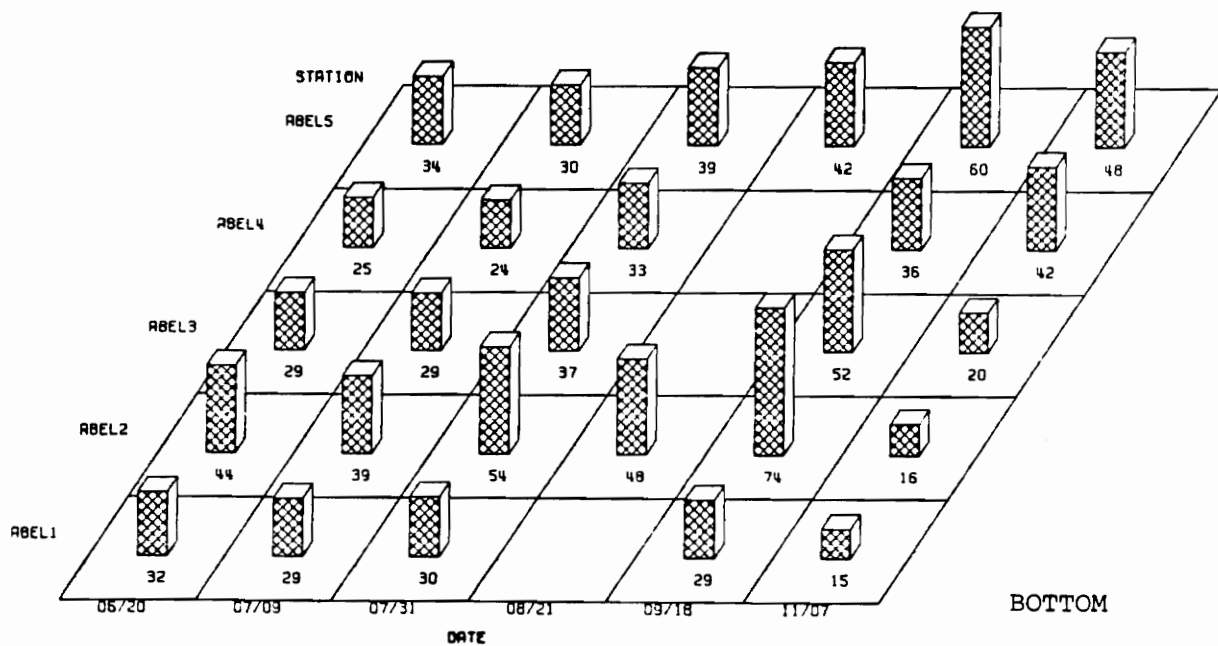
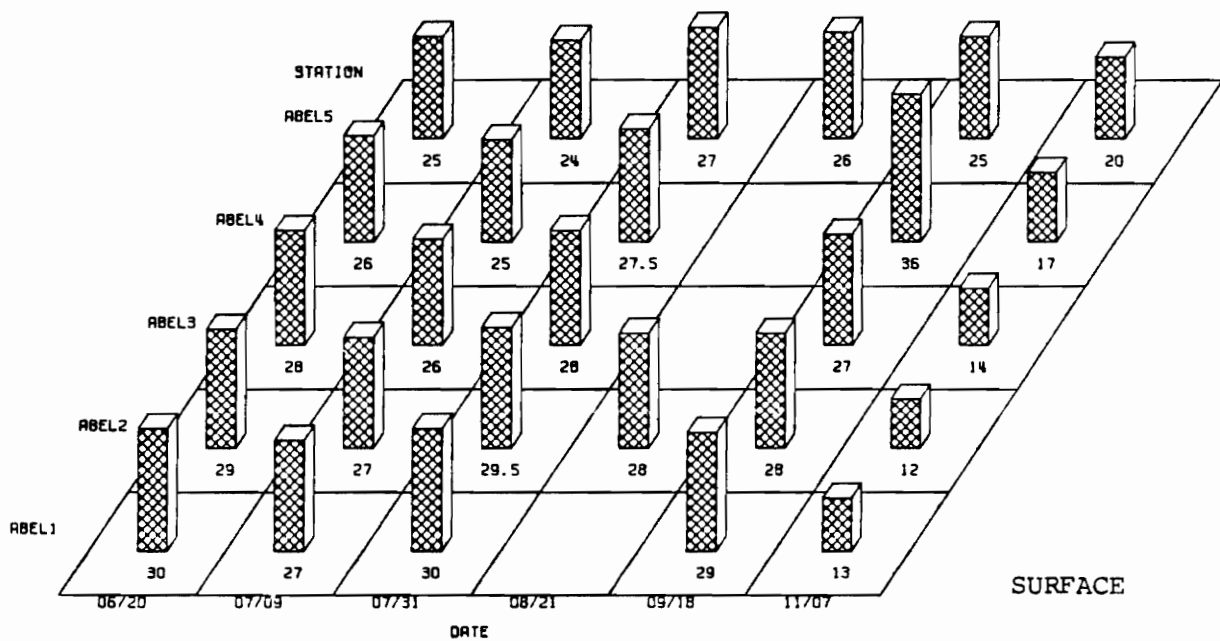


Figure B2 Variations in Abel Lake Alkalinity (mg/L as CaCl₃) on Six Sampling Dates at Five Stations

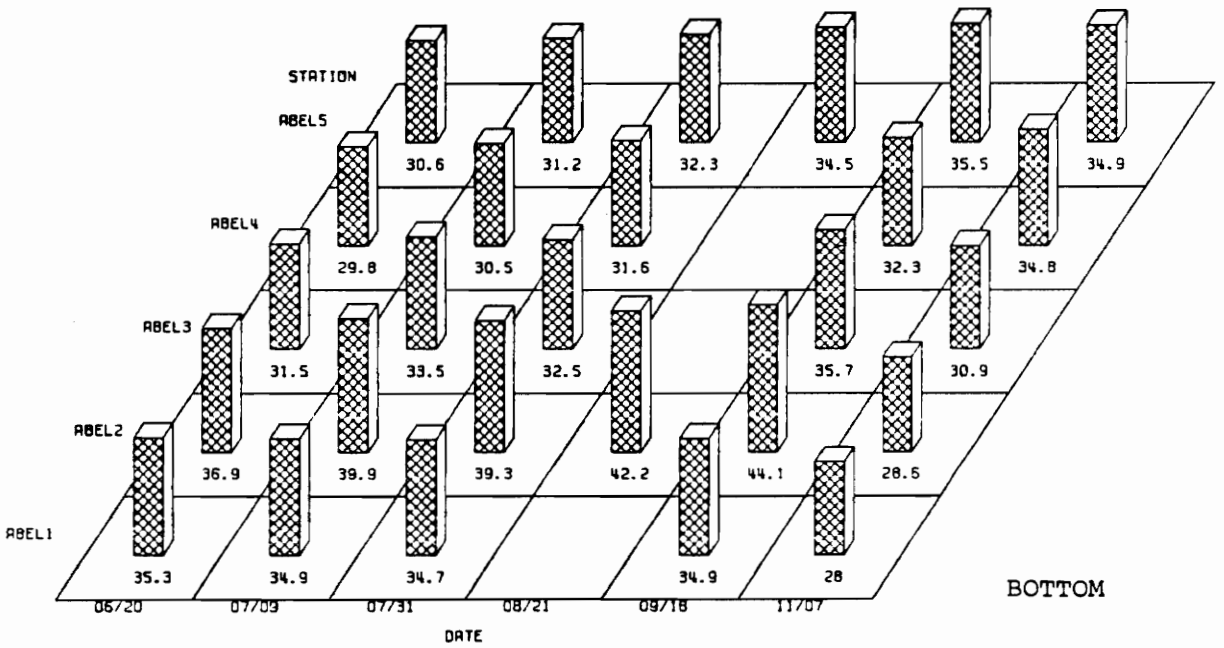
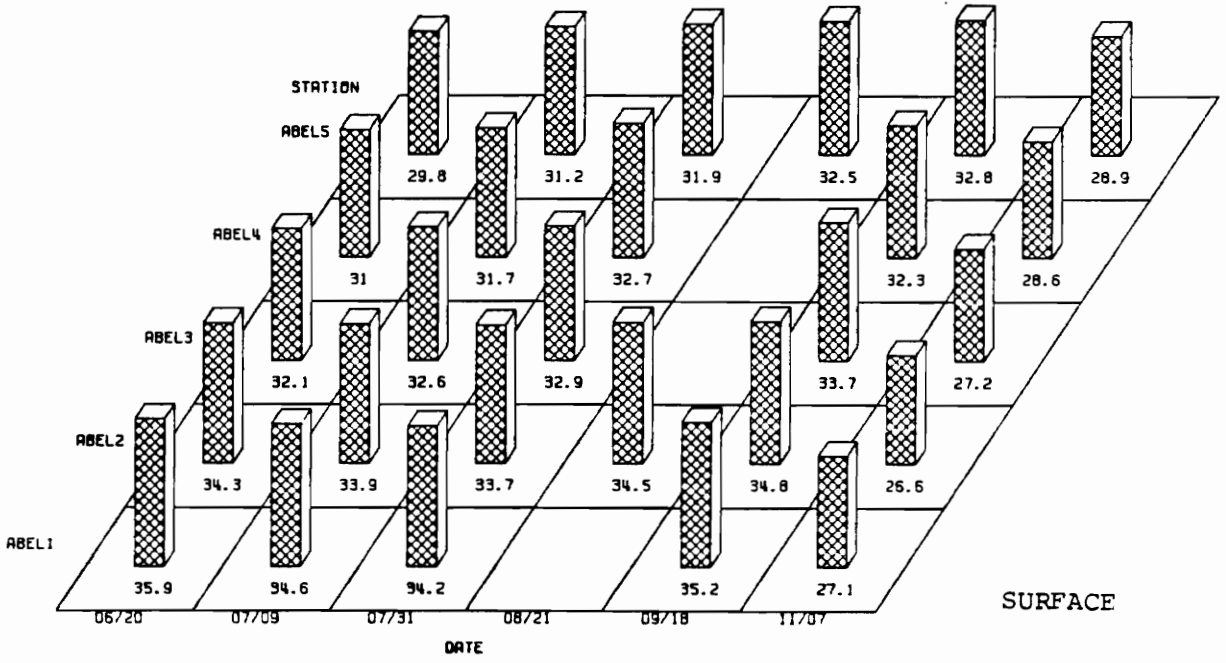


Figure B3 Variations in Abel Lake Hardness (mg/L as CaCl_2) on Six Sampling Dates at Five Stations

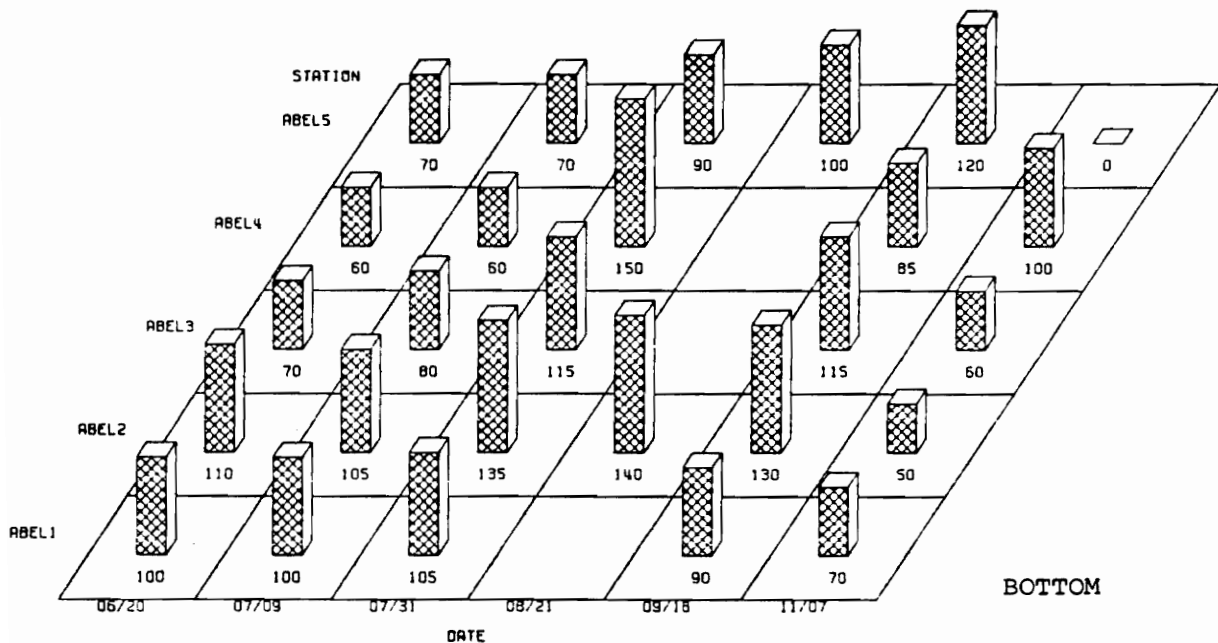
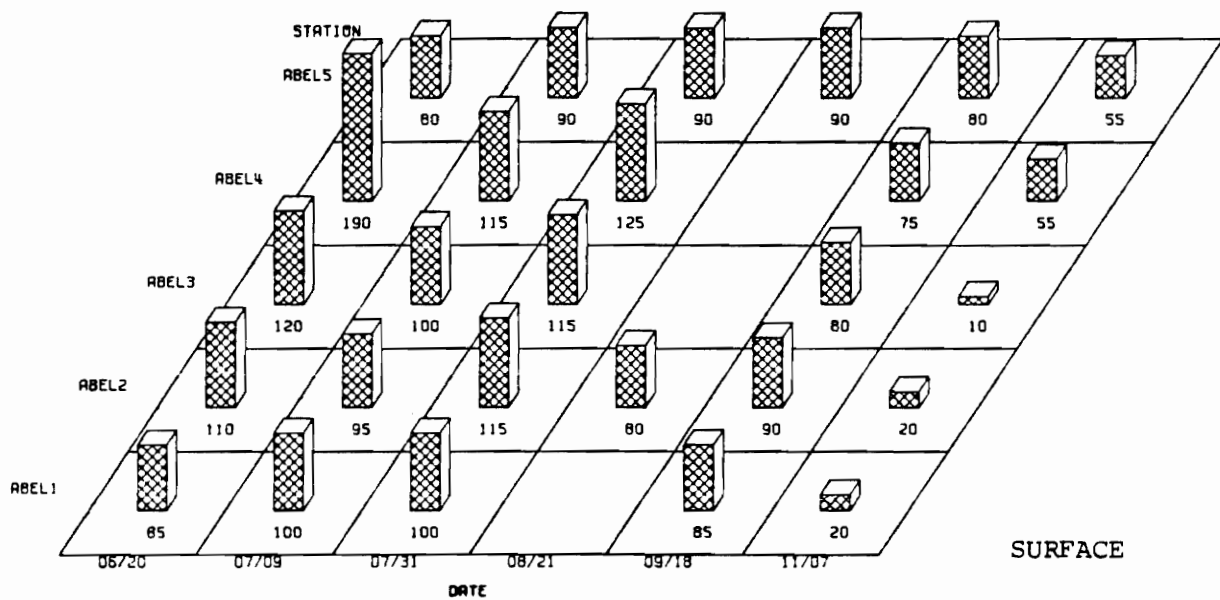


Figure B4 Variations in Abel Lake Conductivity (umhos/cm) on Six Sampling Dates at Five Stations

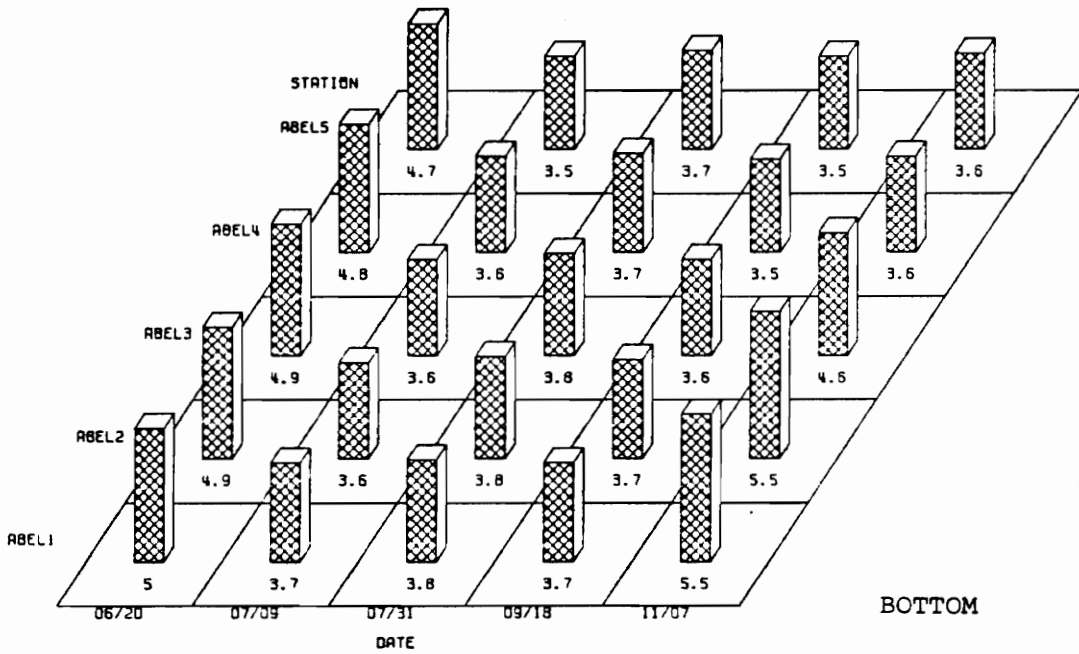
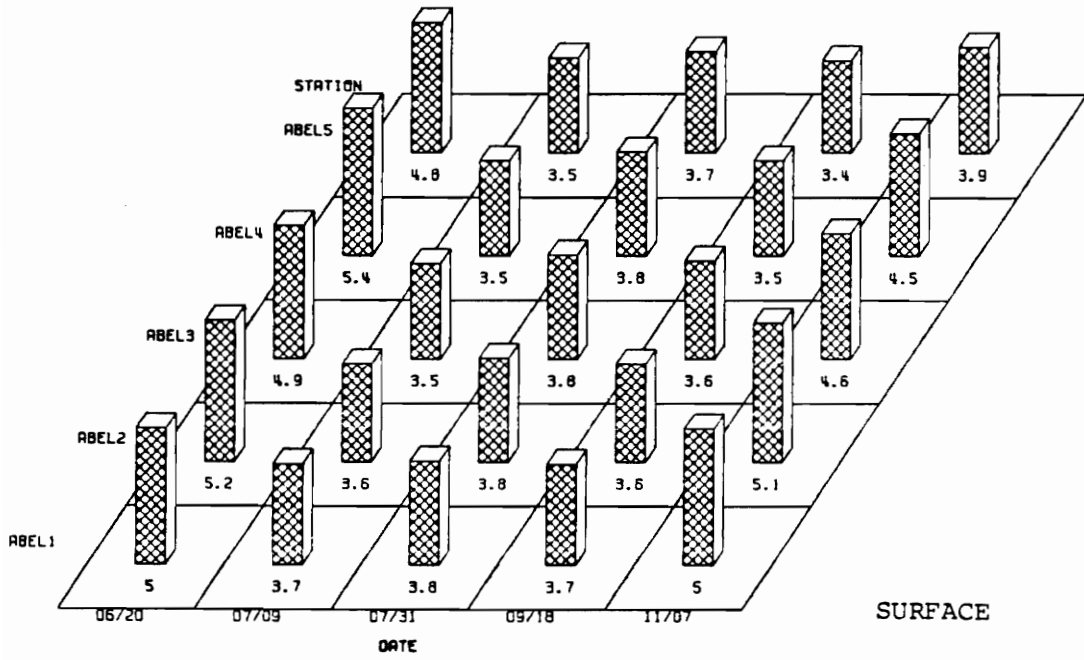


Figure B5 Variations in Abel Lake Chlorides (mg/L) on Five Sampling Dates at Five Stations

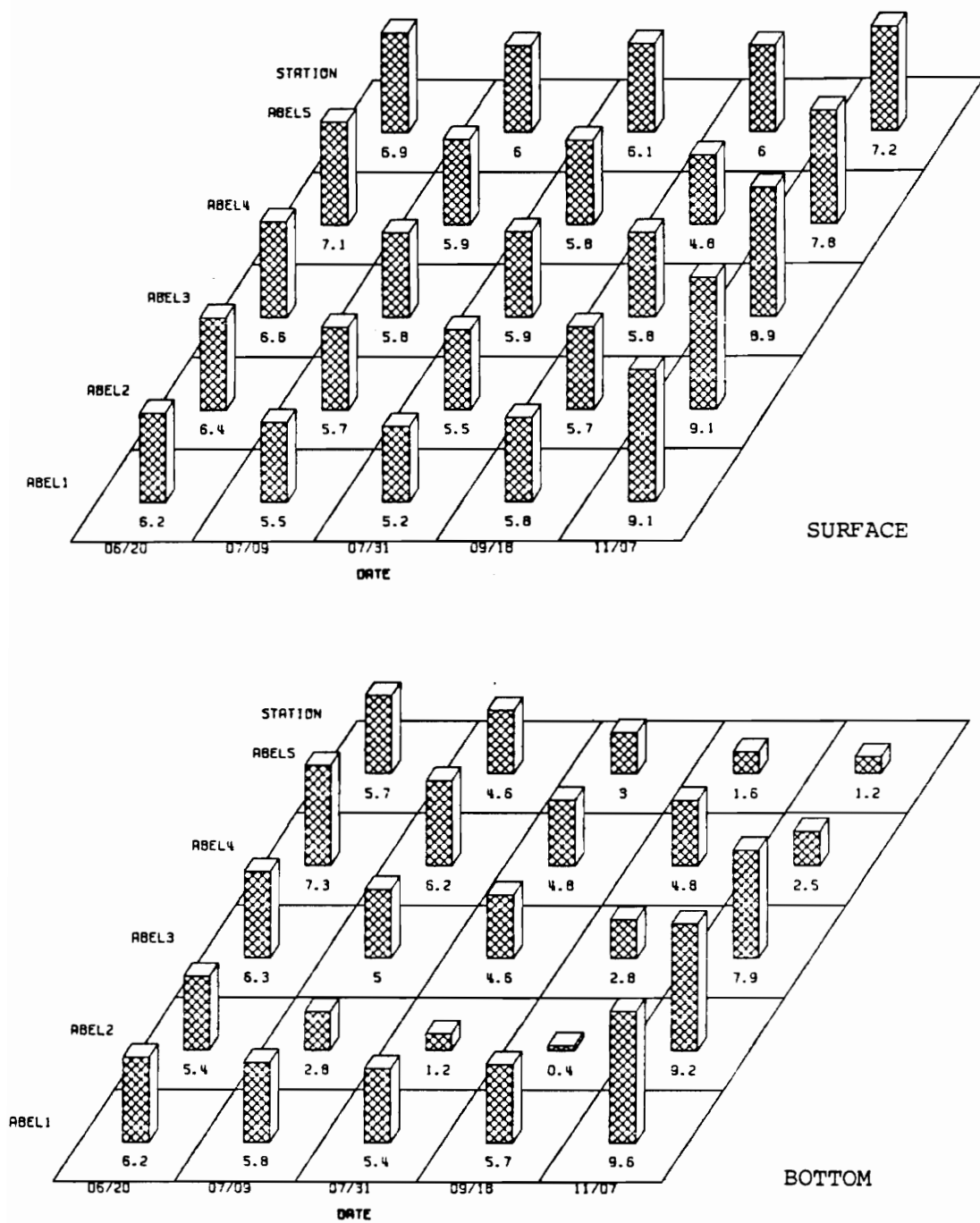


Figure B6 Variations in Abel Lake Sulfates (mg/L) on Five Sampling Dates at Five Stations

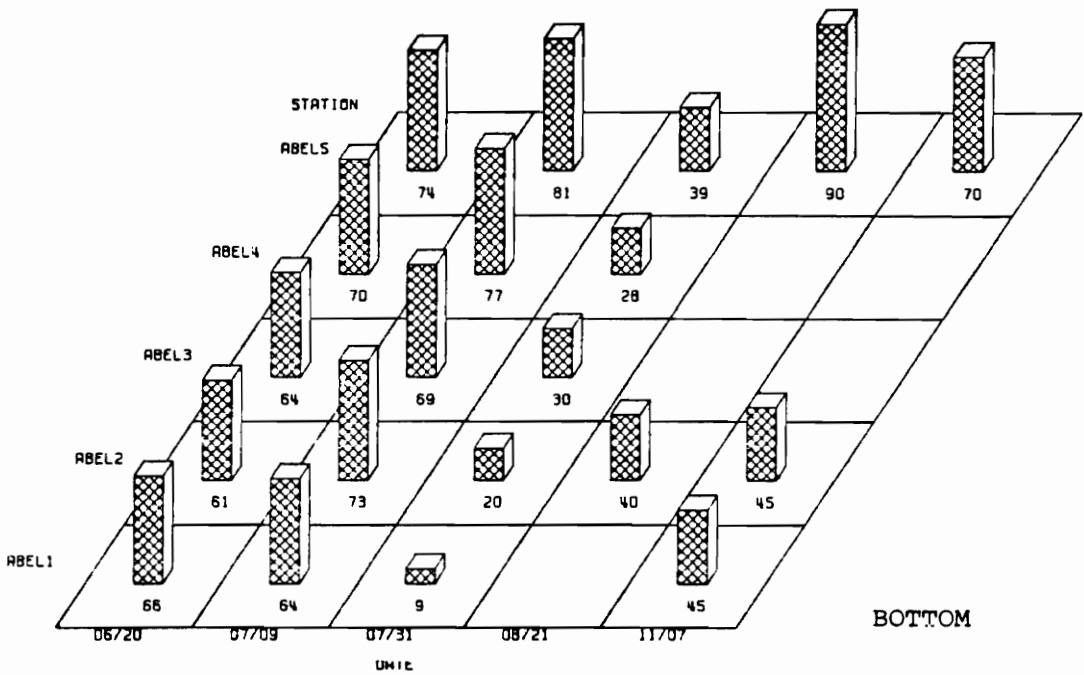
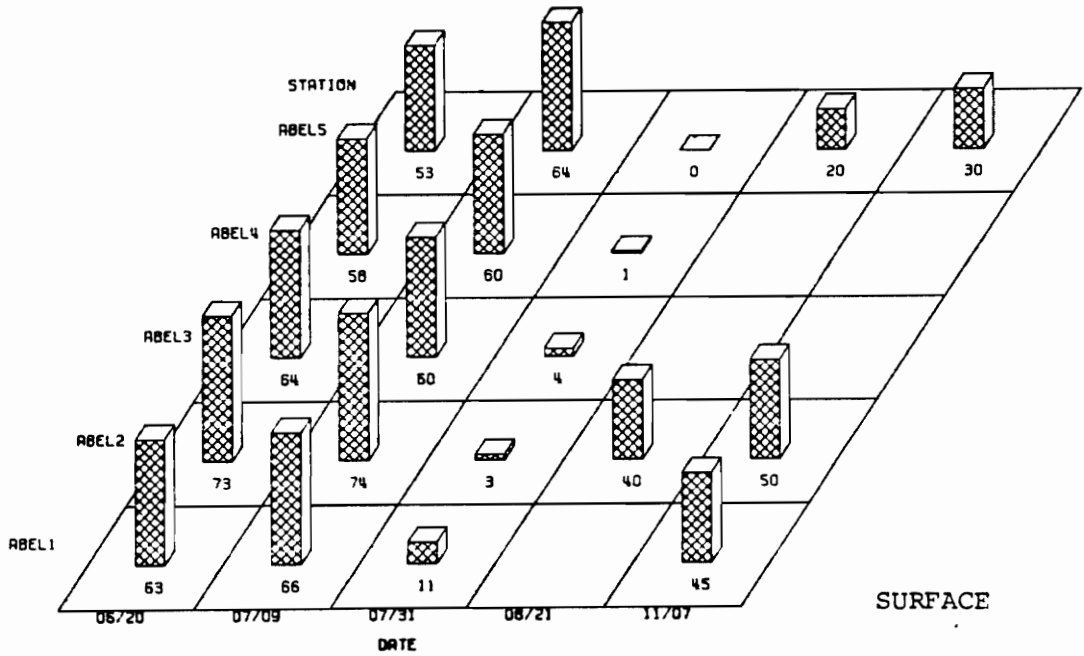


Figure B7 Variations in Abel Lake Total-Phosphate Phosphorus (ug/L) on Four Sampling Dates at Five Stations

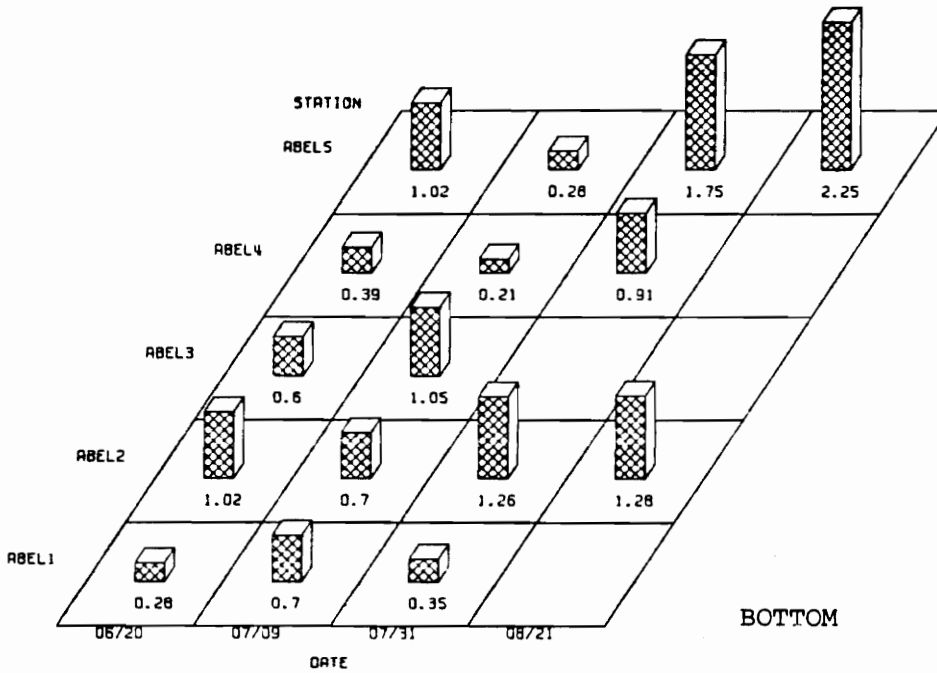
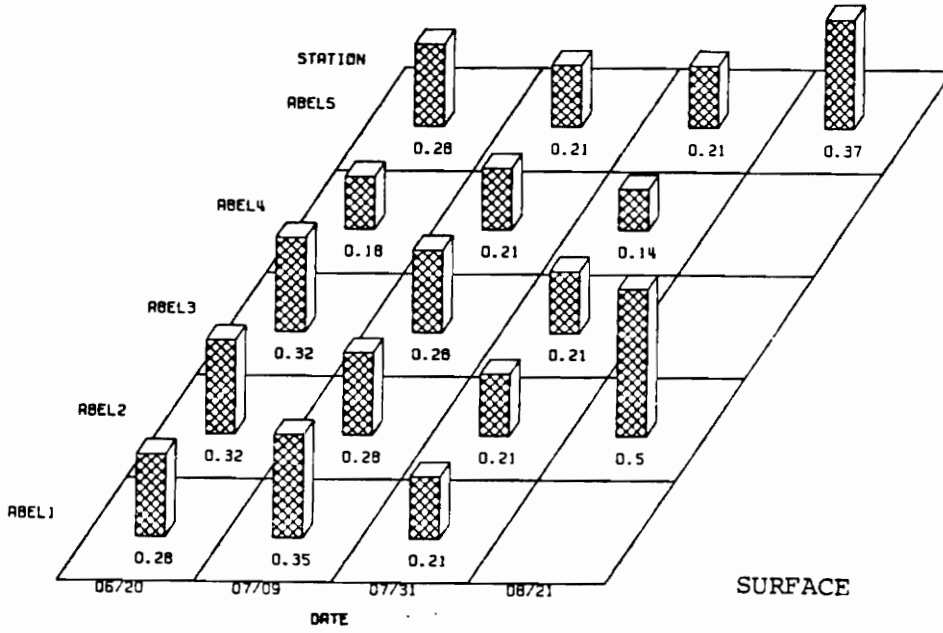


Figure B8 Variations in Abel Lake TKN (mg/L) on Four Sampling Dates at Five Stations

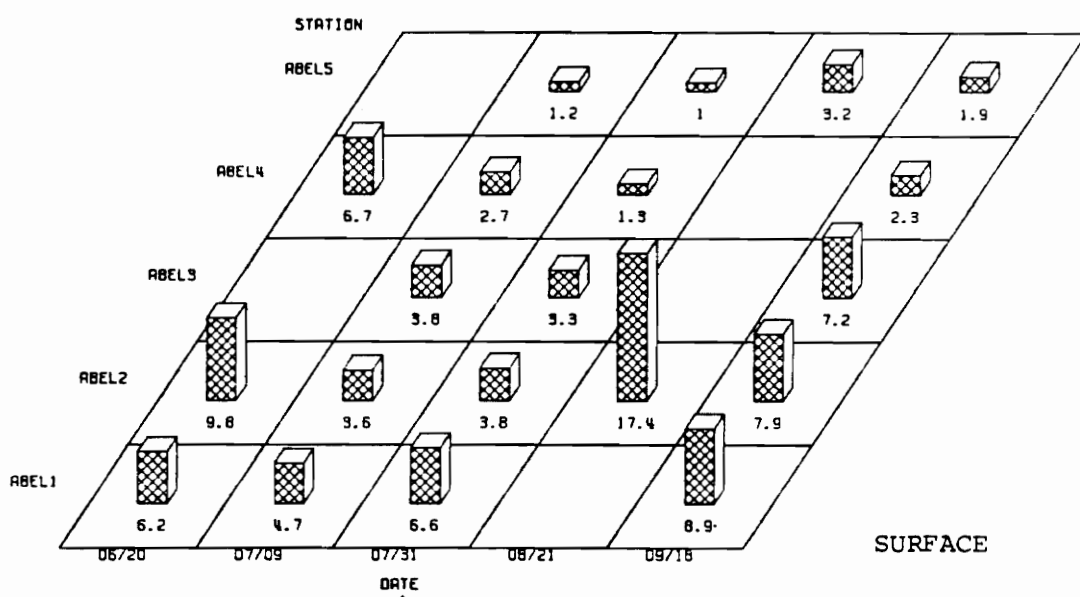


Figure B9 Variations in Abel Lake Chlorophyll-a ($\mu\text{g/L}$) on Four Sampling Dates at Five Stations

APPENDIX C. Raw Data: Limnological Study of Abel Lake,
Summer 1985.

Abel Lake Station 1 Surface
(sampling performed in 1985)

Parameter	06/19	07/09	07/31	09/18	11/07
pH	6.6	7.7	6.8	7.1	6.9
Alkalinity (mg/L as CaCO ₃)	30	27	30	29	13
Hardness (mg/L as CaCO ₃)	36	35	34	35	27
SO ₄ ⁻ (mg/L)	6.2	5.5	5.2	5.8	9.1
Cl ⁻ (mg/L)	5.0	3.7	3.8	3.7	5.0
O-PO ₄ (ug/L)	ND	ND	<0.5	ND	ND
T-PO ₄ (ug/L)	63	66	11	ND	45
TKN (mg/L)	ND	0.35	0.21	ND	ND
NO ₃ ⁻ (mg/L)	ND	ND	<0.5	ND	ND
NO ₂ ⁻ (mg/L)	ND	ND	<0.5	ND	ND
Chlorophyll-a (ug/L)	6.2	4.7	6.6	8.9	ND
Conductivity (umhos/cm)	85	100	100	85	20
Apparent Color	40	27	24	40	ND
True Color	32	18	14	25	134
Secchi Disk (inches)	43	60	58	51	24
Fe (mg/L)	0.60	0.19	0.13	0.33	0.87
Mn (mg/L)	0.02	<0.01	<0.01	0.03	0.09
TOC (mg/L)	4.4	4.5	4.9	ND	11.0
ND = No Data					

Abel Lake Station 1 Bottom
(sampling performed in 1985)

Parameter	06/19	07/09	07/31	09/18	11/07
pH	6.5	7.4	6.9	7.2	6.8
Alkalinity (mg/L as CaCO ₃)	32	29	30	29	15
Hardness (mg/L as CaCO ₃)	33	35	35	35	28
SO ₄ ⁻ (mg/L)	6.2	5.8	5.4	5.7	9.6
Cl ⁻ (mg/L)	5.0	3.7	3.8	3.7	5.5
O-PO ₄ (ug/L)	ND	ND	<0.5	ND	ND
T-PO ₄ (ug/L)	66	64	9	ND	45
TKN (mg/L)	0.28	0.70	0.35	ND	ND
NO ₃ ⁻ (mg/L)	ND	ND	<0.5	ND	ND
NO ₂ ⁻ (mg/L)	ND	ND	<0.5	ND	ND
Conductivity (umhos/cm)	100	100	105	90	70
Apparent Color	42	42	25	45	ND
True Color	30	25	14	30	134
Fe (mg/L)	0.60	0.19	0.14	0.31	0.78
Mn (mg/L)	0.04	0.01	<0.01	0.02	0.08
TOC (mg/L)	4.6	4.4	4.5	4.8	9.8
ND = No Data					

Abel Lake Station 2 Surface
(sampling performed in 1985)

Parameter	06/19	07/09	07/31	08/21	09/18	11/07
pH	7.0	7.7	7.0	7.0	7.2	6.9
Alkalinity (mg/L as CaCO ₃)	29	27	30	28	28	12
Hardness (mg/L as CaCO ₃)	34	34	34	35	35	28
SO ₄ ⁻ (mg/L)	6.4	5.7	5.5	ND	5.7	9.1
Cl ⁻ (mg/L)	5.2	3.6	3.8	ND	3.6	5.1
O-PO ₄ (ug/L)	ND	ND	<0.5	<0.5	ND	ND
T-PO ₄ (ug/L)	73	74	3	40	ND	50
TKN (mg/L)	0.32	0.28	0.21	0.50	ND	ND
NH ₃ ⁻ -N (mg/L)	ND	ND	ND	0.01	ND	ND
NO ₃ ⁻ (mg/L)	ND	ND	<0.5	<0.5	ND	ND
NO ₂ ⁻ (mg/L)	ND	ND	<0.5	<0.5	ND	ND
Chlorophyll-a (ug/L)	9.8	3.6	3.8	17.4	7.9	ND
Conductivity (umhos/cm)	110	95	115	80	90	20
Apparent Color	30	24	19	37	37	ND
True Color	24	19	13	13	20	134
Secchi Disk (inches)	62	82	81	77	70	18
Fe (mg/L)	0.40	0.18	0.12	0.20	0.25	0.90
Mn (mg/L)	<0.01	<0.01	<0.01	0.01	0.01	0.09
TOC (mg/L)	4.4	4.5	4.8	4.5	4.7	12.3
ND = No Data						

Abel Lake Station 2 Bottom
(sampling performed in 1985)

Parameter	06/19	07/09	07/31	08/21	09/18	11/07
pH	6.6	6.3	6.4	7.0	7.3	6.9
Alkalinity (mg/L as CaCO ₃)	44	39	53	28	74	16
Hardness (mg/L as CaCO ₃)	37	40	39	35	44	29
SO ₄ ⁻ (mg/L)	5.4	2.8	1.2	ND	0.4	9.2
Cl ⁻ (mg/L)	4.9	3.6	3.8	ND	3.7	5.5
O-PO ₄ (ug/L)	ND	ND	<0.5	<0.5	ND	ND
T-PO ₄ (ug/L)	61	73	20	40	ND	45
TKN (mg/L)	1.02	0.70	1.26	1.28	ND	ND
NH ₃ ⁻ -N (mg/L)	ND	ND	ND	0.88	ND	ND
NO ₃ ⁻ (mg/L)	ND	ND	<0.5	<0.5	ND	ND
NO ₂ ⁻ (mg/L)	ND	ND	<0.5	<0.5	ND	ND
Conductivity (umhos/cm)	110	105	135	140	130	50
Apparent Color	196	330	400	440	900	ND
True Color	176	279	348	392	700	134
Fe (mg/L)	5.79	8.71	6.54	20.9	25.0	0.84
Mn (mg/L)	2.95	2.95	2.69	3.68	4.61	0.10
TOC (mg/L)	6.5	6.7	7.6	8.5	9.2	10.1
ND = No Data						

Abel Lake Station 3 Surface
(sampling performed in 1985)

Parameter	06/19	07/09	07/31	09/18	11/07
pH	7.2	7.6	7.0	7.5	6.9
Alkalinity (mg/L as CaCO ₃)	28	26	28	27	14
Hardness (mg/L as CaCO ₃)	32	33	33	34	27
SO ₄ ⁻ (mg/L)	6.6	5.8	5.9	5.8	8.9
Cl ⁻ (mg/L)	4.9	3.5	3.8	3.6	4.6
O-PO ₄ (ug/L)	ND	ND	<0.5	ND	ND
T-PO ₄ (ug/L)	64	60	4	ND	ND
TKN (mg/L)	0.32	0.28	0.21	ND	ND
NO ₃ ⁻ (mg/L)	ND	ND	<0.5	ND	ND
NO ₂ ⁻ (mg/L)	ND	ND	<0.5	ND	ND
Chlorophyll-a (ug/L)	ND	3.8	3.3	7.2	ND
Conductivity (umhos/cm)	120	100	115	80	10
Apparent Color	24	34	15	30	ND
True Color	19	30	14	20	134
Secchi Disk (inches)	84	113	105	96	18
Fe (mg/L)	0.29	0.18	0.12	0.12	0.80
Mn (mg/L)	0.04	<0.01	0.01	<0.01	0.14
TOC (mg/L)	4.2	5.4	4.6	4.4	13.3
ND = No Data					

Abel Lake Station 3 Bottom
(sampling performed in 1985)

Parameter	06/19	07/09	07/31	09/18	11/07
pH	6.9	6.3	6.5	7.6	6.9
Alkalinity (mg/L as CaCO ₃)	29	29	37	52	20
Hardness (mg/L as CaCO ₃)	32	34	33	36	31
SO ₄ ⁻ (mg/L)	6.3	5.0	4.6	2.8	7.9
Cl ⁻ (mg/L)	4.9	3.6	3.8	3.6	4.6
O-PO ₄ (ug/L)	ND	ND	<0.5	ND	ND
T-PO ₄ (ug/L)	64	69	30	ND	ND
TKN (mg/L)	0.60	1.05	ND	ND	ND
NO ₃ ⁻ (mg/L)	ND	ND	<0.5	ND	ND
NO ₂ ⁻ (mg/L)	ND	ND	<0.5	ND	ND
Conductivity (umhos/cm)	70	80	115	115	60
Apparent Color	118	249	200	465	ND
True Color	96	210	180	390	102
Fe (mg/L)	1.75	6.50	8.36	15.0	1.26
Mn (mg/L)	1.94	2.28	2.20	2.59	0.34
TOC (mg/L)	5.7	5.8	7.3	7.7	11.0
ND = No Data					

Abel Lake Station 4 Surface
(sampling performed in 1985)

Parameter	06/19	07/09	07/31	09/18	11/07
pH	7.3	7.7	7.0	7.6	6.9
Alkalinity (mg/L as CaCO ₃)	26	25	28	26	17
Hardness (mg/L as CaCO ₃)	31	32	33	33	29
SO ₄ ⁻ (mg/L)	7.1	5.9	5.8	5.9	7.8
Cl ⁻ (mg/L)	5.4	3.5	3.8	3.4	4.5
O-PO ₄ (ug/L)	ND	ND	<0.5	ND	ND
T-PO ₄ (ug/L)	58	60	1	ND	ND
TKN (mg/L)	0.18	0.21	0.14	ND	ND
NO ₃ ⁻ (mg/L)	ND	ND	<0.5	ND	ND
NO ₂ ⁻ (mg/L)	ND	ND	<0.5	ND	ND
Chlorophyll-a (ug/L)	6.7	2.7	1.3	2.3	ND
Conductivity (umhos/cm)	90	115	125	75	55
Apparent Color	8	37	17	25	ND
True Color	6	32	12	17	100
Secchi Disk (inches)	85	125	119	103	18
Fe (mg/L)	0.26	0.18	0.12	0.09	0.65
Mn (mg/L)	0.03	0.01	0.01	<0.01	0.15
TOC (mg/L)	4.2	4.2	4.9	ND	10.5
ND = No Data					

Abel Lake Station 4 Bottom
(sampling performed in 1985)

Parameter	06/19	07/09	07/31	09/18	11/07
pH	7.0	6.3	6.5	7.6	6.5
Alkalinity (mg/L as CaCO ₃)	25	24	33	36	42
Hardness (mg/L as CaCO ₃)	30	31	32	32	35
SO ₄ ⁻ (mg/L)	7.3	6.2	4.8	4.8	2.5
Cl ⁻ (mg/L)	4.8	3.6	3.7	3.5	3.6
O-PO ₄ (ug/L)	ND	ND	<0.5	ND	ND
T-PO ₄ (ug/L)	70	77	28	ND	ND
TKN (mg/L)	0.39	0.21	0.91	ND	ND
NO ₃ ⁻ (mg/L)	ND	ND	<0.5	ND	ND
NO ₂ ⁻ (mg/L)	ND	ND	<0.5	ND	ND
Conductivity (umhos/cm)	60	60	150	85	100
Apparent Color	62	110	34	255	ND
True Color	46	82	27	210	425
Fe (mg/L)	0.94	0.77	6.01	5.93	16.0
Mn (mg/L)	1.24	1.47	1.85	1.87	2.45
TOC (mg/L)	4.4	4.9	6.6	5.2	9.5
ND = No Data					

Abel Lake Station 5 Surface
(sampling performed in 1985)

Parameter	06/19	07/09	07/31	08/21	09/18	11/07
pH	7.2	7.5	7.1	6.9	7.3	6.9
Alkalinity (mg/L as CaCO ₃)	25	24	39	26	25	20
Hardness (mg/L as CaCO ₃)	30	31	32	33	33	29
SO ₄ ⁻ (mg/L)	6.9	6.0	6.1	ND	6.0	7.2
Cl ⁻ (mg/L)	4.8	3.5	3.7	ND	3.4	3.9
O-PO ₄ (ug/L)	ND	ND	<0.5	<0.5	ND	ND
T-PO ₄ (ug/L)	53	64	<0.5	20	ND	30
TKN (mg/L)	0.28	0.21	0.21	0.37	ND	ND
NH ₃ ⁻ -N (mg/L)	ND	ND	ND	<.0	01 ND	ND
NO ₃ ⁻ (mg/L)	ND	ND	<0.5	<0.5	ND	ND
NO ₂ ⁻ (mg/L)	ND	ND	<0.5	<0.5	ND	ND
Chlorophyl-a (ug/L)	ND	1.2	1.0	3.2	1.9	ND
Conductivity (umhos/cm)	80	90	90	90	80	55
Apparent Color	5	34	17	34	29	ND
True Color	3	32	13	18	17	60
Secchi Disk (inches)	82	135	131	ND	107	31
Fe (mg/L)	0.22	0.15	0.12	0.18	0.11	0.60
Mn (mg/L)	0.03	0.01	<0.01	0.01	<0.01	0.22
TOC (mg/L)	3.9	4.0	4.2	4.0	3.8	7.4
ND = No Data						

Abel Lake Station 5 Bottom
(sampling performed in 1985)

Parameter	06/19	07/09	07/31	08/21	09/18	11/07
pH	7.1	6.3	6.4	6.8	7.2	6.6
Alkalinity (mg/L as CaCO ₃)	34	30	39	42	60	48
Hardness (mg/L as CaCO ₃)	31	31	32	35	36	35
SO ₄ ⁻ (mg/L)	5.7	4.6	3.0	ND	1.6	1.2
Cl ⁻ (mg/L)	4.7	3.5	3.7	ND	3.5	3.6
O-PO ₄ (ug/L)	ND	ND	<0.5	<0.5	ND	ND
T-PO ₄ (ug/L)	74	81	39	90	ND	70
TKN (mg/L)	1.02	0.28	1.75	2.25	ND	ND
NH ₃ ⁻ -N (mg/L)	ND	ND	ND	1.52	ND	ND
NO ₃ ⁻ (mg/L)	ND	ND	<0.5	<0.5	ND	ND
NO ₂ ⁻ (mg/L)	ND	ND	<0.5	<0.5	ND	ND
Conductivity (umhos/cm)	70	70	90	100	120	0
Apparent Color	150	315	384	500	660	ND
True Color	150	261	364	465	540	830
Fe (mg/L)	2.81	6.99	13.3	16.5	19.8	19.8
Mn (mg/L)	3.34	3.40	3.55	3.76	4.00	3.70
TOC (mg/L)	6.2	6.5	9.5	9.9	9.8	11.6
ND = No Data						

APPENDIX D Water Quality Characteristics of Tributaries
to Abel Lake.

Abel Lake Inlets
(sampling performed in 1985)

Parameter	08/21			1107	
	CREEK 1	CREEK 2	CREEK 3	CREEK 1	CREEK 3
pH	6.9	7.0	6.9	5.8	7.0
Alkalinity (mg/L as CaCO ₃)	24	19	10	21	8
Hardness (mg/L as CaCO ₃)	39	25	12	33	14
SO ₄ ⁻ (mg/L)	ND	ND	ND	7.5	5.5
Cl ⁻ (mg/L)	ND	ND	ND	4.5	2.8
O-PO ₄ (ug/L)	30	<0.5	19	35	25
T-PO ₄ (ug/L)	50	20	20	35	25
TKN (mg/L)	ND	0.60	0.48	ND	ND
NH ₃ ⁻ -N (mg/L)	0.02	0.01	0.01	ND	ND
NO ₃ ⁻ &NO ₃ ⁻ (mg/L)	0.14	0.03	0.09	ND	ND
Chlorophyl-a (ug/L)	8.1	1.2	3.6	ND	ND
Conductivity (umhos/cm)	90	55	30	60	20
Apparent Color	90	61	69	ND	ND
True Color	77	46	51	76	29
Fe (mg/L)	0.36	0.17	0.17	0.72	0.14
Mn (mg/L)	0.04	0.01	0.02	0.05	0.02
TOC (mg/L)	7.7	3.8	3.8	6.7	2.5
ND = No Data					

APPENDIX E Fractionation Data - TOC, THMFP, and THM Yield

Fractionation Data - TOC, THMFP, and THM Yield

Sample Size-Range	THMFP (ug/L)	TOC (mg/L)	THM-Yield
	<u>Site No. 2 Surface</u>		
0-500	55	0.97	57
500-1K	26	0.31	84
1K-5K	111	1.76	63
5K-10K	62	0.85	73
10K-30K	4	0	0
30K-GF filtered ^a	16	0.47	34
Particulate	11	0.38	29
Whole ^b	285	4.72	60
	<u>Site No. 2 Bottom</u>		
0-500	26	0.95	27
500-1K	53	0.78	68
1K-5K	111	1.97	56
5K-10K	81	0.54	150
10K-30K	0	0.10	0
30K-GF filtered	97	1.45	67
Particulate	78	2.05	38
Whole	434	7.84	55

^aGF filtered - Glass Fiber filter used to separate particulate fraction of sample from dissolved fraction.

^bWhole sample is term used for unfractionated sample.

Fractionation Data - TOC, THMFP, and THM Yield

Sample Size-Range	THMFP (ug/L)	TOC (mg/L)	THM-Yield
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Site No. 5 Bottom

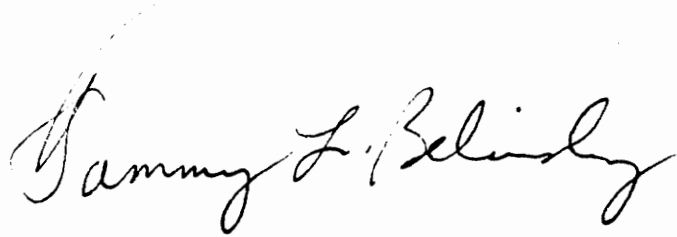
0-500	11	0.77	14
500-1K	1	1.12	1
1K-5K	22	1.30	17
5K-10K	21	0.83	25
10K-30K	6	0.23	26
30K-GF filtered	312	4.83	65
Particulate	285	5.12	56
Whole	658	14.2	46

Site: Potomac Creek

0-500	87	1.3	67
500-1K	23	0.6	38
1K-5K	121	1.34	90
5K-10K	88	1.37	64
10K-30K	0	0	0
30K-GF filtered	112	0.38	295
Particulate	52	0	0
Whole	456	4.82	95

VITA

Tammy Belinsky was born on September 24, 1961 in Washington, D.C. and is still seeking truth and purpose in life.

A handwritten signature in cursive script that reads "Tammy L. Belinsky". The signature is written in black ink and is centered on the page.