SPATIAL AND SEASONAL VARIABILITY IN WATER QUALITY OF DEVILS LAKE, NORTH DAKOTA, SEPTEMBER 1988 THROUGH OCTOBER 1990

By Steven K. Sando and Robert M. Lent

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
degree Fahrenheit (°F)	(1)	degree Celsius
foot (ft)	0.3048	meter
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
ton, short (2,000 lb)	0.9072	megagram

[1] Temp °C = (temp °F-32)/1.8.

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Microsiemens per centimeter at 25 degrees Celsius (µS/cm) replaces micromhos per centimeter at 25 degrees Celsius used for specific conductance in older reports. The two units are equivalent.

Milligrams per kilogram (mg/kg) is a unit expressing the concentration of a chemical constituent in solid material as weight (milligrams) of chemical constituent per weight (kilogram) of dry solid material; 1 mg/kg is approximately equal to 1 ppm (part per million).

Milligrams per liter (mg/L) is a unit expressing the concentration of a chemical constituent in solution as weight (milligrams) of solute per unit volume (liter) of water; 1 mg/L equals 1,000 µg/L.

Spatial and Seasonal Variability in Water Quality of Devils Lake, North Dakota, September 1988 Through October 1990

By Steven K. Sando *and* Robert M. Lent

Abstract

Devils Lake, in northeastern North Dakota, is a closed-basin lake characterized by large fluctuations in water level and in concentrations of dissolved chemical constituents. A study was conducted to assess spatial and seasonal variability in water-quality conditions in Devils Lake during September 1988 through October 1990.

Specific conductance, which generally increased from west to east in Devils Lake and East Devils Lake, ranged from 3,580 to 20,100 microsiemens per centimeter. pH, water temperature, and dissolved oxygen generally were similar among sites. Devils Lake generally does not undergo thermal stratification during open-water periods but does undergo inverse thermal stratification in the winter. Vertical variability of water-column properties during open-water periods generally was small, but near-bottom dissolved oxygen was less than near-surface dissolved oxygen during summer sampling periods. The potential exists for establishment of near-bottom anoxia during the summer and during the winter.

Concentrations of all major ions generally increased eastward through Devils Lake and East Devils Lake, but sodium, sulfate, and chloride were enriched relative to the other major ions.

Dissolved-solids concentrations varied both spatially and seasonally. Median dissolved-solids concentrations generally increased from west to east. Dissolved-solids concentrations generally were largest in the winter when ions were concentrated because of ice formation and smallest in the spring when water was diluted because of icemelt, surface-water inflow, and seasonal precipitation. Dissolved-solids concentrations generally increased in the summer and fall when evaporation exceeded surface-water inflow and precipitation. Although the dissolved-solids concentration of Devils Lake generally fluctuates inversely with water level, the dissolved-solids mass generally fluctuates directly with water level. During periods of extremely low water levels, dissolved solids may be lost from Devils Lake.

Concentrations of nutrients in the euphotic zone varied spatially and seasonally. Dissolved nitrite and dissolved nitrite plus nitrate concentrations generally were below the detection limit of 0.10 milligram per liter. Total ammonia and dissolved ammonia concentrations generally were below 0.10 milligram per liter, except during winter sampling periods. Total nitrogen concentrations were extremely large and generally were similar to concentrations reported for hypereutrophic systems. Total nitrogen concentrations commonly were between 1.0 and 8.6 milligrams per liter. Total ammonia, dissolved ammonia, and total nitrogen concentrations generally were larger at shallower sampling sites than at deeper sampling sites; sediment-water interactions may influence concentrations of nitrogen species. The ratio of sediment surface area

to lake volume for a given part of the lake may partly explain spatial variability in concentrations of nitrogen species.

Total nitrogen concentrations generally were smallest in the fall, increased in the winter, remained the same or decreased slightly in the spring, and increased again in the summer. Phosphorus concentrations generally were smallest in the fall, increased in the winter, decreased in the spring, and increased again in the summer.

INTRODUCTION

Devils Lake is the terminal lake in a 3,810-mi^2 closed basin in northeastern North Dakota (fig. 1). The lake is of great biologic and economic significance to the region because it serves as a major staging area for migrating waterfowl and supports an important sport fishery. Devils Lake is characterized by large fluctuations in water level and in concentrations of dissolved chemical constituents. These large fluctuations have a major effect on the biology of Devils Lake and have caused problems and concerns for residents of surrounding communities and those dependent upon Devils Lake for livelihood or recreation. High water levels have inundated roads, agricultural land, and residential property and have posed a flood threat to the city of Devils Lake, a National Guard camp, and road, sewer, and lagoon systems of several other communities. Low water levels have restricted boat access, reduced waterfowl habitat, and adversely affected sport fish populations because of large dissolved-solids concentrations. The sport fishery, migratory waterfowl, and recreational activities on and in the lake also have been adversely affected by nuisance algal blooms caused by large nutrient concentrations.

Many groups, including State and Federal agencies and national fishing, hunting, recreational, and environmental organizations, have expressed concern about the effects of fluctuating water levels and are seeking means to stabilize the water level and water quality of Devils Lake (North Dakota State Water Commission, 1988). The North Dakota State Water Commission (1988) identified two primary management proposals: (1) The diversion of water from the Missouri River as part of the operation of the Garrison Diversion Unit to supplement inflow to Devils Lake during dry years and to provide a source of relatively fresh water, and (2) the construction of an outlet to regulate water levels and to provide flood control during wet years. The popularity and priority of these two proposals vary for different interest groups and also seem to change, depending on the status and trend of lake water levels. Despite differences in opinions among various groups, there is general agreement that insufficient knowledge exists to adequately evaluate potential water-quality effects of the management proposals with respect to (1) changes in concentrations of water-quality constituents as related to water-level fluctuations, (2) the amount of nutrients contributed to the lake by different sources, and (3) the effect of the interaction of dissolved solids and nutrients in relation to eutrophication of the lake.

Detailed interpretive studies that focused on water-quality aspects of Devils Lake were conducted by Pope (1909), Nerhus (1920), Young (1924), Swenson and Colby (1955), and Mitten and others (1968). Although these studies have been significant in understanding Devils Lake and associated lakes, they were conducted during periods when the stage of Devils Lake was less than 1,420 ft above sea level. This lake level has been identified by the North Dakota Game and Fish Department (Terry Steinwand, Chief of Fisheries Division, oral commun., 1990) as the minimum level necessary for sustaining sport fish populations. Much additional data have been collected for Devils Lake since the last detailed interpretive study. In 1988, the U.S. Geological Survey, in cooperation with the North Dakota Game and Fish Department, began a study to assess spatial and seasonal variability in water-quality conditions in Devils Lake to provide additional information for the evaluation of Devils Lake management proposals.

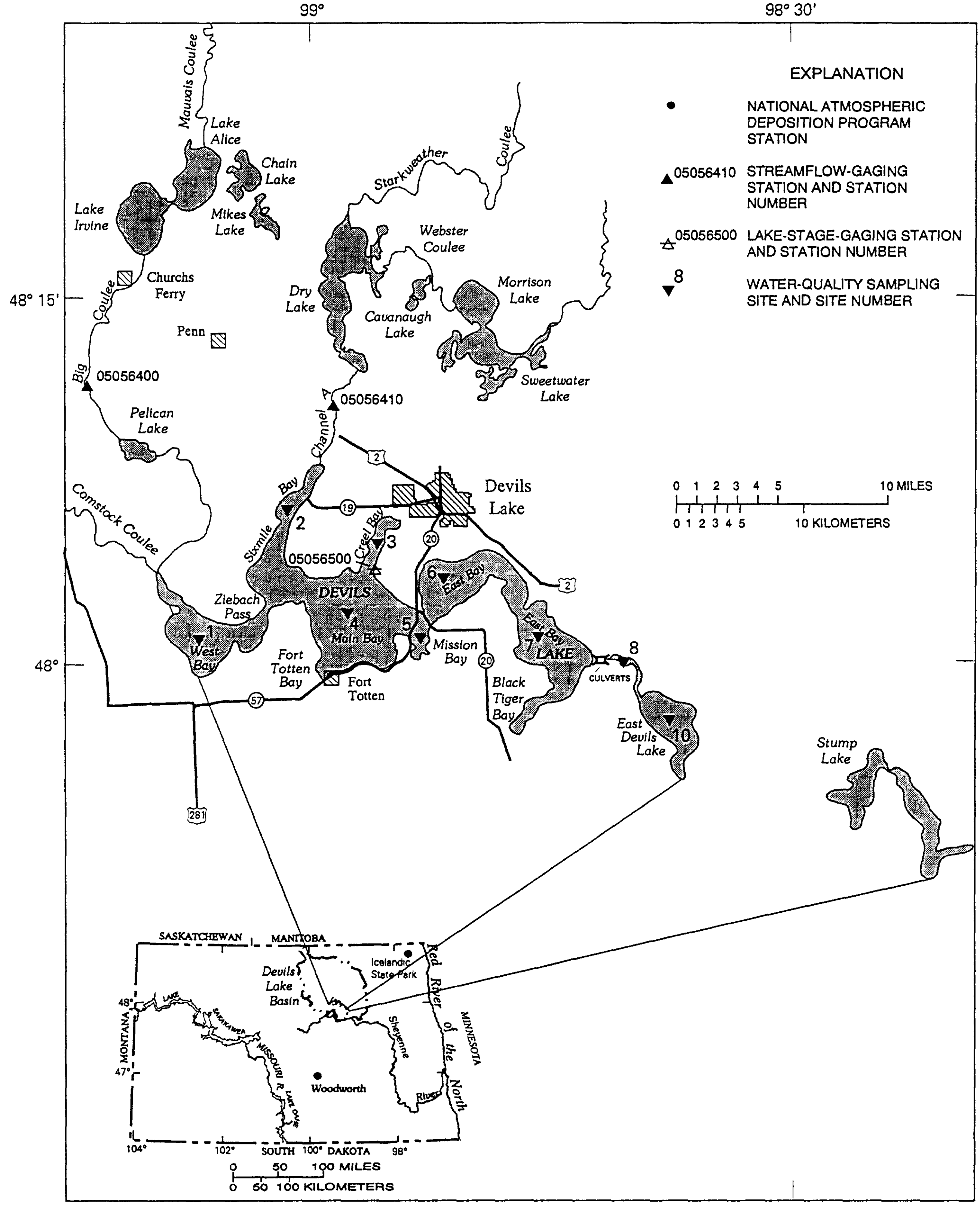

Figure 1. Location of Devils Lake Basin, National Atmospheric Deposition program stations, streamflow-gaging stations, lake-stage-gaging station, and water-quality sampling sites.

Purpose and Scope

This report describes the results of the water-quality study of Devils Lake and East Devils Lake. The study, which was conducted during September 1988 through October 1990, was designed to document the spatial and seasonal variability in water-column properties, major ions, and nutrients in Devils Lake and East Devils Lake. The results of the study were combined with historic water-quality information to determine long-term variability in water-quality conditions in Devils Lake. A detailed description of data-collection methods and all data collected during the study are presented in Sando and Sether (1993).

Description of Study Area

The hydrology of the Devils Lake Basin has been described in detail by Wiche (1986) and Ryan and Wiche (1988). The following discussion is derived largely from those earlier reports.

The Devils Lake Basin is a 3,810-mi^2 closed basin in northeastern North Dakota (fig. 1). About 3,320 mi^2 of the total 3,810 mi^2 is tributary to Devils Lake; the remainder is tributary to Stump Lake. The topographic relief, surficial landforms, and sediments are of glacial origin. A large number of shallow depressions and potholes occur throughout the basin. The eastern, western, and northern boundaries of the Devils Lake Basin are poorly defined low divides. The southern boundary is a series of recessional moraines that lie between Devils Lake and the Sheyenne River.

Before 1979, most discharge to Devils Lake flowed through an interconnected chain of lakes, namely Sweetwater Lake, Morrison Lake, Dry Lake, Chain Lake, Lake Alice (Lac aux Mortes), and Lake Irvine, and then into Big Coulee (fig. 1), which is the principal natural stream that enters Devils Lake. A small quantity of runoff entered Devils Lake by overland flow from drainage areas adjacent to the lake. In 1979, the Ramsey County and Cavalier County Water Management Boards completed the construction of Channel A, which connects Dry Lake to Sixmile Bay, Devils Lake. Construction of Channel A modified the drainage pattern in the basin; drainage into Sweetwater, Morrison, and Dry Lakes is conveyed to Devils Lake by Channel A, and the remaining discharge follows the natural watercourse.

Devils Lake consists of several bays that are, to some extent, isolated from each other (fig. 1). West Bay is a large, shallow bay that extends to the west from Main Bay. West Bay is connected to Sixmile Bay and Main Bay by a narrow channel. Sixmile Bay and Creel Bay are long, narrow bays that extend to the north from Main Bay. Mission Bay is connected to Main Bay on the west by a channel under Highway 57 and to East Bay on the northeast by a channel under Highway 20. East Bay is connected to East Devils Lake on the east by four culverts.

The primary sources of water for Devils Lake are surface-water inflow, precipitation on the lake surface, and ground-water inflow. Surface-water inflow enters Devils Lake in three ways (Wiche, 1986, p. 19): Inflow through Big Coulee (the major tributary to Devils Lake), inflow through Channel A and Comstock Coulee, and overland flow from drainage areas adjacent to Devils Lake. Wiche (1986) developed a water-balance model to estimate the combined contribution of these three sources and determined that the mean annual inflow during 1931-83 was about 30,000 acre-ft and the median annual inflow was about 8,500 acre-ft. The minimum annual inflow was zero and the maximum annual inflow was about 248,000 acre-ft. The large difference in the mean and median annual inflows indicates that the annual inflow distribution is skewed and significantly influenced by relatively few large values.

Precipitation on the lake surface is an important source of recharge to Devils Lake. Annual precipitation for 1951-80 at the city of Devils Lake is 16.52 in. (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data and Information Service, 1982). About

75 percent of the precipitation falls from April to September, usually during thunderstorms (Mitten and others, 1968). Annual precipitation for 1870-90 (Fort Totten) and 1897-1990 (city of Devils Lake) is shown in figure 2.

The extent of ground-water interaction with Devils Lake is uncertain, but hydraulic connection between Devils Lake and underlying aquifers probably is poor (Paulson and Akin, 1964). In previous water-budget studies of the lake, the assumption was made that ground-water inflow was negligible (Swenson and Colby, 1955; Mitten and others, 1968; Wiche, 1986). Pusc (1993) recently estimated that ground-water inflow to Devils Lake is about 3,000 acre-ft/yr, which is greater than previously thought but which is still much less than surface-water inflow or precipitation on the lake.

Devils Lake has no surface outlet below about 1,453 ft above sea level, an elevation that the lake has not approached since recorded observations began. Because ground-water interaction with the lake probably is small and ground-water flow appears to be toward the lake, evaporation is the only outflow of water from the lake (Pusc, 1993). Mean annual free water surface evaporation in the Devils Lake area has been estimated to be about 34 in. (Farnsworth and others, 1982).

The combination of variable surface-water inflow, a relatively small amount of ground-water inflow, and evaporation generally in excess of precipitation has resulted in large water-level fluctuations of Devils Lake during extended periods of time (fig. 2). During 1867 to 1990, the water level of Devils Lake generally declined from a maximum of 1,438.3 ft above sea level in 1867 to a minimum of 1,400.9 ft above sea level in 1940, rose erratically to a peak of about 1,429 ft above sea level in 1987, and then generally declined to 1,423.5 ft above sea level in October 1990. The maximum depth of Devils Lake varied from about 40 ft in 1867 to about 3 ft in 1940. The maximum depth was about 25 ft in October 1990.

DATA COLLECTION

A detailed description of data-collection methods and results is given in Sando and Sether (1993). The purpose of this section is to provide a summary of sampling methods and frequency.

During the period of study, daily streamflow discharge and specific-conductance data were collected at Big Coulee near Churchs Ferry, N. Dak. (station number 05056400), and at Channel A near Penn, N. Dak. (station number 05056410) (fig. 1). Selected properties (specific conductance, pH, water temperature, and dissolved oxygen) were measured and water-quality samples were collected five times per year at these two stations. However, because flow in the two tributaries was infrequent and of relatively short duration, only two samples at Big Coulee near Churchs Ferry, N. Dak., and three samples at Channel A near Penn, N. Dak., were collected in 1989. No samples at Big Coulee near Churchs Ferry, N. Dak., and three samples at Channel A near Penn, N. Dak., were collected in 1990. The streamflow and water-quality data were published in Harkness and others (1990, 1991).

Continuous water-level data were collected at Devils Lake near Devils Lake, N. Dak. (station number 05056500) (fig. 1). These data were used in conjunction with elevation-area-capacity tables to estimate the volume and surface area of Devils Lake.

Water-quality data were collected at nine sampling sites on Devils Lake and East Devils Lake (fig. 1) during the study period. Water-column properties [specific conductance, pH, water temperature, light transmission, Secchi-disk transparency depth (Secchi depth), and dissolved oxygen] were measured and water-quality samples were collected during 11 sampling periods. Light-transmission and Secchi-depth data were used to define the euphotic and aphotic zones. The euphotic zone is the volume of water from

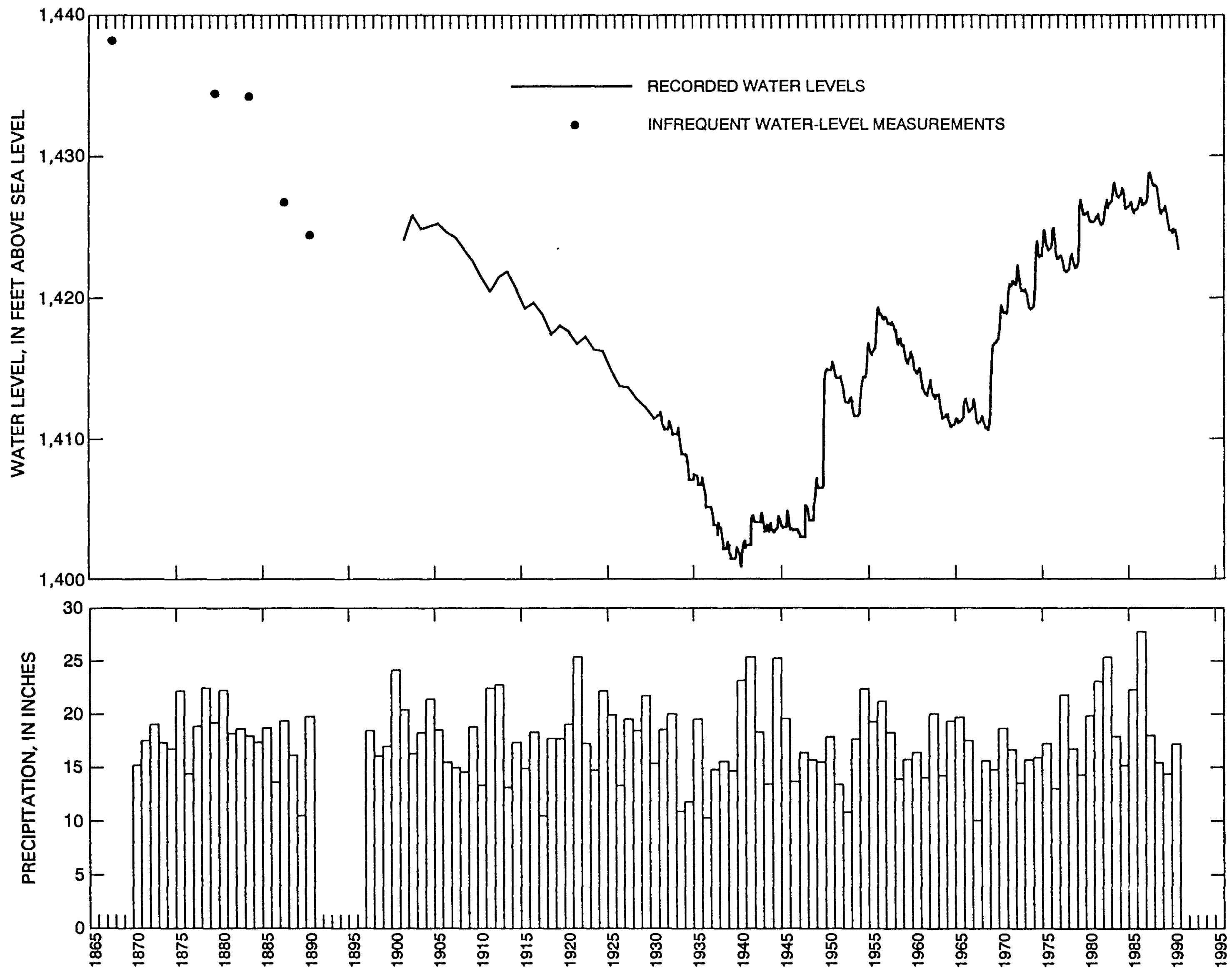

Figure 2. Historic water levels for Devils Lake, 1867-1990, and annual precipitation, 1870-90 (Fort Totten) and 1897-1990 (city of Devils Lake). (Modified from Wiche, 1986.)

the lake surface to the depth at which 99 percent of the surface light has dispersed. This generally is the zone in which photosynthetic activity occurs. The aphotic zone is the volume of water below the euphotic zone. Water samples generally were collected from the top, middle, and bottom of the euphotic zone, which is defined by photometer readings or Secchi-depth measurements, and composited. Water samples also were collected from the aphotic zone during the September and October 1990 sampling periods and analyzed separately. The number of samples from the aphotic zone varied and sometimes the samples were composited (Sando and Sether, 1993). These aphotic-zone data were used only to evaluate differences between euphotic zone and aphotic zone constituent concentrations for those sampling periods and were excluded from all other data analyses.

At sites 1 through 7, water-column properties were measured and water-quality samples were collected during all 11 sampling periods. At site 8 (East Devils Lake inlet), water-column properties (except for light transmission) were measured during all 11 sampling periods, but water-quality samples were collected during the first 7 sampling periods (September 1988 through February 1990) only. By February 1990, the water level of East Devils Lake had declined to an extent that there was concern that site 8 would become isolated from the main part of East Devils Lake. Also, preliminary analytical results indicated that water samples collected at site 8 probably were not representative of the water quality of the main part of East Devils Lake. Therefore, in May 1990, the East Devils Lake sampling site was changed from site 8 to site 10 (fig. 1).

Accepted water-quality principles were used to review laboratory analytical results for accuracy and acceptability. pH and specific-conductance data were not included in the data analysis when field values differed from laboratory determinations by more than 10 percent. Of all water samples collected, 91 percent had cation-anion milliequivalent concentrations within 5 percent. The greatest difference was 6.2 percent.

Bottom-material samples were collected four times during this study with a stainless-steel Ponar grab sampler. The samples were collected at all sampling sites and analyzed for nutrients.

SPATIAL AND SEASONAL VARIABILITY IN WATER QUALITY

Water-Column Properties

Water-column property data were analyzed to determine patterns of spatial and seasonal variability in Devils Lake and East Devils Lake. Water-column property distributions, excluding secchi depths, in water samples collected at sampling sites on Devils Lake and East Devils Lake during September 1988 through October 1990 are shown in figure 3. Because of the difference in number and timing of water-column property measurements, comparison of distributions between site 10 and the other sites may be misleading. Also, occasional instrument malfunction resulted in missing or partial water-column property profiles for some sampling periods at some sites, but the missing data probably were not so extensive as to affect general among-site comparisons of distributions.

In addition to spatial variability, water-column properties vary with season. For example, water-column property depth profiles at site 4 (Main Bay) for October 25, 1989, through October 24, 1990, indicate a typical pattern of seasonal distribution in Devils Lake and East Devils Lake (fig. 4).

Specific conductance ranged from 3,580 µS/cm at 25°C at site 1 (West Bay) on May 9, 1989, to 20,100 µS/cm at 25°C at site 8 on February 7, 1990. Specific conductance generally increased from west

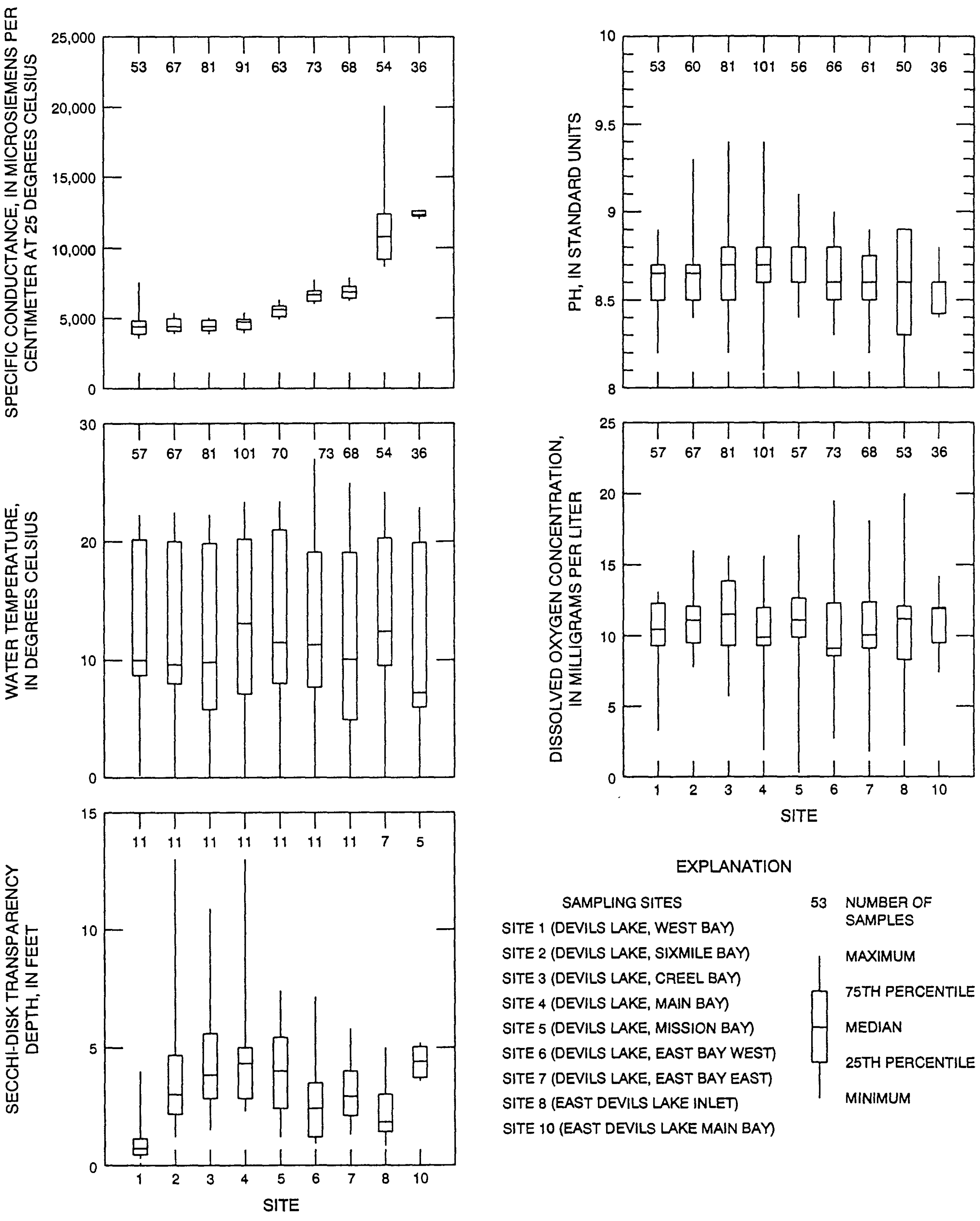

Figure 3. Water-column property distributions in water samples collected at sampling sites on Devils Lake and East Devils Lake, September 1988 through October 1990.

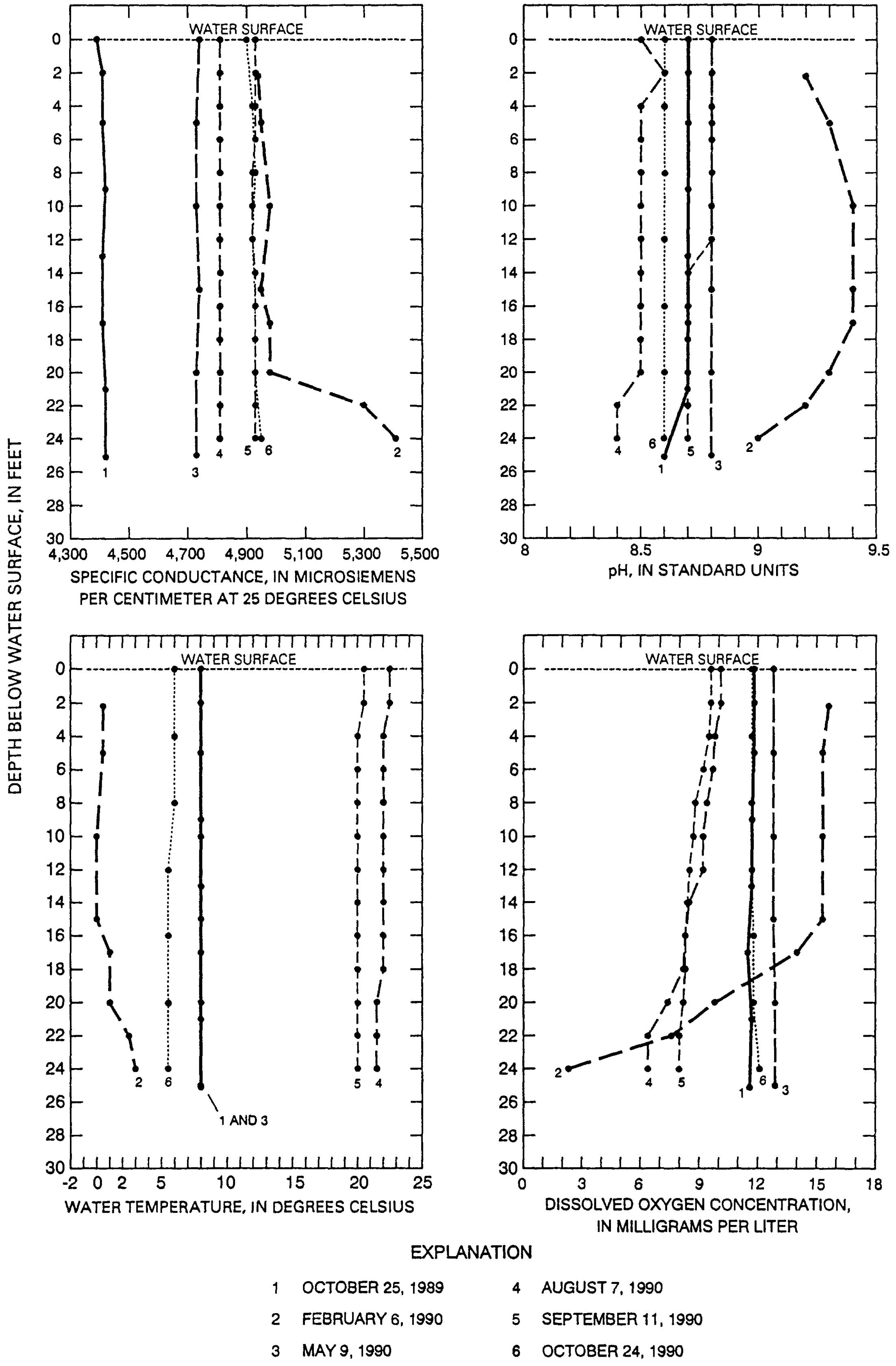

Figure 4. Depth profiles of specific conductance, pH, water temperature, and dissolved oxygen at site 4 (Devils Lake, Main Bay), October 25, 1989, through October 24, 1990.

to east in Devils Lake and East Devils Lake (fig. 3). Specific-conductance values at all sites generally were largest in the winter, smallest in the spring, and increased in the summer.

Vertical variability of specific conductance during open-water periods generally was small (fig. 4). The vertical similarity probably indicates that Devils Lake and East Devils Lake generally were well mixed with respect to major ions during open-water periods. Vertical variability of specific conductance generally was greater during ice cover than during open-water periods. Depth profiles for winter sampling periods indicate near-bottom specific conductance generally was slightly greater than near-surface specific conductance, indicating that bottom sediments may be a source of major ions to the lake.

pH ranged from 8.0 at site 8 on October 26, 1989, to 9.4 at sites 3 (Creel Bay) and 4 on February 6, 1990. pH generally was similar among sites (fig. 3). Although seasonal variations were not large, pH values generally were smallest in the summer, largest in the winter, and intermediate in the spring and fall.

Vertical variability of pH during open-water periods generally was small (fig. 4). Vertical variability generally was greater during ice cover than during open-water periods. Depth profiles for winter sampling periods indicate near-bottom pH generally was less than near-surface pH.

Water temperature ranged from zero at all sites during one or both winter sampling periods to 27.0°C at site 6 (East Bay west) on August 15, 1989. Water temperature generally was similar among sites (fig. 3).

Vertical variability of water temperature during open-water periods generally was small (fig. 4). The vertical similarity in temperature indicates that Devils Lake generally was not thermally stratified when depth-profile measurements were made during open-water periods. Wind-generated vertical mixing generally prevents establishment of strong thermal stratification for extended open-water periods.

Secchi depth ranged from 3.6 in. at site 1 on October 24, 1990, to 156 in. at sites 2 (Sixmile Bay) and 4 on January 30, 1989. Secchi-depth distributions at selected sampling sites on Devils Lake during September 1988 through October 1990 (fig. 5) indicate shallower sampling sites generally have smaller Secchi depths than deeper sampling sites. The Kruskal-Wallis one-way analysis of variance on ranks (Iman and Conover, 1983) indicates significant differences in Secchi depth among sites (a significance level of 5 percent was used in all statistical analyses for this study). Dunn's multiple-comparison procedure (Hollander and Wolfe, 1973) indicates that Secchi depths for site 1 were significantly smaller than for sites 2, 3, 4, and 10.

Secchi depths at selected sites on Devils Lake (fig. 5) indicate light transmission generally was greatest in the winter and least in the summer. Light transmission was greater during the winter when algal growth and resuspension of sediments by wind-generated turbulence was reduced. Light transmission was less in the summer when increased algal growth and resuspension of sediments contributed to turbidity.

Depth profiles of percent of surface radiation at site 4 for spring, summer, and fall sampling periods (photometer readings were not made during winter sampling periods) show light transmission through the water column was greater in the fall than in the spring and summer (fig. 6).

Dissolved oxygen concentrations ranged from 0.3 mg/L near the lake bottom at site 5 (Mission Bay) on August 15, 1989, to 20.0 mg/L near the surface at site 8 on August 15, 1989 (fig. 3). Dissolved oxygen concentrations generally were similar at all sites (fig. 3).

Vertical variability of dissolved oxygen during spring and fall sampling periods generally was small (fig. 4). Near-bottom dissolved oxygen was less than near-surface dissolved oxygen during summer sampling periods, but near-bottom anoxia was not measured. The mean near-bottom dissolved oxygen

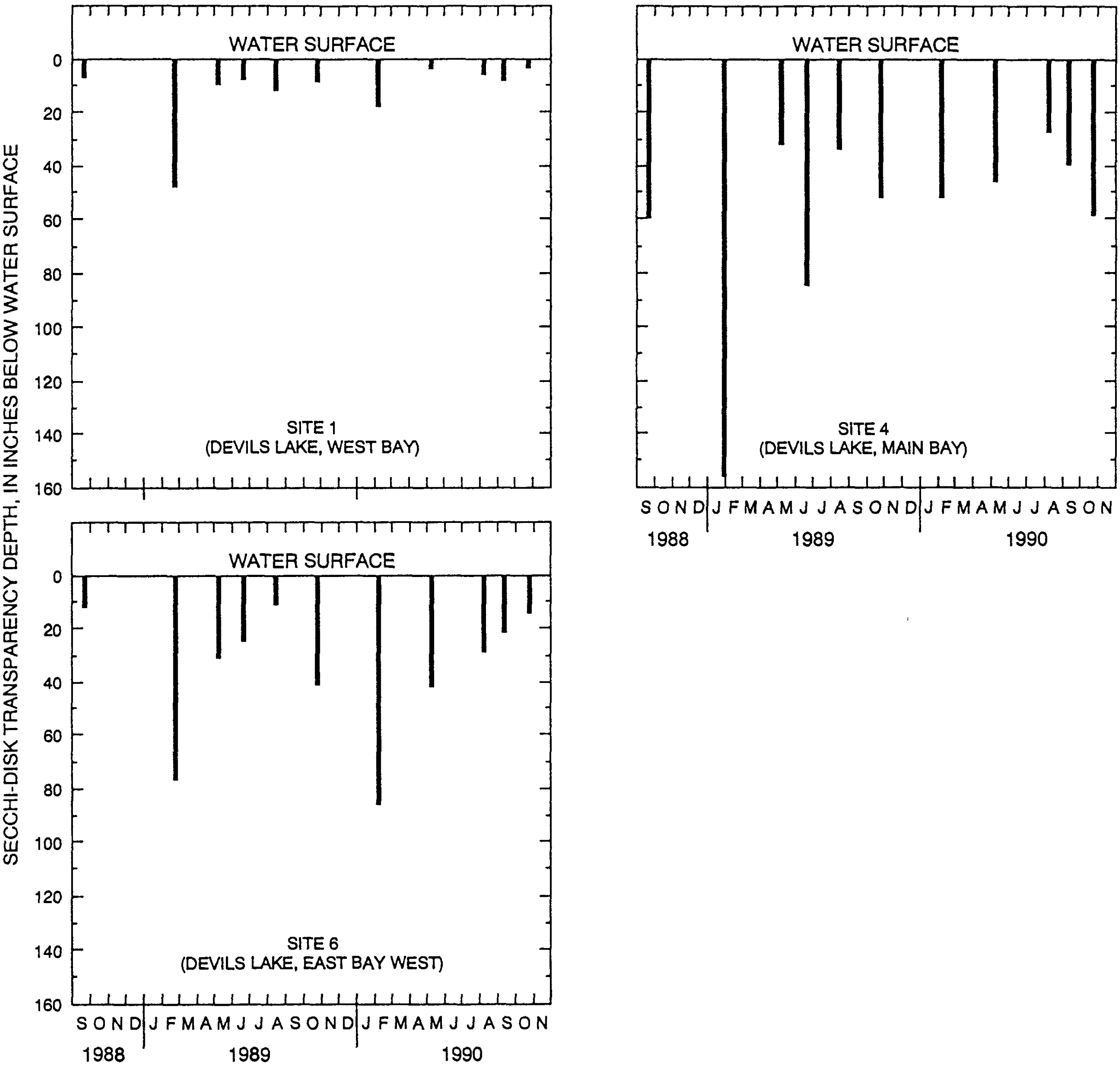

Figure 5. Secchi-disk transparency depth distributions at selected sampling sites on Devils Lake, September 1988 through October 1990.

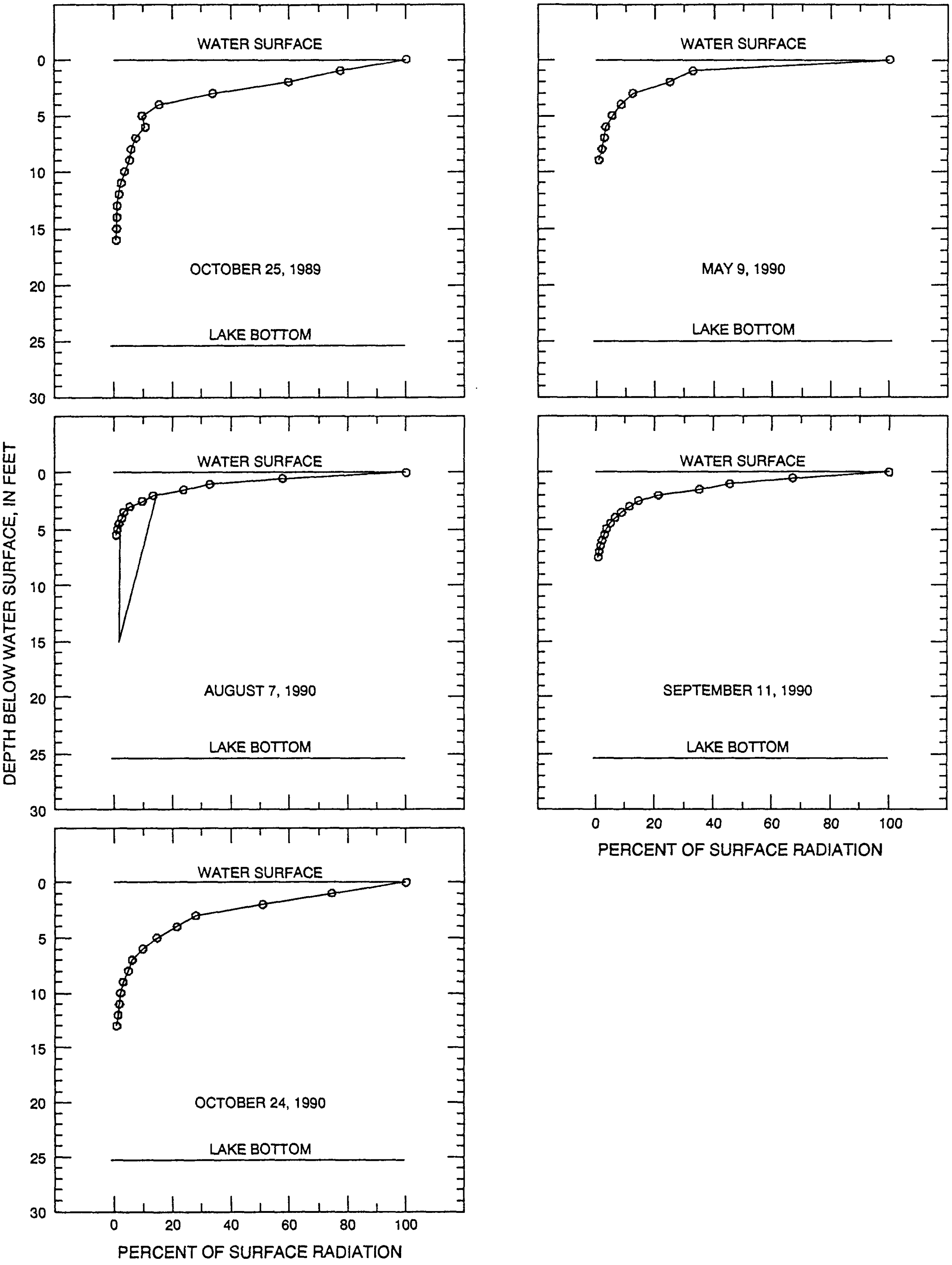

Figure 6. Depth profiles of percent of surface radiation at sampling site 4 (Devils Lake, Main Bay), October 25, 1989, through October 24, 1990.

concentration for summer sampling periods was 7.7 mg/L. Vertical variability of dissolved oxygen was greatest during winter sampling periods. The mean near-bottom dissolved oxygen concentration for winter sampling periods was 5.3 mg/L. Although near-bottom anoxia was not measured, the potential exists for establishment of near-bottom anoxia during extended periods of calm in the summer and during periods of inverse thermal stratification in the winter.

Dissolved Solids and Major Ions

Ionic Proportions

Ionic proportions in water samples collected from the nine sampling sites on Devils Lake were similar. Calcium, magnesium, and sodium were the dominant cations and concentrations generally were similar (table 1). Sulfate was the dominant anion (table 1). In a water-chemical-type classification presented by Barica (1975), major water types are defined by the ratio of the most abundant anion, based on milliequivalent concentration, to the next two most abundant anions; and subclasses are defined by the ratio of most abundant cation to the next two most abundant cations. On the basis of this classification, water samples collected at Big Coulee near Churchs Ferry, N. Dak., are a true sulfate mixed calcium sodium type and water samples collected at Channel A near Penn, N. Dak., are a true sulfate mixed sodium calcium type.

Concentrations of all major ions, except calcium, bicarbonate, and sulfate, were larger in water samples from Devils Lake and East Devils Lake than in water samples from the two tributaries. Equivalent concentrations of all major ions generally increase eastward through Devils Lake and East Devils Lake, but sodium, sulfate, and chloride are enriched relative to the other major ions. The smaller calcium concentrations in water samples from Devils Lake and East Devils Lake compared to calcium concentrations in water samples from the two tributaries probably are because of calcium-carbonate precipitation. Saturation indices for selected minerals in water samples collected from Devils Lake and East Devils Lake during September 1988 through October 1990 indicate all lake samples were supersaturated with respect to calcite.

Spatial Variability

Dissolved-solids distributions in water samples collected at sampling sites on Devils Lake and East Devils Lake during September 1988 through October 1990 (fig. 7) indicate dissolved-solids concentrations generally increased eastward through Devils Lake and East Devils Lake. The Kruskal-Wallis one-way analysis of variance on ranks indicates significant differences among sites. Fisher's least-significant difference procedure for ranks (Iman and Conover, 1983) was conducted to test for significant differences between individual pairs of sites. This procedure indicates that water samples collected from easternmost sites [sites 5, 6, 7 (East Bay east), 8, and 10] had significantly larger dissolved-solids concentrations than water samples collected from westernmost sites (sites 1, 2, 3, and 4). Water samples collected from sites 6, 7, 8, and 10 also had significantly larger dissolved-solids concentrations than water samples collected from site 5; and water samples collected from sites 8 and 10 had significantly larger dissolved-solids concentrations than water samples collected from sites 6 and 7.

Spatial variability of dissolved solids in Devils Lake and East Devils Lake occurs as less-concentrated water enters the western part of the lake and becomes progressively more concentrated by evaporation as it moves eastward through Devils Lake and East Devils Lake. Median dissolved-solids concentrations in water samples collected from the two major tributaries to Devils Lake were 534 mg/L for Big Coulee (calculated from 162 samples collected during October 1957 through April 1989) and 803 mg/L for

Table 1. Mean percent of total milliequivalents per liter of cations and total milliequivalents per liter of anions in water samples collected during September 1988 through October 1990

[The total milliequivalents per liter of cations was calculated as the sum of calcium, magnesium, sodium, and potassium; the total milliequivalents per liter of anions was calculated as the sum of bicarbonate, sulfate, and chloride]

			Mean percent of total milliequivalents per liter of cations				Mean percent of total milliequivalents per liter of anions		
Gaging-station number or site number	Gaging-station name or site name	Number of samples	Calcium, dissolved	Magnesium, dissolved	Sodium, dissolved	Potassium, dissolved	Bicarbonate	Sulfate, dissolved	Chloride, dissolved
05056400	Big Coulee near Churchs Ferry, N. Dak.	2	39.8	24.1	32.9	3.2	18.4	71.9	9.6
05056410	Channel A near Penn, N. Dak.	6	30.8	27.1	39.5	3.0	23.7	70.9	5.5
1	Devils Lake, West Bay	11	5.7	27.2	62.8	4.3	18.1	64.7	17.2
2	Devils Lake, Sixmile Bay	11	5.6	26.7	63.0	4.8	17.3	64.9	17.7
3	Devils Lake, Creel Bay	11	5.9	27.2	62.2	4.7	17.4	64.8	17.8
4	Devils Lake, Main Bay	11	6.0	27.3	62.0	4.6	17.6	64.6	17.9
5	Devils Lake, Mission Bay	11	4.7	26.3	64.6	4.4	14.7	67.3	18.0
6	Devils Lake, East Bay west	11	4.1	25.6	65.7	4.5	12.9	68.2	18.8
7	Devils Lake, East Bay east	11	4.0	26.3	64.9	4.8	12.4	68.8	18.7
8	East Devils Lake inlet	7	2.8	23.3	69.7	4.2	9.9	70.3	19.8
10	East Devils Lake main bay	4	2.9	25.5	67.4	4.5	9.0	70.1	20.9

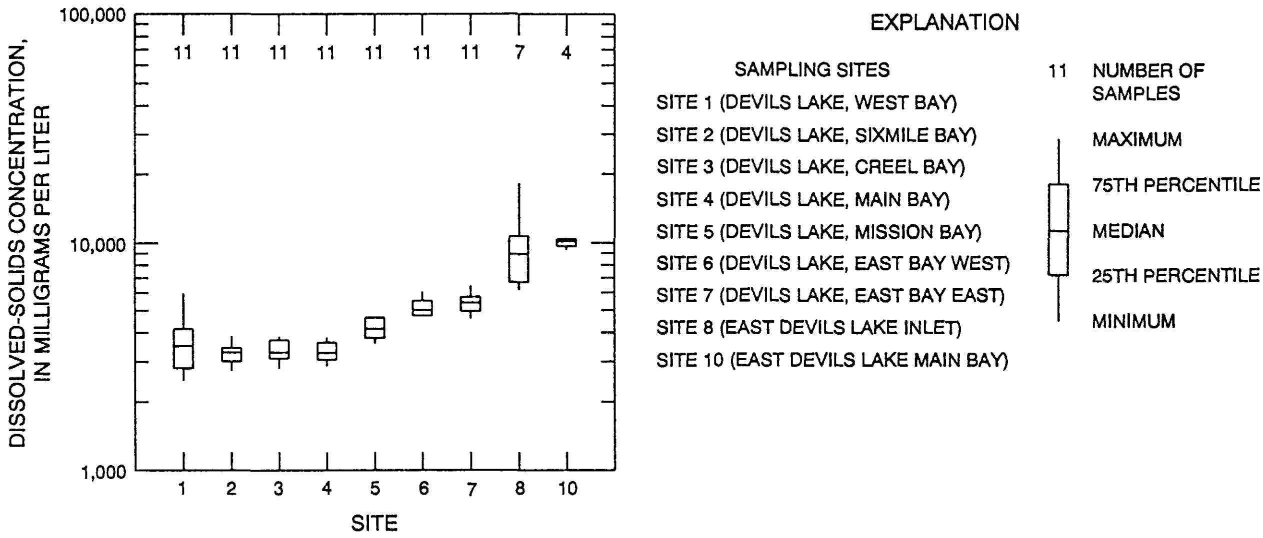

Figure 7. Dissolved-solids distributions in water samples collected at sampling sites on Devils Lake and East Devils Lake, September 1988 through October 1990.

Channel A (calculated from 23 samples collected during May 1984 through April 1990). These concentrations are substantially smaller than dissolved-solids concentrations in any water samples collected from Devils Lake and East Devils Lake during the study period.

Water samples collected from sites 1 through 4, the four Devils Lake sampling sites west of Highway 57, had similar median dissolved-solids concentrations. Dissolved-solids distributions for sites 2 through 4 were similar (fig. 7), which probably indicates that this part of the lake was fairly well mixed. West Bay is considerably shallower than the other bays west of Highway 57, and movement of water between West Bay and Main Bay is partially restricted by Ziebach Pass (fig. 1).

The median dissolved-solids concentration for site 5 was about 4,200 mg/L, the median concentrations for sites 6 and 7 were between about 5,000 and 5,400 mg/L, and the median concentrations for sites 8 and 10 were between about 9,000 and 10,000 mg/L. Because of the restrictions between Main, Mission, and East Bays, water in Mission Bay is partially isolated and dissolved-solids concentrations for site 5 are intermediate between concentrations for sites 4 and 6.

Similar dissolved-solids concentration medians and distributions for sites 6 and 7 indicate that East Bay is fairly well mixed. Median dissolved-solids concentrations for sites 6 and 7 were about 1,000 mg/L larger than the median concentration for site 5 and about 2,000 mg/L larger than the median concentration for site 4.

Median dissolved-solids concentrations for sites 8 and 10 were about 3,500 to 5,000 mg/L larger than median concentrations for sites 6 and 7. East Devils Lake is the most isolated part of the Devils Lake system; movement of water is restricted to four culverts connecting East Bay with East Devils Lake. Dissolved-solids distribution at site 8 was very different from dissolved-solids distribution at site 10 because of differences in lake depth and differences in timing of sample collection. As previously noted, the East Devils Lake sampling site was moved from site 8 to site 10 because of declining water levels. Therefore, the data for site 8 and site 10 were collected at different water levels and at different times. The difference between dissolved solids at site 8 and dissolved solids at other sites was very large because East Devils Lake inlet is shallow, somewhat isolated, and responsive to diluting or concentrating effects.

Dissolved-solids and major-ion concentrations in water samples collected from different depths at sites 4 and 10 on September 11-12, 1990, are shown in table 2. The similarity in dissolved-solids and major-ion concentrations between the euphotic zone and the aphotic zone at each site is consistent with the general lack of vertical variability of specific conductance during the study period. This vertical similarity indicates that, during the sampling periods, the water column was well mixed.

Seasonal Variability

Dissolved-solids concentrations in water samples collected at selected sampling sites on Devils Lake and East Devils Lake during September 1988 through October 1990 are shown in figure 8. Dissolved-solids concentrations generally were largest in the winter when ions were concentrated because of ice formation. Dissolved solids generally are excluded from ice during ice formation, resulting in increased dissolved-solids concentrations in the remaining liquid water. Dissolved-solids concentrations generally were smallest in the spring due to dilution by icemelt, surface-water inflow, and precipitation. The general increase during summer and fall open-water periods is caused by concentration of solutes during periods when evaporation exceeds surface-water inflow and precipitation. The general pattern of seasonal variability of dissolved-solids concentrations for prairie lakes is characterized by concentrations that are largest in the winter, smallest in the spring, and increasing through the summer and fall. This pattern has been described by previous investigators, such as Rawson and Moore (1944) and LaBaugh (1989).

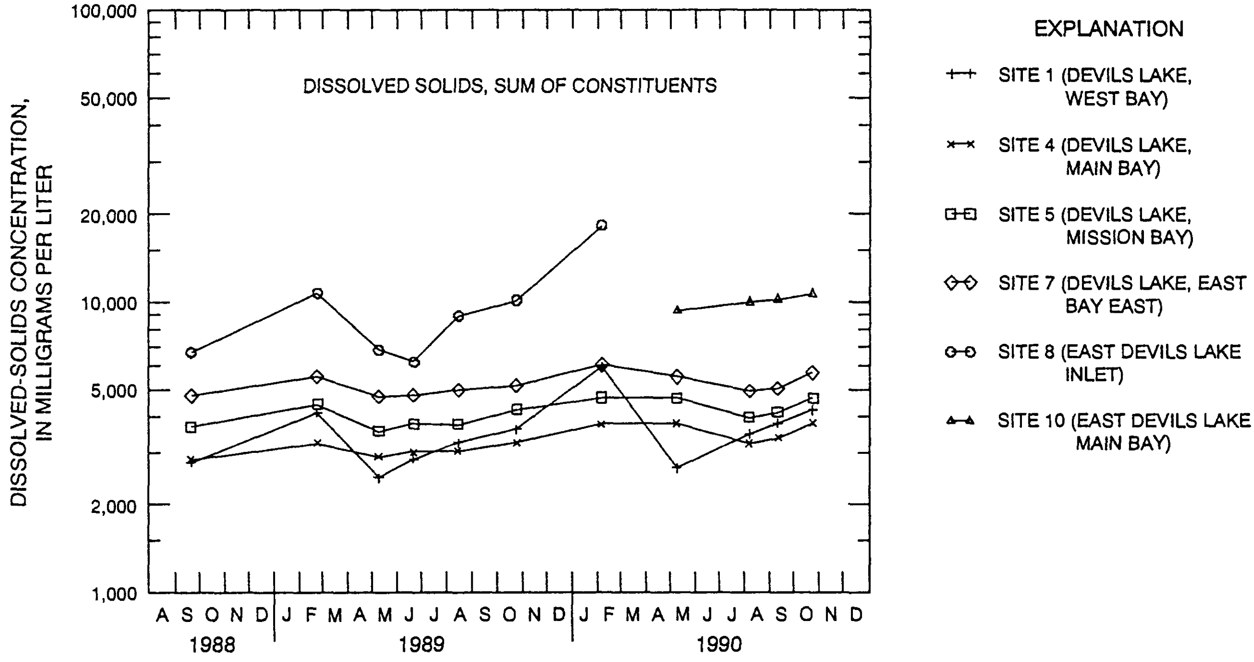

Figure 8. Dissolved-solids concentrations in water samples collected at selected sampling sites on Devils Lake and East Devils Lake, September 1988 through October 1990.

Table 2. Dissolved-solids and major-ion concentrations in water samples collected from the euphotic and aphotic zones at site 4 (Devils Lake, Main Bay) and site 10 (East Devils Lake main bay), September 11-12, 1990

[Water samples collected from each zone were composited; concentrations are in milligrams per liter]

Sample zone	Number of samples com-posited	Calcium, dissolved	Magnesium, dissolved	Sodium, dissolved	Potassium, dissolved	Alkalinity, total as $CaCO_3$	Sulfate, dissolved	Chloride, dissolved	Fluoride, dissolved	Silica, dissolved	Dissolved solids, calculated, sum of constituents
Site 4											
Euphotic	3	54	180	740	98	460	1,700	340	0.1	8.4	3,400
Aphotic	1	52	170	830	110	460	1,700	300	.1	9.0	3,450
Site 10											
Euphotic	3	90	460	2,300	290	680	5,500	1,100	1.3	11	10,200
Aphotic	1	94	450	2,400	260	670	5,400	1,200	.2	11	10,200

Long-Term Variability

Many hydrologic studies of Devils Lake have involved the collection of water-quality data. Data from Pope (1909), Daudt (1911), Nerhus (1920), Young (1924), Swenson and Colby (1955), Mitten and others (1968), Shubert (1976), DeGroot (1980), and Holme (1986) were used to evaluate long-term variability in dissolved-solids concentrations in Devils Lake.

The annual mean dissolved-solids concentration in water samples collected from the part of Devils Lake west of Highway 20 (fig. 1) and the water level for that part of the lake for 1899 through 1990 are shown in figure 9. Very few previous studies of Devils Lake included water-quality data for sampling sites in East Bay or East Devils Lake; therefore, only data from the part of Devils Lake west of Highway 20 were used to develop figure 9.

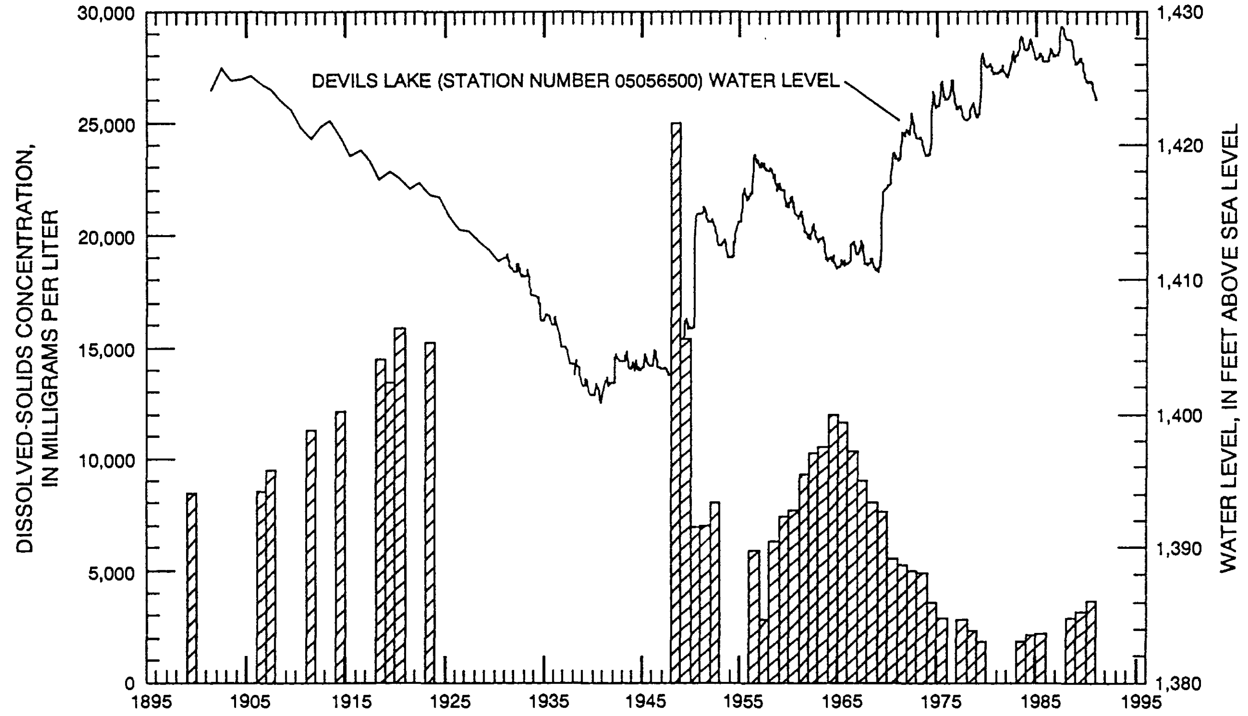

Figure 9. Annual mean dissolved-solids concentration in water samples collected from the part of Devils Lake west of Highway 20 and water level for that part of the lake, 1899 through 1990. (From Pope, 1909; Daudt, 1911; Nerhus, 1920; Young, 1924; Swenson and Colby, 1955; Mitten and others, 1968; Shubert, 1976; DeGroot, 1980; Holme, 1986.)

The procedures used to calculate the annual mean dissolved-solids concentrations shown in figure 9 may affect comparability of the individual values but do not obscure the general pattern of variability associated with water-level fluctuations. The number and location of sampling sites where water samples were collected to determine the annual mean dissolved-solids concentration of the lake varied during the 92-year period, but Devils Lake west of Highway 20 generally is well mixed and dissolved-solids concentrations are spatially similar. The number and timing of sample collections also varied, but most samples were collected between June and October when the dissolved-solids mass in Devils Lake is fairly constant within a given year. Two methods were used to determine dissolved-solids concentrations--summation of dissolved-solids constituents and residue on evaporation at 180°C. However, dissolved-solids concentrations determined as residue on evaporation at 180°C exceeded dissolved-solids concentrations calculated as the sum of constituents by an average of only 2.2 percent for 95 samples. Also, dissolved-solids concentrations for 1961-68 were estimated from a graph of dissolved solids versus time presented by Shubert (1976).

Generally, dissolved-solids concentration fluctuates inversely with water level (fig. 9). When evaporation is greater than inflow into Devils Lake and precipitation falling on the lake surface, the water level decreases and concentrations of most ions increase. Conversely, when evaporation is less than runoff into Devils Lake and precipitation falling on the lake surface, the water level increases and concentrations of most ions decrease. Farmer (1973) and Shubert (1976) also discussed the inverse relation between dissolved-solids concentration in Devils Lake and the water level of Devils Lake.

The dissolved-solids mass in Devils Lake remained fairly stable during the study period and ranged from 2.85 million tons on February 7, 1990, to 3.26 million tons on May 9, 1990. The dissolved-solids mass in East Devils Lake also was stable and ranged from 1.21 to 1.31 million tons. Because of drought conditions, external sources of dissolved solids to Devils Lake and East Devils Lake were negligible during the study period. Seasonal patterns in dissolved-solids mass fluctuations during the study period were not readily apparent. Although the dissolved-solids concentration of Devils Lake generally fluctuates inversely with water level, the dissolved-solids mass generally fluctuates directly with water level. During periods of extremely low water levels, dissolved solids may be lost from Devils Lake by wind transport of solids (removal of aerosols or removal of deposited solids from exposed sediments) or incorporated into sediment pore water.

The ionic proportions associated with variable dissolved-solids concentrations in water samples collected during this study are similar to the long-term proportions (table 1). Analyses of water in Devils Lake for 1909-90 indicate sodium was the most abundant cation and sulfate was the most abundant anion. However, when water in Devils Lake was relatively dilute, other ions generally increased in proportion to sodium and sulfate. During September 1988 through October 1990, when the water level of Devils Lake had a mean elevation of about 1,425 ft above sea level and the mean dissolved-solids concentration was about 3,320 mg/L, water in Main Bay was a mixed sulfate chloride mixed sodium magnesium type. Similarly, in the fall of 1975, when the water level of Devils Lake was about 1,425 ft above sea level and the dissolved-solids concentration was about 3,380 mg/L, water in Main Bay was an intermediate sulfate bicarbonate intermediate sodium magnesium type. When water in Devils Lake is more concentrated, sodium and sulfate generally increase in proportion to other ions. In the fall of 1960, when the water level of Devils Lake was about 1,415 ft above sea level and the dissolved-solids concentration was about 7,940 mg/L, water in Main Bay was a true sulfate true sodium type. Also, in 1948, when the water level of Devils Lake was about 1,404 ft above sea level and the dissolved-solids concentration was 25,000 mg/L, water in Main Bay was a true sulfate true sodium type.

Nutrients

Nitrogen

Nitrogen species discussed in this report include dissolved nitrite, dissolved nitrite plus nitrate, total ammonia, dissolved ammonia, and total ammonia plus organic nitrogen concentrations in water samples collected from the euphotic zone and total nitrite plus nitrate, total ammonia, and total ammonia plus organic nitrogen concentrations in bottom-material samples. Total nitrogen concentrations also are discussed and were calculated by adding dissolved nitrite plus nitrate and total ammonia plus organic nitrogen concentrations for water samples and by adding total nitrite plus nitrate and total ammonia plus organic nitrogen concentrations for bottom-material samples.

Spatial Variability

Total ammonia, dissolved ammonia, and total nitrogen distributions in water samples collected from the euphotic zone at sampling sites on Devils Lake and East Devils Lake during September 1988 through October 1990 are shown in figure 10. Distributions are not shown for dissolved nitrite and dissolved nitrite plus nitrate because concentrations generally were below the detection limit of 0.10 mg/L, except during winter sampling periods at some sites. Total ammonia and dissolved ammonia concentrations generally were below 0.10 mg/L and occasionally were below the detection limit of 0.01 mg/L, except during winter sampling periods. Total nitrogen concentrations in Devils Lake and East Devils Lake were extremely large and generally were similar to concentrations reported for hypereutrophic systems (Barica, 1974, 1975). Total nitrogen concentrations in Devils Lake and East Devils Lake during the study period commonly were between 1.0 and 8.6 mg/L.

The Kruskal-Wallis one-way analysis of variance on ranks, which was used to test for differences in concentrations of nitrogen species among sites, indicates significant differences for total ammonia, dissolved ammonia, and total nitrogen. Results of Fisher's least-significant difference procedure for ranks are shown in table 3. Shallower sampling sites (sites 1, 6, 7, and 8) tended to have significantly larger total ammonia, dissolved ammonia, and total nitrogen concentrations than deeper sampling sites.

Table 3. Results of Fisher's least-significant difference procedure for ranks to test for significant differences (alpha = 0.05) in concentrations of nitrogen species between individual pairs of sampling sites on Devils Lake and East Devils Lake

Species	Significant differences between individual pairs of sampling sites
Ammonia, total	Site 1 greater than sites 2, 3, 4, and 10; site 6 greater than sites 4 and 10; site 7 greater than sites 2, 3, 4, and 10; site 8 greater than sites 2, 3, 4, 5, and 10.
Ammonia, dissolved	Site 1 greater than sites 2, 4, and 10; site 5 greater than site 10; sites 6, 7, and 8 greater than sites 2, 3, 4, and 10.
Nitrogen, total	Sites 1, 6, 7, 8, and 10 greater than sites 2, 3, 4, and 5.

A general, though not always consistent, relation exists between total ammonia, dissolved ammonia, and total nitrogen concentrations and water depth (fig. 11). Spearman's rank correlation (Iman and Conover, 1983) was used to test the strength of the decreasing monotonic relation between median concentrations of nitrogen species and median water depths. The decreasing monotonic relations between median total ammonia and median water depth and between dissolved ammonia concentrations and median water depth were significant. The relation between median total nitrogen concentration and median water depth was not monotonic, probably because total nitrogen concentrations at site 10 were large relative to other nutrient concentrations.

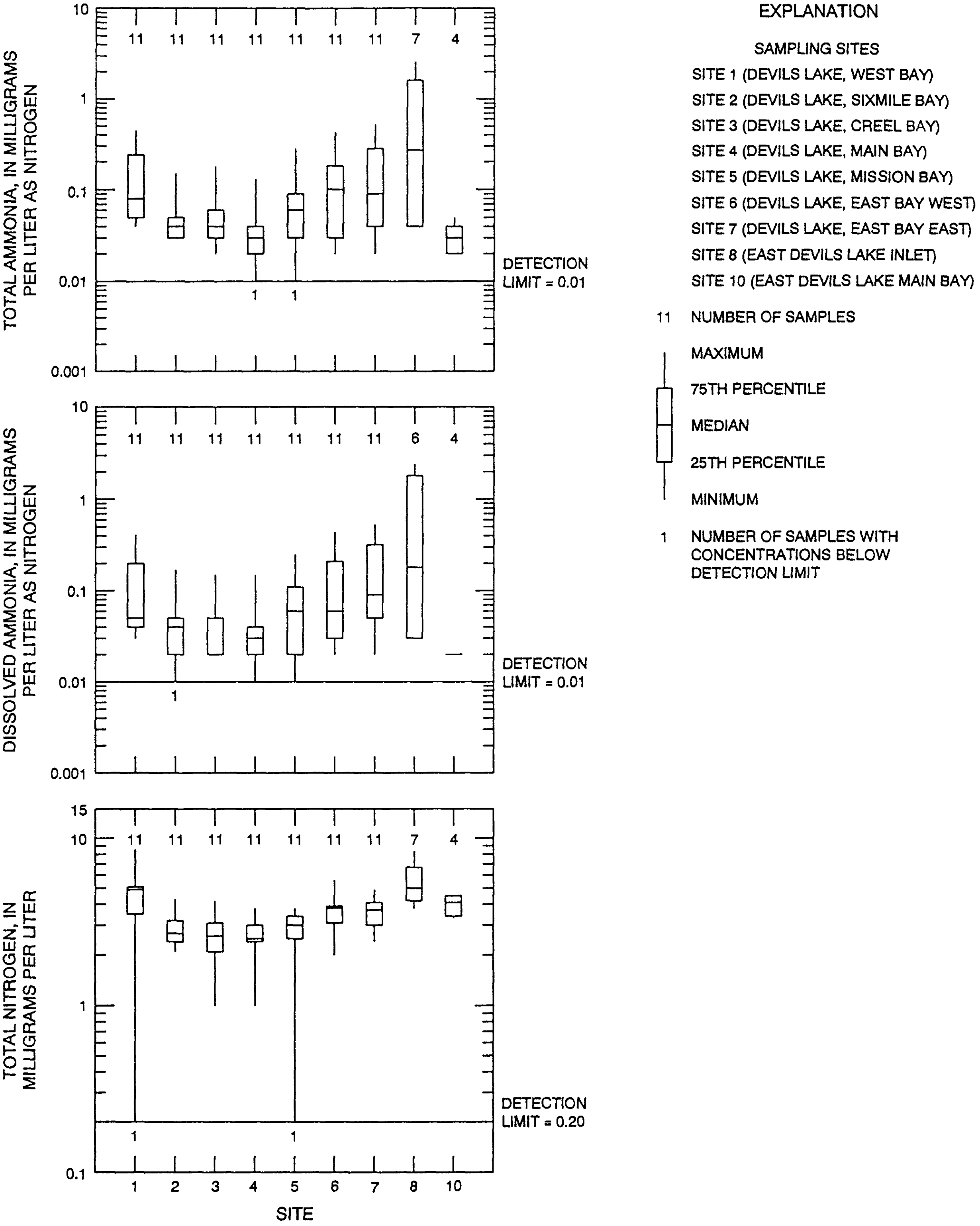

Figure 10. Total ammonia, dissolved ammonia, and total nitrogen distributions in water samples collected from the euphotic zone at sampling sites on Devils Lake and East Devils Lake, September 1988 through October 1990.

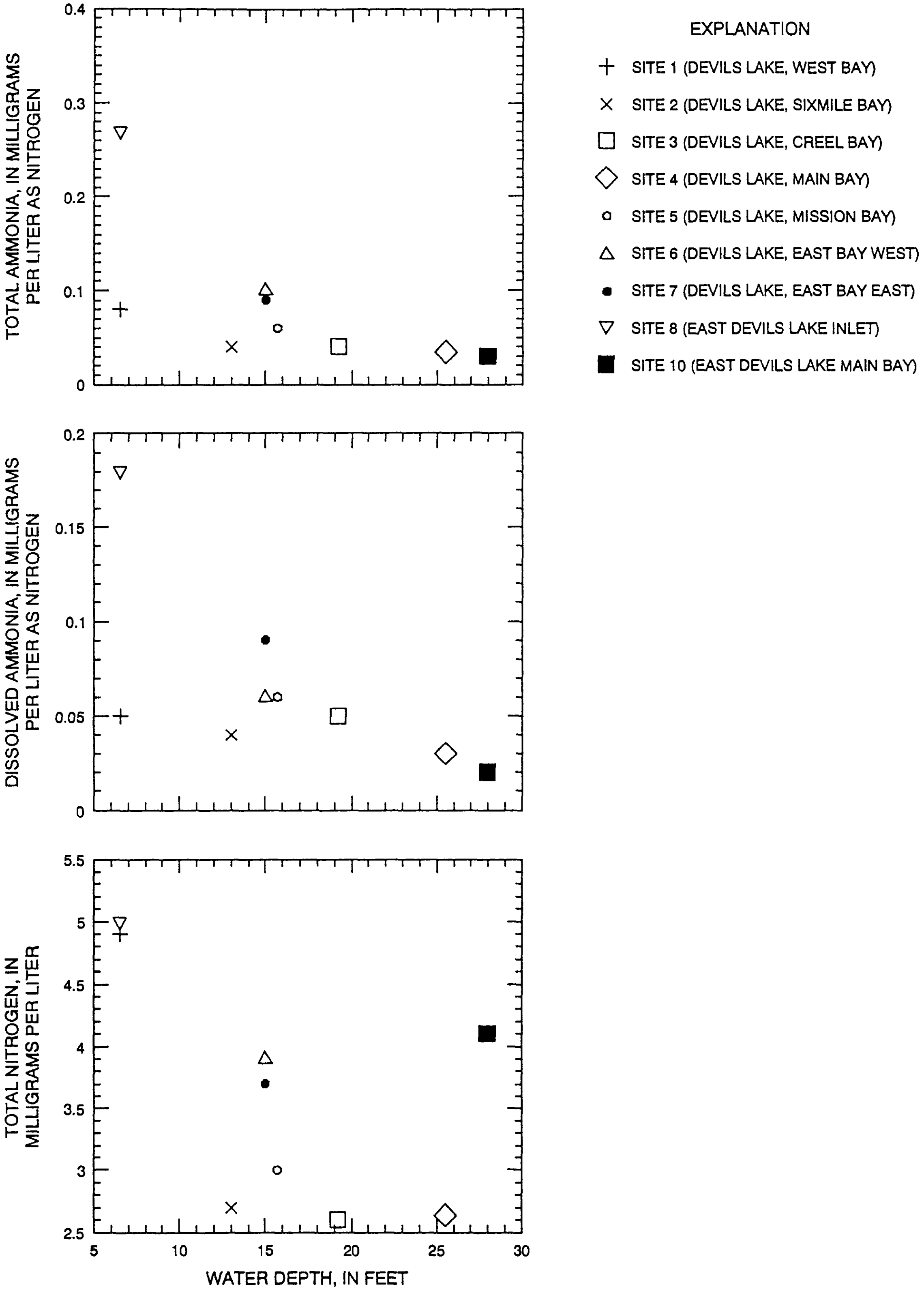

Figure 11. Median total ammonia, dissolved ammonia, and total nitrogen concentrations in water samples collected from the euphotic zone at sampling sites on Devils Lake and East Devils Lake and median water depth, September 1988 through October 1990.

Rawson (1939) and Sakamoto (1966) noted a general relation between lake depth and lake productivity. Fee (1979) examined the depth-productivity relation for lakes and determined that lake productivity was strongly correlated to the ratio of sediment surface area in contact with the epilimnion to the volume of the epilimnion. Fee reasoned that lakes for which this ratio is large have a greater capability for nutrient regeneration from the sediments into the trophogenic zone (the zone characterized by photosynthetic production; comparable to the euphotic zone) than lakes for which this ratio is small. The greater nutrient regeneration capacity results in greater primary productivity. Therefore, the ratio of sediment surface area to lake volume for a given part of the lake may partly explain spatial variability in concentrations of nitrogen species in Devils Lake and East Devils Lake.

Important processes that result in movement of nitrogen from sediments include diffusion of ammonia from sediments when reducing conditions exist at the sediment-water interface either during ice cover or during calm open-water periods (Barica, 1975) and release of accumulated dissolved and particulate nitrogen by physical resuspension of upper layers of sediments (Barica, 1975; Kenney, 1985). The importance of bottom-sediment processes to nutrient budgets in Devils Lake was documented by Komor (1992), Lent (1994), and Lent and others (1994). Komor (1992) and Lent (1994) calculated benthic fluxes of nutrients from bottom sediments to Devils Lake on the basis of pore-water data. Lent (1994) showed that benthic fluxes may be the dominant source of nutrients to Devils Lake. Lent and others (1994) confirmed this conclusion on the basis of intensive sampling of tributary inflow and lake water during 1993.

Concentrations of nitrogen species in water samples collected from the euphotic and aphotic zones at selected sampling sites on Devils Lake during the September and October 1990 sampling periods are shown in table 4. Dissolved nitrite and dissolved nitrite plus nitrate concentrations generally were below the detection limit. At sampling sites where these concentrations were detectable, there was little difference between concentrations in the euphotic zone and concentrations in the aphotic zone. During the October 1990 sampling period, total ammonia and dissolved ammonia concentrations in the euphotic zone were similar to total ammonia and dissolved ammonia concentrations in the aphotic zone (table 4). The similar concentrations indicate that Devils Lake generally was well mixed during the October 1990 sampling period. Also during the October 1990 sampling period, most total nitrogen concentrations in the euphotic zone were slightly larger than total nitrogen concentrations in the aphotic zone.

Median concentrations of nitrogen species in bottom-material samples collected at sampling sites on Devils Lake and East Devils Lake during 4 of the 11 sampling periods (Sando and Sether, 1993) are shown in table 5. Because the East Devils Lake sampling site was changed from site 8 to site 10 in May 1990, only one sample was collected at site 8 and three samples were collected at site 10. Median total ammonia concentrations ranged from 6.7 mg/kg at site 10 to 100 mg/kg at site 4. Median total nitrogen concentrations ranged from 5,100 mg/kg at site 7 to 12,000 mg/kg at site 1. Median concentrations of nitrogen species generally were larger at sites 1, 3, and 4 than at other sites (table 5). The large concentrations of nitrogen species at site 1 may be caused by the contribution of nitrogen by Big Coulee and by the subsequent sorption of particulate nitrogen onto sediments in West Bay. The large concentrations of nitrogen species at site 3 may be caused by past discharges of raw sewage, treated wastewater effluent, and stormwater runoff from the city of Devils Lake into the northern end of Creel Bay. The large concentrations of nitrogen species at site 4 may result from contributions of nitrogen by West Bay and Creel Bay; site 4 is in the flow path of water moving from those bays.

Seasonal Variability

Dissolved nitrite plus nitrate, dissolved ammonia, and total nitrogen concentrations in water samples collected from the euphotic zone at sampling sites on Devils Lake and East Devils Lake during September

Table 4. Concentrations of nitrogen species in water samples collected from the euphotic and aphotic zones at selected sampling sites on Devils Lake on September 11-12 and October 24-25, 1990

[Concentrations are in milligrams per liter; <, less than]

Species	Sample zone	Devils Lake, West Bay (site 1)	Devils Lake, Sixmile Bay (site 2)	Devils Lake, Creel Bay (site 3)	Devils Lake, Mission Bay (site 5)	Devils Lake, East Bay east (site 7)
		September 11-12, 1990				
Nitrite, dissolved	Euphotic	0.01	<0.01	<0.01	<0.01	0.02
	Aphotic	<.01	.01	<.01	<.01	.03
Nitrite plus nitrate, dissolved	Euphotic	<.10	<.10	<.10	<.10	<.10
	Aphotic	<.10	<.10	<.10	<.10	<.10
Ammonia, total	Euphotic	.12	.04	.03	.03	.09
	Aphotic	.03	.04	.03	.04	.09
Ammonia, dissolved	Euphotic	.04	.04	.05	.04	.09
	Aphotic	.10	.05	.04	.06	.10
Nitrogen, total	Euphotic	<.20	3.1	3.1	<.20	2.4
	Aphotic	1.7	3.4	.70	<.20	2.1

Table 4. Concentrations of nitrogen species in water samples collected from the euphotic and aphotic zones at selected sampling sites on Devils Lake on September 11-12 and October 24-25, 1990—Continued

[Concentrations are in milligrams per liter; <, less than]

Species	Sample zone	Devils Lake, West Bay (site 1)	Devils Lake, Sixmile Bay (site 2)	Devils Lake, Creel Bay (site 3)	Devils Lake, Mission Bay (site 5)	Devils Lake, East Bay east (site 7)
		October 24-25, 1990				
Nitrite, dissolved	Euphotic	0.03	0.02	<0.01	<0.01	0.02
	Aphotic	.01	<.01	<.01	<.01	<.01
Nitrite plus nitrate, dissolved	Euphotic	<.10	<.10	<.10	<.10	<.10
	Aphotic	<.10	<.10	<.10	<.10	<.10
Ammonia, total	Euphotic	.32	.09	.07	.06	.07
	Aphotic	.29	.10	.06	.07	.07
Ammonia, dissolved	Euphotic	.20	.07	.05	.06	.05
	Aphotic	.21	.08	.06	.06	.05
Nitrogen, total	Euphotic	5.1	3.2	3.0	3.4	3.9
	Aphotic	4.5	3.0	2.7	3.2	3.8

Table 5. Median concentrations of nitrogen species in bottom-material samples collected at selected sampling sites on Devils Lake and East Devils Lake

[Concentrations are in milligrams per kilogram dry weight; <, less than]

Species	Devils Lake, West Bay (site 1)	Devils Lake, Sixmile Bay (site 2)	Devils Lake, Creel Bay (site 3)	Devils Lake, Main Bay (site 4)	Devils Lake, Mission Bay (site 5)	Devils Lake, East Bay west (site 6)	Devils Lake, East Bay east (site 7)	East Devils Lake main bay (site 10)
Nitrite plus nitrate, total	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
Ammonia, total	98	63	78	100	58	37	46	6.7
Nitrogen, total	12,000	6,200	10,000	8,200	6,400	7,900	5,100	6,200
Number of samples	4	4	4	4	4	4	4	3

1988 through October 1990 are shown in figure 12. The unusually small total nitrogen concentrations in water samples collected at several sites on September 11-12, 1990, may have resulted from sample contamination during processing. Caution should be used in drawing conclusions concerning seasonal variability in concentrations of nitrogen species because of these unusual total nitrogen concentrations.

Seasonal variability in concentrations of nitrogen species collected from the euphotic zone generally was similar among sites. Total nitrogen concentrations generally were smallest in the fall, increased in the winter, remained the same or decreased in the spring, and increased again in the summer. Barica (1974) and LaBaugh (1989) noted similar seasonal patterns for nitrogen in prairie lakes and wetlands. The small total nitrogen concentrations in the fall occur as algal populations decline and organic detritus settles from the water column. Turbulent and thermal mixing cause oxic conditions to exist throughout the water column. Oxic conditions favor retention of ammonia within the sediments (Wetzel, 1983). The large total nitrogen concentrations that occur in the winter are accompanied by large dissolved ammonia concentrations. Microbial decomposition of sedimentary organic matter during ice cover often results in near-bottom dissolved oxygen depletion and establishment of reducing conditions in and near the sediments in Devils Lake. The adsorptive capacity of the sediments is less when reducing conditions exist and ammonia can be released (Wetzel, 1983). Microbial deamination of organic nitrogen compounds also produces dissolved ammonia (Barica, 1974). Nitrification also can occur and results in the accumulation of dissolved nitrite plus nitrate. Small algal populations and the concentrating effect of ion freezeout during ice formation also contribute to the large total nitrogen concentrations that occur in the winter. In the spring, the ice cover breaks up, water is circulated by turbulent and thermal mixing, and solute concentrations are diluted by icemelt. Much of the available dissolved nitrogen is assimilated by early season algal growth, and dissolved ammonia and dissolved nitrite plus nitrate concentrations generally are small. Also, reestablishment of oxic conditions throughout the water column may increase the capability of sediments to retain ammonia. In the summer, dissolved inorganic nitrogen is rapidly assimilated by algae. Ammonia released from the sediments is assimilated and largely retained in the water column. Concentrations of dissolved inorganic nitrogen are very small except during periods when algal blooms are collapsing. A collapse probably was occurring during the June 20-21, 1989, sampling period as evidenced by the larger dissolved ammonia and dissolved nitrite plus nitrate concentrations throughout Devils Lake and East Devils Lake at that time. In addition to assimilation of dissolved nitrogen from the water column, fixation of atmospheric nitrogen by heterocystous blue-green algae contributes to the large total nitrogen concentrations that occur in the summer in Devils Lake and East Devils Lake.

Phosphorus

Spatial Variability

Total phosphorus, dissolved phosphorus, and dissolved orthophosphate distributions in water samples collected from the euphotic zone at sampling sites on Devils Lake and East Devils Lake during September 1988 through October 1990 are shown in figure 13. The Kruskal-Wallis one-way analysis of variance on ranks (Iman and Conover, 1983) indicates no significant differences in concentrations of phosphorus species among sites. Phosphorus species distributions (fig. 13) indicate that the dissolved phosphorus and dissolved orthophosphate concentrations at site 1 generally were smaller than the dissolved phosphorus and dissolved orthophosphate concentrations at other sites, but the total phosphorus concentration generally was similar to that at other sites.

Concentrations of phosphorus species in water samples collected from the euphotic and aphotic zones at selected sampling sites on Devils Lake during the September and October 1990 sampling periods are shown in table 6. The differences between phosphorus species concentrations in the two zones generally

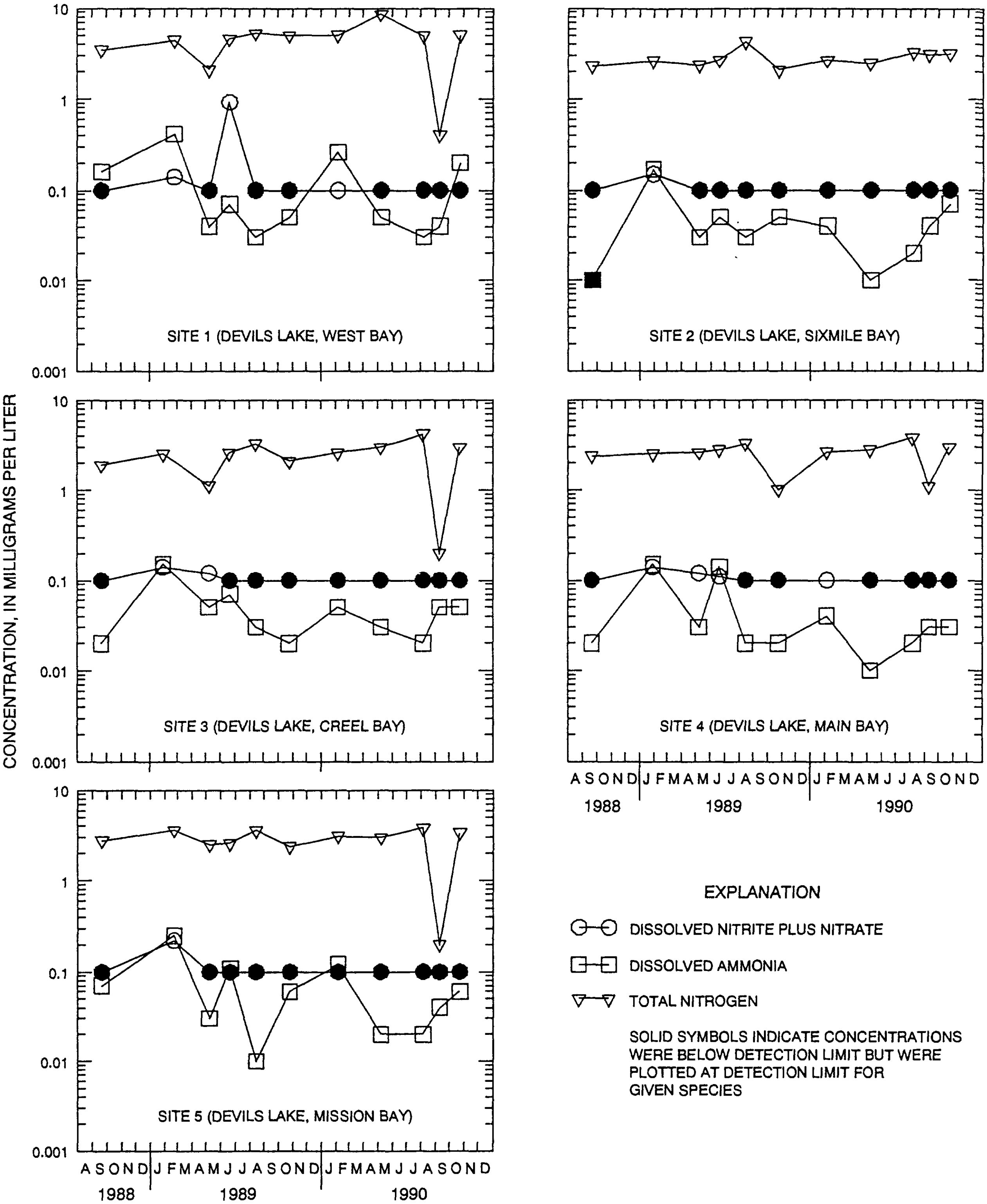

Figure 12. Dissolved nitrite plus nitrate, dissolved ammonia, and total nitrogen concentrations in water samples collected from the euphotic zone at sampling sites on Devils Lake and East Devils Lake, September 1988 through October 1990.

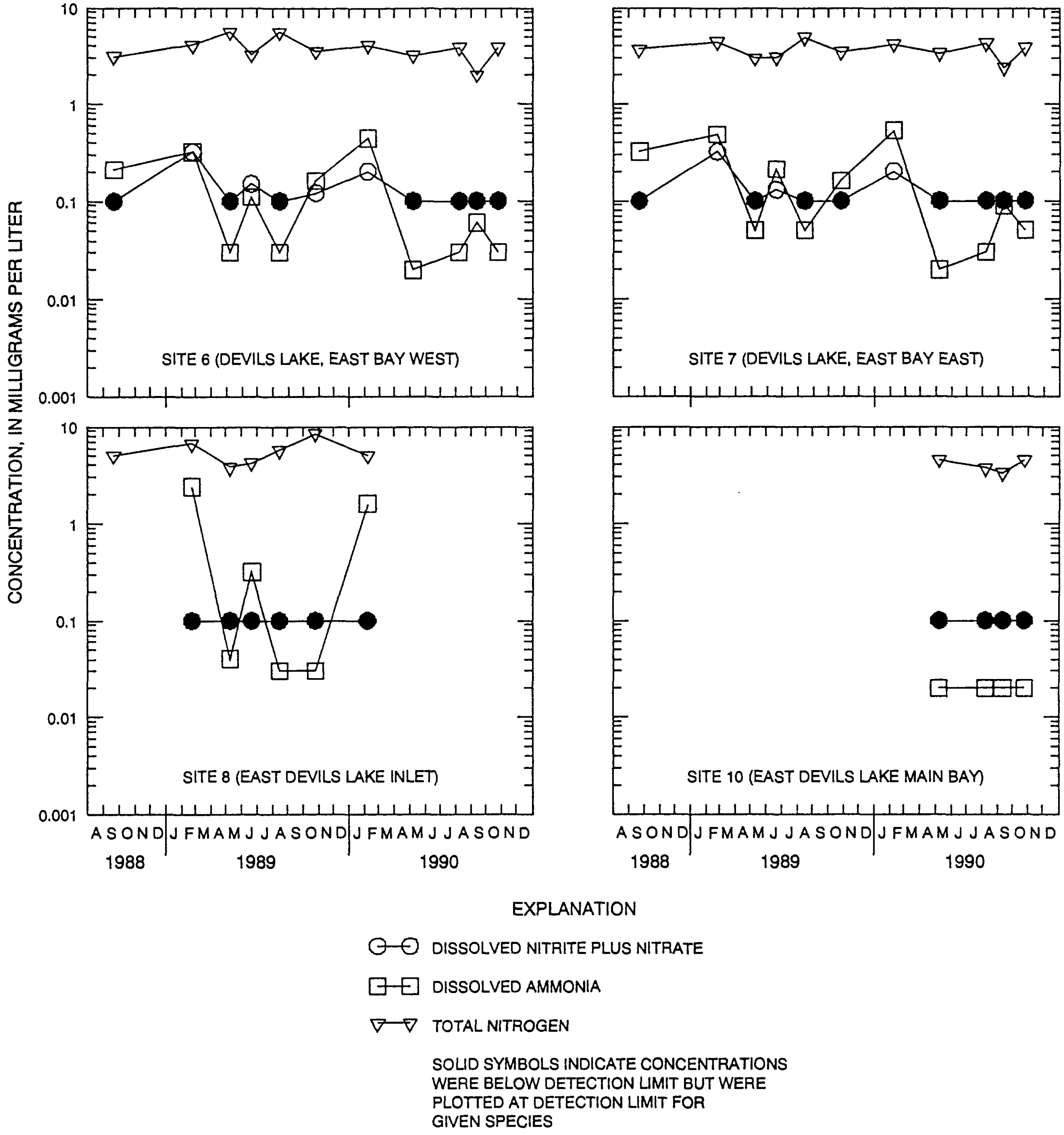

Figure 12. Dissolved nitrite plus nitrate, dissolved ammonia, and total nitrogen concentrations in water samples collected from the euphotic zone at sampling sites on Devils Lake and East Devils Lake, September 1988 through October 1990--Continued.

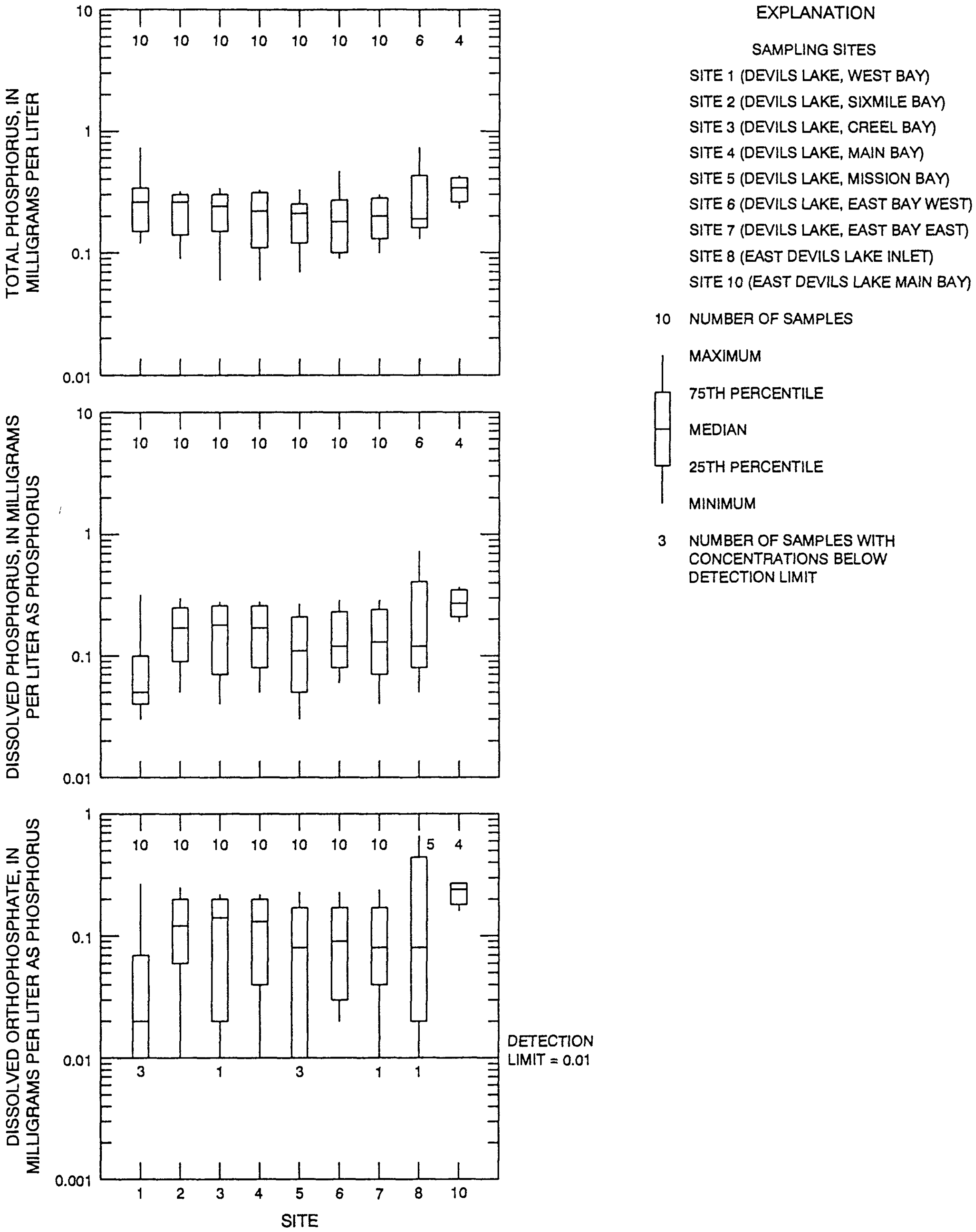

Figure 13. Total phosphorus, dissolved phosphorus, and dissolved orthophosphate distributions in water samples collected from the euphotic zone at sampling sites on Devils Lake and East Devils Lake, September 1988 through October 1990.

Table 6. Concentrations of phosphorus species in water samples collected from the euphotic and aphotic zones at selected sampling sites on Devils Lake on September 11-12 and October 24-25, 1990

[Concentrations are in milligrams per liter; <, less than]

Species	Sample zone	Devils Lake, West Bay (site 1)	Devils Lake, Sixmile Bay (site 2)	Devils Lake, Creel Bay (site 3)	Devils Lake, Mission Bay (site 5)	Devils Lake, East Bay east (site 7)
		September 11-12, 1990				
Phosphorus, total	Euphotic	0.14	0.14	0.18	0.15	0.12
	Aphotic	.12	.16	.14	.09	.09
Phosphorus, dissolved	Euphotic	.06	.05	.09	.06	.04
	Aphotic	.08	.04	.10	.08	.06
Orthophosphate, dissolved	Euphotic	.07	.01	.03	<.01	<.01
	Aphotic	.02	.01	.03	<.01	.01
		October 24-25, 1990				
Phosphorus, total	Euphotic	0.12	0.09	0.06	0.07	0.10
	Aphotic	.10	.07	.05	.06	.08
Phosphorus, dissolved	Euphotic	.03	.06	.05	.03	.07
	Aphotic	.02	.05	.06	.03	.04
Orthophosphate, dissolved	Euphotic	<.01	.02	.01	<.01	.03
	Aphotic	<.01	.02	.01	<.01	.02

were small for both sampling periods. The similar concentrations indicate that Devils Lake generally was well mixed during the September and October 1990 sampling periods.

Median concentrations of phosphorus species in bottom-material samples collected at sampling sites on Devils Lake and East Devils Lake during 4 of the 11 sampling periods are shown in table 7. Because the East Devils Lake sampling site was changed from site 8 to site 10 in May 1990, only one sample was collected at site 8 and three samples were collected at site 10. Median total phosphorus concentrations ranged from 580 mg/kg at site 1 to 1,000 mg/kg at site 3. The median total phosphorus concentrations were largest at sites 3 and 4 (table 7). Long-term discharge of sewage effluent and stormwater runoff from the city of Devils Lake into the northern end of Creel Bay may have contributed to these larger concentrations. The median total phosphorus concentrations were smaller at sites 1and 2 than at sites 3 and 4. The smaller concentrations at sites 1 and 2 may indicate that long-term phosphorus loading by tributary inflow into West Bay and Sixmile Bay may have been less than phosphorus loading by discharge of sewage effluent and stormwater runoff into Creel Bay.

Seasonal Variability

Total phosphorus, dissolved phosphorus, and dissolved orthophosphate concentrations in water samples collected from the euphotic zone at sampling sites on Devils Lake and East Devils Lake during September 1988 through October 1990 are shown in figure 14. Seasonal variability in total phosphorus, dissolved phosphorus, and dissolved orthophosphate generally was similar. Phosphorus concentrations generally were smallest in the fall, increased in the winter, decreased in the spring, and increased again in the summer (fig. 14). The small phosphorus concentrations in the fall develop as algal populations decline, settle from the water column, and deposit in the sediments. Relatively low water temperatures in the fall also retard microbial activity and allow little release of dissolved phosphorus from decomposition as algae sink. In the winter, microbial decomposition of sedimented organic matter occurs and dissolved organic and inorganic phosphorus is released from the sediments. Also, microbial consumption of oxygen in the sediments results in establishment of reducing conditions in and near the sediments and causes dissolved orthophosphate to be released from the sediments as phosphorus-metal and phosphorus-clay complexes dissolve and anaerobic decomposition of organic matter occurs. During both winter sampling periods, dissolved phosphorus species comprised nearly all of the phosphorus present at most sampling sites (fig. 14). The concentrating effect of ion freezeout during ice formation also may contribute to the larger phosphorus concentrations that occur in the winter. In the spring, the ice cover breaks up and water is circulated by turbulent and thermal mixing. Some of the available dissolved phosphorus is assimilated by early season algal growth and there is a greater decrease in dissolved phosphorus than in total phosphorus between the winter and the spring (fig. 14). Reestablishment of oxic conditions near the sediments probably results in a loss of dissolved inorganic phosphorus from solution as phosphorus coprecipitates with metal ions such as iron and also adsorbs on positively charged clay particles (Wetzel, 1983). In the summer, water temperature and solar radiation increase, algal growth increases, and more of the phosphorus occurs in particulate form than in dissolved form. Reducing conditions may be established near the sediments during calm periods and dissolved phosphorus can be released from the sediments. Evaporative concentration also may contribute to the larger phosphorus concentrations that occur in the summer.

Total phosphorus concentrations in water samples collected from the euphotic zone during the fall sampling periods (September 20-21, 1988, October 25-26, 1989, and October 24-25, 1990) indicate a general decrease in total phosphorus concentrations during the study period (fig. 14). The decrease may be caused by small phosphorus inputs to Devils Lake and East Devils Lake and also may indicate a net flux of phosphorus from the water to the sediments during the study period.

Table 7. Median total phosphorus concentrations in bottom-material samples collected at selected sampling sites on Devils Lake and East Devils Lake
[Concentrations are in milligrams per kilogram dry weight]

	Devils Lake, West Bay (site 1)	Devils Lake, Sixmile Bay (site 2)	Devils Lake, Creel Bay (site 3)	Devils Lake, Main Bay (site 4)	Devils Lake, Mission Bay (site 5)	Devils Lake, East Bay west (site 6)	Devils Lake, East Bay east (site 7)	East Devils Lake main bay (site 10)
Phosphorus, total	580	680	1,000	980	790	800	780	660
Number of samples	4	4	4	4	4	4	4	3

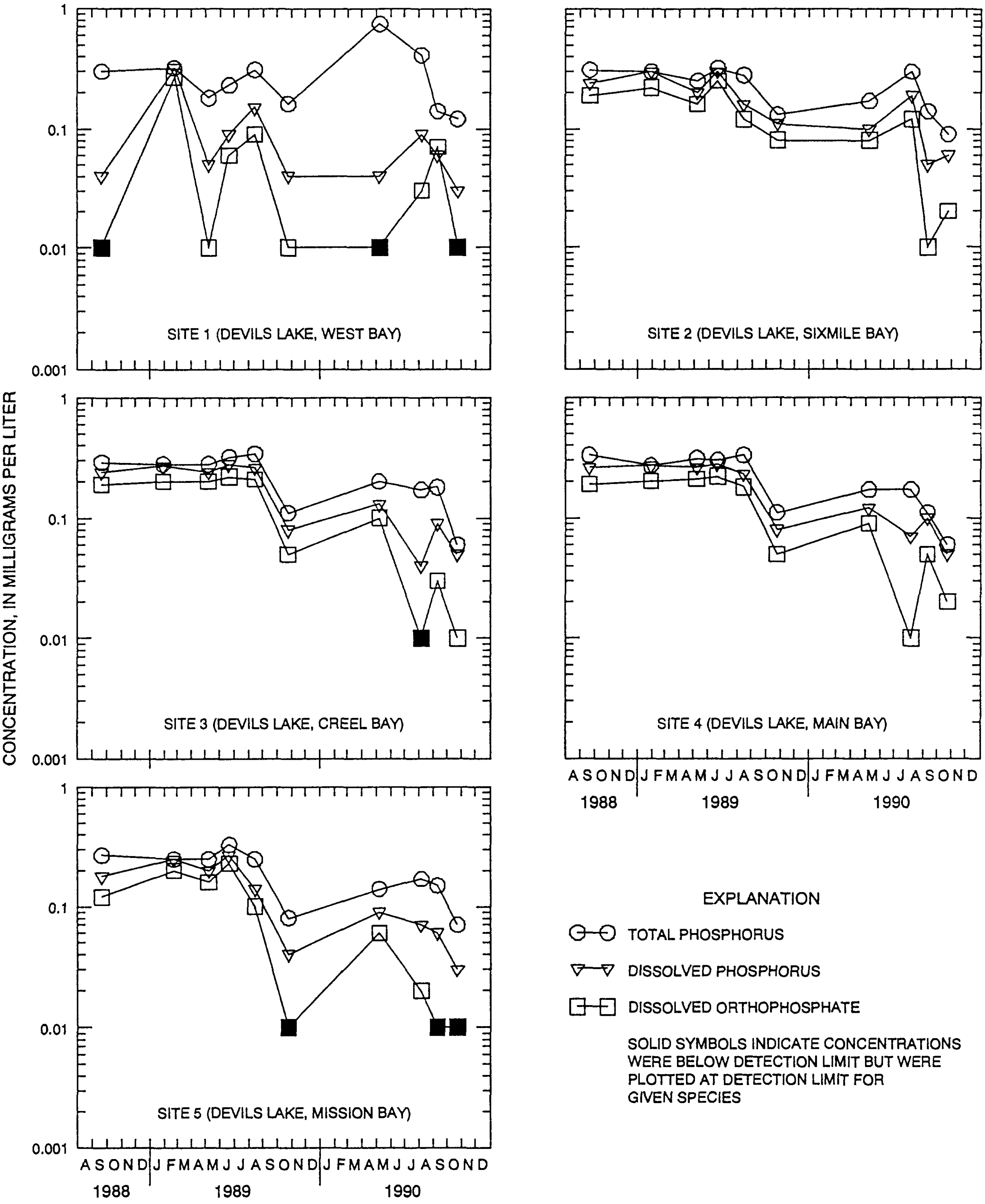

Figure 14. Total phosphorus, dissolved phosphorus, and dissolved orthophosphate concentrations in water samples collected from the euphotic zone at sampling sites on Devils Lake and East Devils Lake, September 1988 through October 1990.

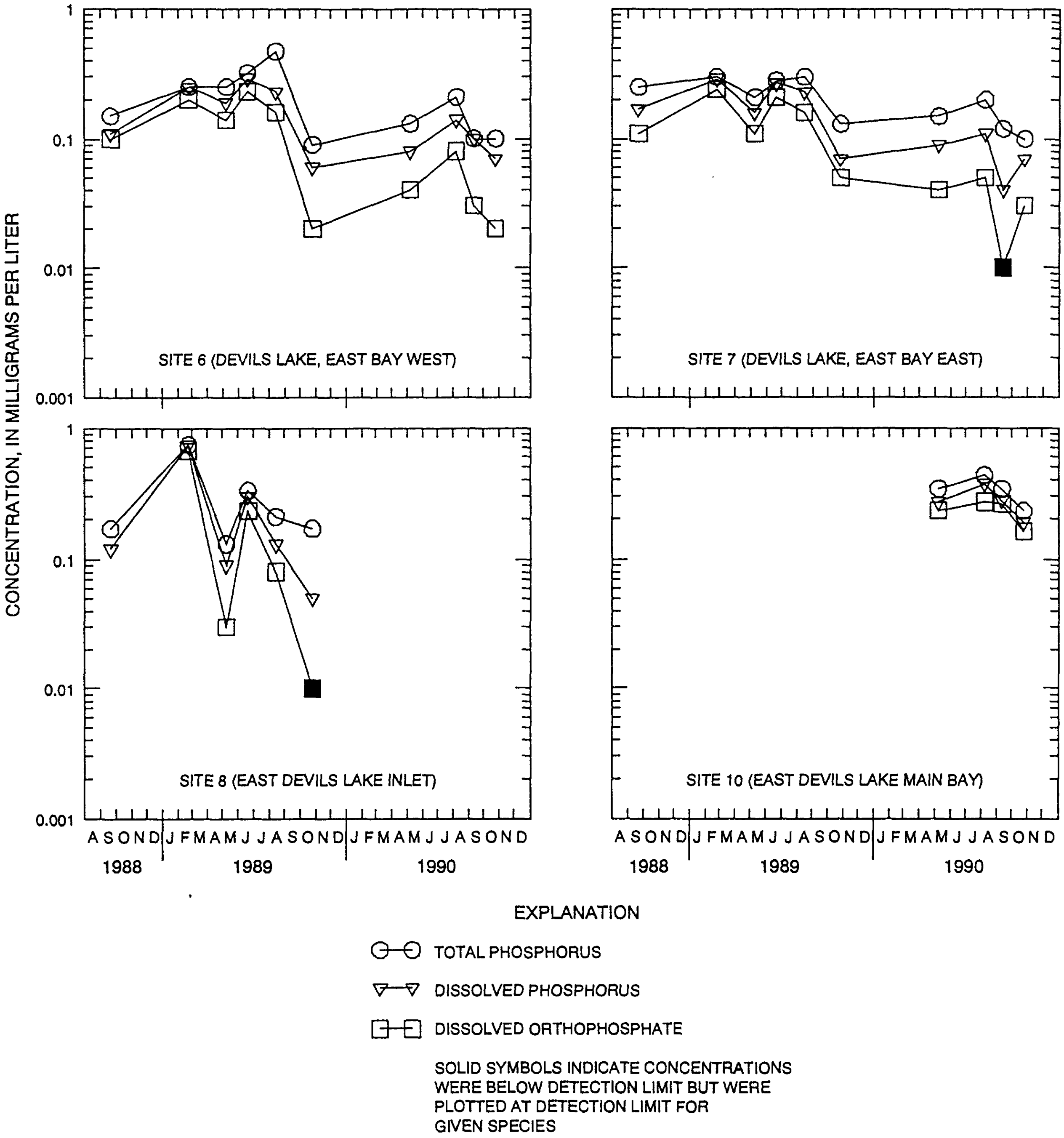

Figure 14. Total phosphorus, dissolved phosphorus, and dissolved orthophosphate concentrations in water samples collected from the euphotic zone at sampling sites on Devils Lake and East Devils Lake, September 1988 through October 1990--Continued.

Long-Term Variability

Nutrient (both nitrogen and phosphorus) data are considerably more sparse in previous investigations than are major-ion data. When nutrient data have been reported, analytical procedures generally have not been recorded in detail and it is difficult to confidently discern whether samples were filtered and concentrations represent dissolved fractions or whether samples were unfiltered and concentrations represent both dissolved and particulate fractions. Nutrient concentrations are substantially influenced by biological processes, and seasonal variability of nutrient concentrations is greater than that of major-ion concentrations. It is difficult to make comparisons between reported results when the frequency and seasonal timing of sample collection differ. Also, nutrient concentrations in Devils Lake and East Devils Lake are influenced substantially by sediment-water interactions, and spatial variability of nutrient concentrations can be greater than that of major-ion concentrations. Therefore, differences in sampling site locations between studies also would be expected to substantially affect the comparability of nutrient results from different studies. For these reasons, detailed discussion of long-term variability in nutrient concentrations in Devils Lake and East Devils Lake is inappropriate, and only a general discussion is provided.

The annual mean concentrations of selected nutrient species in water samples collected from Main Bay during selected years are shown in table 8. No concentrations of nutrient species were recorded before 1948. Because of differences in sampling site locations and seasonal timing of sample collection, caution should be used in attempting to discern long-term variability in nutrients in Devils Lake. No obvious long-term pattern in phosphorus concentrations is apparent from the data. There may be an inverse relation between nitrogen concentrations and water level. If this relation does exist, it probably is caused by increased interaction between the sediments and the water column at lower water levels rather than by evaporative concentration effects. Nutrients do not accumulate in the water column in Devils Lake but, instead, are assimilated by organisms and generally removed from the water column by settling during the fall. Nutrients accumulate in the sediments, which may act as a source for internal loading of nutrients into the water column. During a given time period, concentrations of nutrient species most probably are influenced by oxidation-reduction conditions, water depth, turbulence, and factors that affect algal growth.

SUMMARY

Devils Lake, in northeastern North Dakota, is a closed-basin lake characterized by large fluctuations in water level and in concentrations of dissolved chemical constituents. Devils Lake consists of several bays that are, to some extent, isolated from each other. The bays include, from west to east, West Bay, Main Bay, Sixmile Bay, Creel Bay, Mission Bay, and East Bay. East Devils Lake is located to the east of East Bay and is connected to East Bay by culverts.

Water-column properties were measured and water-quality samples were collected from the two major tributaries to Devils Lake, Big Coulee and Channel A. Water-column property data and other water-quality data were collected at nine sampling sites on Devils Lake and East Devils Lake during September 1988 through October 1990 to assess spatial and seasonal variability in water-quality conditions in Devils Lake. Water-column properties (specific conductance, pH, water temperature, light transmission, Secchi-disk transparency depth, and dissolved oxygen) were measured and water-quality samples were collected during 11 sampling periods.

Specific conductance, which generally increased from west to east in Devils Lake and East Devils Lake, ranged from 3,580 microsiemens per centimeter at site 1 (West Bay) on May 9, 1989, to 20,100 microsiemens per centimeter at site 8 (East Devils Lake inlet) on February 7, 1990. Specific-

Table 8. Annual mean concentrations of selected nutrient species in water samples collected from Devils Lake, Main Bay, and water level of Devils lake during selected years

(mg/L, milligrams per liter; --, no data)

Year	Approximate water level (feet above sea level	Number of sampling periods	Approximate time period	Annual mean nitrate nitrogen (mg/L)	Annual mean ammonia plus organic nitrogen (mg/L)	Annual mean phosphorus (mg/L)	Annual mean orthophosphate phosphorus (mg/L)
[1]1948	1,403	1	November	17	--	--	--
[1]1949	1,406	3	May-June	1.3	--	--	--
[1]1950	1,411	11	May-December	2.1	--	--	--
[2]1956	1,418	3	January, June, December	.51	--	--	--
[2]1957	1,418	2	April, October	.45	--	--	--
21958	1,418	2	January, June	.37	--	--	--
21959	1,415	1	October	.26	--	0.37	--
21960	1,415	2	May, September	.46	--	.05	--
[3]1978	1,422	20	January-November	.35	--	.44	0.23
[4]1984	1,427	9	January-October	.08	1.7	.51	.31
1989	1,426	5	January-October	.07	2.4	.26	.17
1990	1,424	5	February-October	.02	2.6	.14	.07

[1] Swenson and Colby (1955).

[2] Mitten and others (1968).

[3] DeGroot (1980).

[4] Holme (1986).

conductance values at all sites generally were largest in the winter, smallest in the spring, and increased in the summer. Vertical variability of specific conductance during open-water periods generally was small. During the winter, specific conductance generally increased near lake-bottom sediments, indicating that bottom sediments may be a source of major ions to the lake.

pH, which generally was similar among sites, ranged from 8.0 at site 8 (East Devils Lake inlet) on October 26, 1989, to 9.4 at sites 3 (Creel Bay) and 4 (Main Bay) on February 6, 1990. Although seasonal variations in pH were not large, pH values generally were smallest in the summer, largest in the winter, and intermediate in the spring and fall. Vertical variability of pH during open-water periods generally was small. During the winter, pH generally decreased near lake-bottom sediments, indicating that bottom sediments may be a source of acidity to the lake.

Water temperature, which generally was similar among sites, ranged from zero at all sites during one or both of the winter sampling periods to 27.0 degrees Celsius at site 6 (East Bay west) on August 15, 1989. Devils Lake generally does not undergo thermal stratification during open-water periods but does undergo inverse thermal stratification in the winter.

Secchi-disk transparency depth ranged from 3.6 inches at site 1 (West Bay) on October 24, 1990, to 156 inches at sites 2 (Sixmile Bay) and 4 (Main Bay) on January 30, 1989. Shallower sampling sites generally had smaller Secchi-disk transparency depths than deeper sampling sites. Light transmission generally was greatest in the winter and least in the summer.

Dissolved oxygen concentrations, which generally were similar at all sites, ranged from 0.3 milligram per liter near the lake bottom at site 5 (Mission Bay) on August 15, 1989, to 20.0 milligrams per liter near the surface at site 8 (East Devils Lake inlet) on August 15, 1989. Vertical variability of dissolved oxygen was greatest during the winter. Although near-bottom anoxia was not measured, the potential exists for establishment of near-bottom anoxia during extended periods of calm in the summer and during periods of inverse thermal stratification in the winter.

Ionic proportions in water samples were used to evaluate physical and chemical processes occurring in Devils Lake and East Devils Lake. Concentrations of all major ions, except calcium, bicarbonate, and sulfate were larger in water samples from Devils Lake and East Devils Lake than in water samples from the two tributaries. Concentrations of all major ions generally increased eastward through Devils Lake and East Devils Lake, but sodium, sulfate, and chloride were enriched relative to the other major ions. For example, water samples collected at Big Coulee were a true sulfate mixed calcium sodium type and water samples collected at Channel A were a true sulfate mixed sodium calcium type.

Evaporitic concentration results in spatial variations in dissolved-solids concentrations in Devils Lake and East Devils Lake. Median dissolved-solids concentrations generally increased from west to east. Median dissolved-solids concentrations in water samples collected from the two major tributaries to Devils Lake were 534 milligrams per liter for Big Coulee and 803 milligrams per liter for Channel A. The median dissolved-solids concentration for site 5 (Mission Bay) was about 4,200 milligrams per liter, the median concentrations for sites 6 (East Bay west) and 7 (East Bay east) were between about 5,000 and 5,400 milligrams per liter, and the median concentrations for sites 8 (East Devils Lake inlet) and 10 (East Devils Lake main bay) were between about 9,000 and 10,000 milligrams per liter. Because of the strong relation between evaporitic concentration and dissolved-solids concentrations, dissolved-solids concentrations in Devils Lake generally fluctuate inversely with water level.

Dissolved-solids concentrations also varied seasonally in Devils Lake during the study period. In the winter, dissolved-solids concentrations generally increased because of ice formation. In the spring, dissolved-solids concentrations generally decreased when water was diluted because of icemelt, surface-water inflow, and seasonal precipitation. In the summer and fall, dissolved-solids concentrations generally increased because of evaporitic concentration.

Although the dissolved-solids concentration of Devils Lake generally fluctuates inversely with water level, the dissolved-solids mass generally fluctuates directly with water level. Therefore, during periods of increased freshwater input, characterized by increasing water level, dissolved-solids concentrations decrease but the total dissolved-solids mass in Devils Lake increases. Conversely, during periods of decreased freshwater input, characterized by declining water levels, dissolved-solids concentrations increase but the total dissolved-solids mass in Devils Lake decreases. During periods of extremely low water levels, dissolved solids may be lost from Devils Lake by wind transport of solids (removal of aerosols or removal of deposited solids from exposed sediments) or incorporated into sediment pore water.

Nutrients concentrations in the water column varied spatially and seasonally in Devils Lake and East Devils Lake. Dissolved nitrite and dissolved nitrite plus nitrate concentrations generally were below detection. Total ammonia and dissolved ammonia concentrations generally were below 0.10 milligram per liter and occasionally were below the detection limit of 0.01 milligram per liter, except during winter sampling periods. Total nitrogen concentrations in Devils Lake and East Devils Lake were extremely large and were similar to concentrations reported for hypereutrophic systems. Total nitrogen concentrations generally were smallest in the fall, increased in the winter, remained the same or decreased slightly in the spring, and increased in the summer.

Total ammonia, dissolved ammonia, and total nitrogen concentrations varied with the water depth of the sampling sites, indicating sediment-water interactions influence nitrogen concentrations in the lake. Shallower sampling sites tended to have significantly larger total ammonia, dissolved ammonia, and total nitrogen concentrations than deeper sampling sites. Shallower sampling sites have a larger ratio of sediment-surface area to lake volume than deeper sampling sites. As water depths decrease, the ratio of sediment-surface area to lake volume increases, resulting in an increased potential for bottom-sediment processes to affect nitrogen concentrations in the lake. Therefore, the variation in water depth may partly explain the variation in nitrogen concentrations in the lake.

Total phosphorus, dissolved phosphorus, and dissolved orthophosphate did not vary systematically among sampling sites in Devils Lake and East Devils Lake. Seasonal variability in total phosphorus, dissolved phosphorus, and dissolved orthophosphate generally was similar. Phosphorus concentrations generally were smallest in the fall, increased in the winter, decreased in the spring, and increased in the summer. Seasonal variations in phosphorus concentration were attributed to seasonal variations in algal populations and to variations in the phosphorus flux from bottom sediments.

Total ammonia, total nitrogen, and total phosphorus concentrations in bottom material varied spatially in Devils Lake and East Devils Lake. Generally, total ammonia and total nitrogen concentrations in bottom material were largest in West Bay, Creel Bay, and Main Bay and smallest in East Bay and East Devils Lake. Median total ammonia concentrations in bottom material ranged from 6.7 milligrams per kilogram at site 10 (East Devils Lake main bay) to 100 milligrams per kilogram at site 4 (Main Bay). Median total nitrogen concentrations in bottom material ranged from 5,100 milligrams per kilogram at site 7 (East Bay east) to 12,000 milligrams per kilogram at site 1 (West Bay). Median total phosphorus concentrations in bottom material ranged from 580 milligrams per kilogram at site 1 (West Bay) to 1,000 milligrams per kilogram at site 3 (Creel Bay). The large concentrations of nitrogen and phosphorus in bottom material at site 3 (Creel Bay) may be caused, in part, by past discharges of raw sewage, treated wastewater effluent, and stormwater runoff from the city of Devils Lake into the northern end of Creel Bay. The large concentrations of nitrogen and phosphorus in bottom material at site 4 (Main Bay) may be caused, in part, by the proximity of Main Bay to West Bay and Creel Bay.

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