U.S. GEOLOGICAL SURVEY
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EVALUATION OF WATER-QUALITY DATA AND MONITORING PROGRAM FOR LAKE TRAVIS, NEAR AUSTIN, TEXAS

Water-Resources Investigations Report 97–4257

Prepared in cooperation with the
LOWER COLORADO RIVER AUTHORITY

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VERTICAL DATUM AND ABBREVIATIONS

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.

Abbreviations:

acre-ft, acre-foot
°C, degree Celsius
°F, degree Fahrenheit
ft, foot
in., inch
mg/L, milligram per liter
mi, mile
mi^2, square mile

Evaluation of Water-Quality Data and Monitoring Program for Lake Travis, Near Austin, Texas

By Walter Rast[1] *and* Raymond M. Slade, Jr.

Abstract

Statistical analyses were made of selected water-quality properties and constituents for Lake Travis, northwest of Austin in central Texas. Objectives for the evaluation were: (1) to provide information on levels of selected water-quality properties or constituents to use as reference values for assessing the future effectiveness of the Lake Travis Nonpoint-Source Control ordinance of the Lower Colorado River Authority; and (2) to determine whether water-quality constituents at any of the sampling sites are statistically redundant with other sites and, thus, can be discontinued without loss of information. The data were grouped into two periods—the thermally stratified period (May through November) and the mixed period (December through April).

Lake Travis is a biologically unproductive reservoir with acceptable water quality for virtually all current water uses. Nutrient (nitrogen, phosphorus) concentrations tend to be small in the reservoir throughout the year, indicating nutrient limitation of maximum phytoplankton biomass. On the basis of traditional limnological properties, Lake Travis exhibits small biological productivity and exceptional water transparency. However, dissolved oxygen concentrations for bottom samples often decrease to less than 5 milligrams per liter throughout the reservoir, especially during the thermally stratified period.

Statistical comparisons were made between data collected at the surface and at the bottom at each sampling site to determine statistical similarities. The available data were insufficient to perform the comparisons for nitrite nitrogen and dissolved orthophosphate phosphorus. In addition, no bottom data were available at the most upstream site because the shallow bottom was commonly above the thermocline.

The multiple-comparison tests indicate that, for some constituents, a single sampling site for a constituent or property might adequately characterize the water quality of Lake Travis for that constituent or property. However, multiple sampling sites are required to provide information of sufficient temporal and spatial resolution to accurately evaluate other water-quality constituents for the reservoir. For example, the water-quality data from surface samples and from bottom samples indicate that nutrients (nitrogen, phosphorus) might require additional sampling sites for a more accurate characterization of their in-lake dynamics.

INTRODUCTION

Lake Travis is one of a chain of seven linearly connected reservoirs that constitute the Highland Lakes on the lower Colorado River in central Texas (fig. 1). The multiple-purpose reservoir is a water resource of considerable economic and aesthetic value. Principal water uses include domestic and industrial water supply, recreation, irrigation, fish and wildlife propagation, and electrical-power generation.

The Lower Colorado River Authority (LCRA) has determined that stormwater runoff is the greatest threat to the water quality and trophic status of the Highland Lakes. Of particular concern is sedimentation, cultural eutrophication, and toxic substance contamination associated with runoff from urban and rural areas. In response to these concerns, the LCRA adopted the Lake

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[1] United Nations Environment Programme, formerly U.S. Geological Survey.

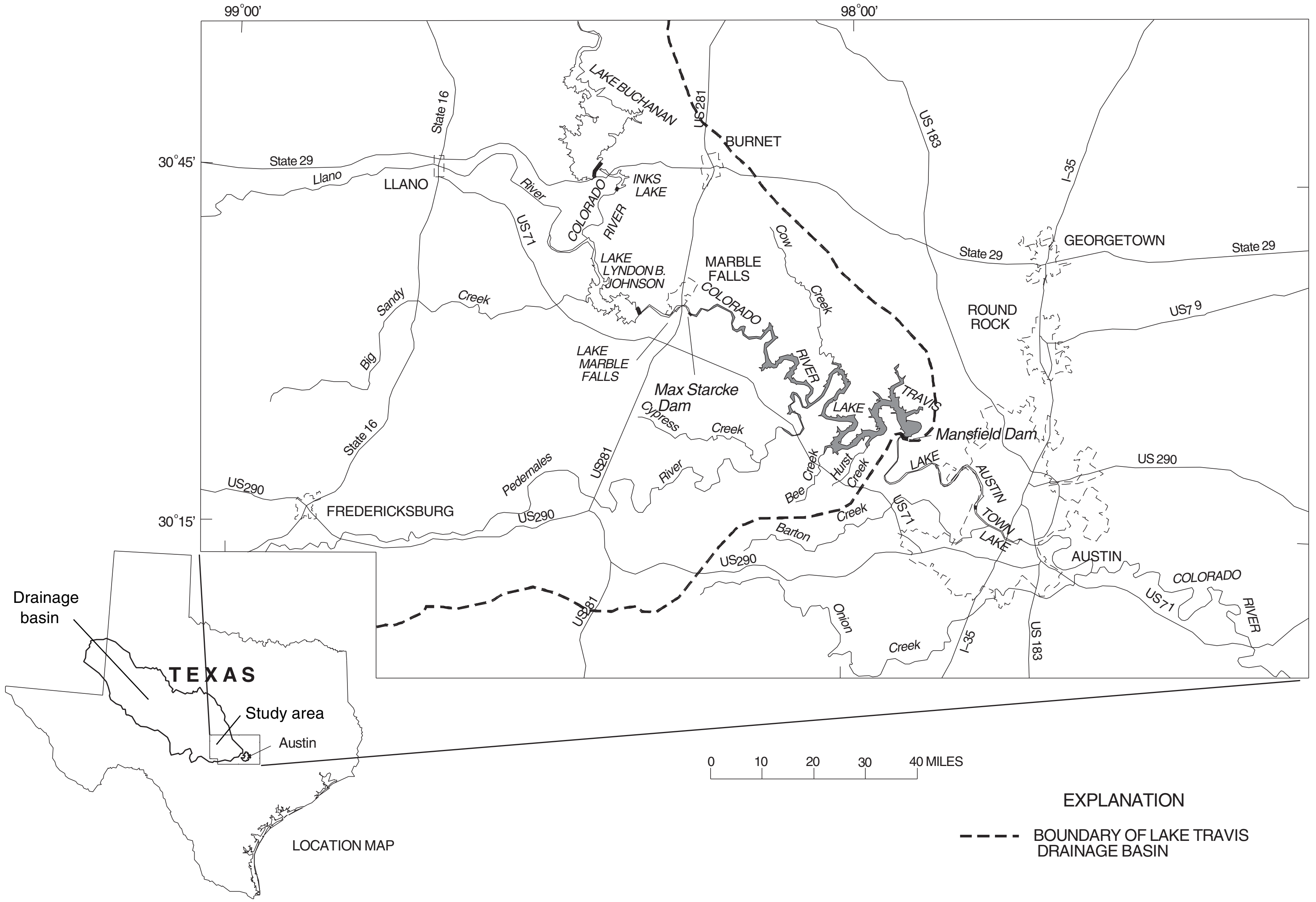

Figure 1. Location of study area.

Table 1. Summary of required annual constituent removal prescribed by the Nonpoint-Source Control ordinance for Lake Travis, near Austin, Texas

[From Lower Colorado River Authority, 1991. <, less than; >, greater than]

Location of property	Slope of property (percent)	Required annual constituent removal (percent)		
		Total suspended solids	Total phosphorus	Oil and grease
Inland	<10	70	70	70
	10 to 20	80	75	75
	>20	90	85	85
Shoreline area	<10	75	75	75
	10 to 20	90	85	85
	>20	90	85	85

Travis Nonpoint-Source Control ordinance (Lower Colorado River Authority, 1991), which became effective February 1, 1990. The ordinance targets three indicator pollutants—total suspended solids, total phosphorus, and oil and grease. Because these constituents are indicator pollutants, control measures for their removal from stormwater runoff are expected to affect other nonpoint-source contaminants as well, including ammonia and nitrate nitrogen, bacteria, trace elements, and pesticides.

Control measures to remove these constituents are developed on the basis of specific physiographic and hydrologic criteria, including location of property in the watershed and slope of the property (table 1). The control measures include best management practices, which might be structural or nonstructural. The ordinance applies to all development activity on property, such as construction of buildings, roads, storage areas, and parking lots, including the clearing of vegetative cover, excavating, dredging, grading, contouring, mining, and depositing of refuse, waste, or fill materials.

Contingent upon the effectiveness of the ordinance in reducing nonpoint-source contaminant loads to Lake Travis, the ordinance eventually could be extended to all reservoirs under the jurisdiction of the LCRA. The LCRA instituted a water-quality monitoring program for the Highland Lakes in the early 1980s before the ordinance was adopted. The capability of this monitoring program, as currently designed, to provide the data and information needed to determine the effectiveness of the ordinance is still being evaluated.

The current background water-quality conditions of the reservoir must be defined to determine the effectiveness of the nonpoint-source control measures. General methods for assessing the water quality of lakes have been derived primarily from studies of nonimpounded natural lakes in the temperate climatic zone of the north-central and upper midwestern United States. Lake Travis is part of a reservoir system in the semiarid climatic zone of the southwestern United States. Using temperate-zone limnological data from natural lakes to evaluate a reservoir, such as Lake Travis, could result in erroneous conclusions regarding past and present water-quality conditions and biological productivity.

Analyses of selected water-quality constituents in Lake Travis were made to define water-quality conditions and to identify sampling sites with statistically similar water-quality data. The investigation was conducted by the U.S. Geological Survey (USGS), in cooperation with the Lower Colorado River Authority. Information provided for selected water-quality constituents can be used by the LCRA as reference values for determining the effectiveness of its Lake Travis Nonpoint-Source Control ordinance.

Purpose and Scope

The purpose of this report is to present the results of (1) an evaluation of water-quality data collected during November 1982–July 1989 in Lake Travis to use as reference values for determining the effectiveness of the LCRA Nonpoint-Source Control ordinance; and (2) an evaluation of the LCRA monitoring program to determine whether water-quality constituents at any of the sampling sites are statistically redundant with another site and can be discontinued without loss of information. Also evaluated and reported is the possible need for additional sampling sites that would more fully characterize the water quality of the reservoir. In this context, statistically significant differences in water quality between adjacent sampling sites might justify the establishment of one or more additional sites. This could possibly mediate, for example, in-lake dynamics of nutrients being influenced by their biochemical uptake and utilization.

Description of the Study Area

Lake Travis, northwest of Austin (fig. 1), has a total drainage basin (including nonimpounded areas) of approximately 1,992 mi^2. The rolling, hilly basin has areas of stony soil and exposed granite and limestone. Much of the basin is rangeland. The basin soils generally are thin, overlying hard limestone, the soils primarily being clay or silty clay of low permeability (Werchan and others, 1974). Grasses, grasslike plants, and shrubs are the predominant vegetation.

Lake Travis on the lower Colorado River is a serpentine-shaped reservoir about 64 mi long, with a maximum width of 11,500 ft. The reservoir extends from immediately below Max Starcke Dam (the impoundment structure for Lake Marble Falls) to Mansfield Dam, about 13 mi northwest of Austin (fig. 1). Most of the reservoir basin and water volume is in Travis County.

Lake Travis has a storage capacity of about 3,223,000 acre-ft and surface area of 44,448 acres. At its conservation and power pool elevation of 681.1 ft above sea level, the reservoir covers 18,929 acres and has a capacity of 1,170,752 acre-ft (Texas Department of Water Resources, 1984). The mean depth of the reservoir is about 67 ft, and the maximum depth is about 200 ft. From 1968 to 1982, the mean annual hydraulic residence time for Lake Travis ranged from 0.5 to 1.6 years (Cleveland and Armstrong, 1987). The U.S. Environmental Protection Agency (1977) reported a mean hydraulic residence time of 1 year, on the basis of outflow data. Lake Buchanan (fig. 1) is the only other reservoir in the Highland Lakes system with a longer hydraulic residence time.

The major hydrologic inputs to Lake Travis are upstream flows of the Colorado River released from Lake Marble Falls and tributary inflow from the Pedernales River (fig. 1). Smaller tributary inflows to the reservoir include Cow Creek, Bee Creek, and Hurst Creek.

The local climate is characterized by short, mild winters; long, moderately hot summers; moderately high humidity; and prevailing southerly winds. The mean annual temperature for 1941–70 is 71 °F. The annual temperature ranges from a mean minimum of 41 °F in January to a mean maximum of 95 ×°F in July (Veenhuis and Slade, 1990, p. 5).

Because of the large areal extent of the Lake Travis drainage basin, the distribution of precipitation varies. Data from the National Weather Service gage in Austin were used to characterize average precipitation. During 1928–82, mean annual precipitation was about 32 in., and annual precipitation ranged from 11 to 51 in. The distribution of precipitation is relatively even throughout the year; however, precipitation usually is greater in spring and early fall. Individual storm precipitation can vary widely; severe thunderstorms with large amounts of precipitation are not uncommon.

Acknowledgments

Special thanks are extended to Pat Hartigan, Chuck Dvorsky, and Geoffrey Saunders of the Lower Colorado River Authority, for providing water-quality data and technical support for the project.

WATER-QUALITY DATA

Collection

The LCRA monitoring program in Lake Travis consists of 10 sites (fig. 2), either in the main body of the reservoir or in principal embayments. Water-quality data at these sites historically have been collected by the LCRA, City of Austin, and Texas Natural Resource Conservation Commission (formerly the Texas Water Commission). Monitoring goals and constituents measured varied among the agencies. Sampling frequency also varied but mostly has been monthly.

The water-quality data for this study were collected from November 1982 to July 1989. The sites sampled only for field measurements generally had a shorter period of record than sites sampled for field and laboratory measurements. From a possible 10 sites with available data (table 2), 5 in-lake sites (700, 600, 340, 240, and 100) and 2 cove sites (220 and 178) were selected for evaluation in this study.

Water-quality measurements were made in the field, and, also, samples were taken for laboratory analysis. Field measurements of specific conductance, pH, temperature, and dissolved oxygen were made at the surface and at about 5-ft intervals throughout the water column during the thermally stratified period (May through November). During the mixed period (December through April), field measurements were

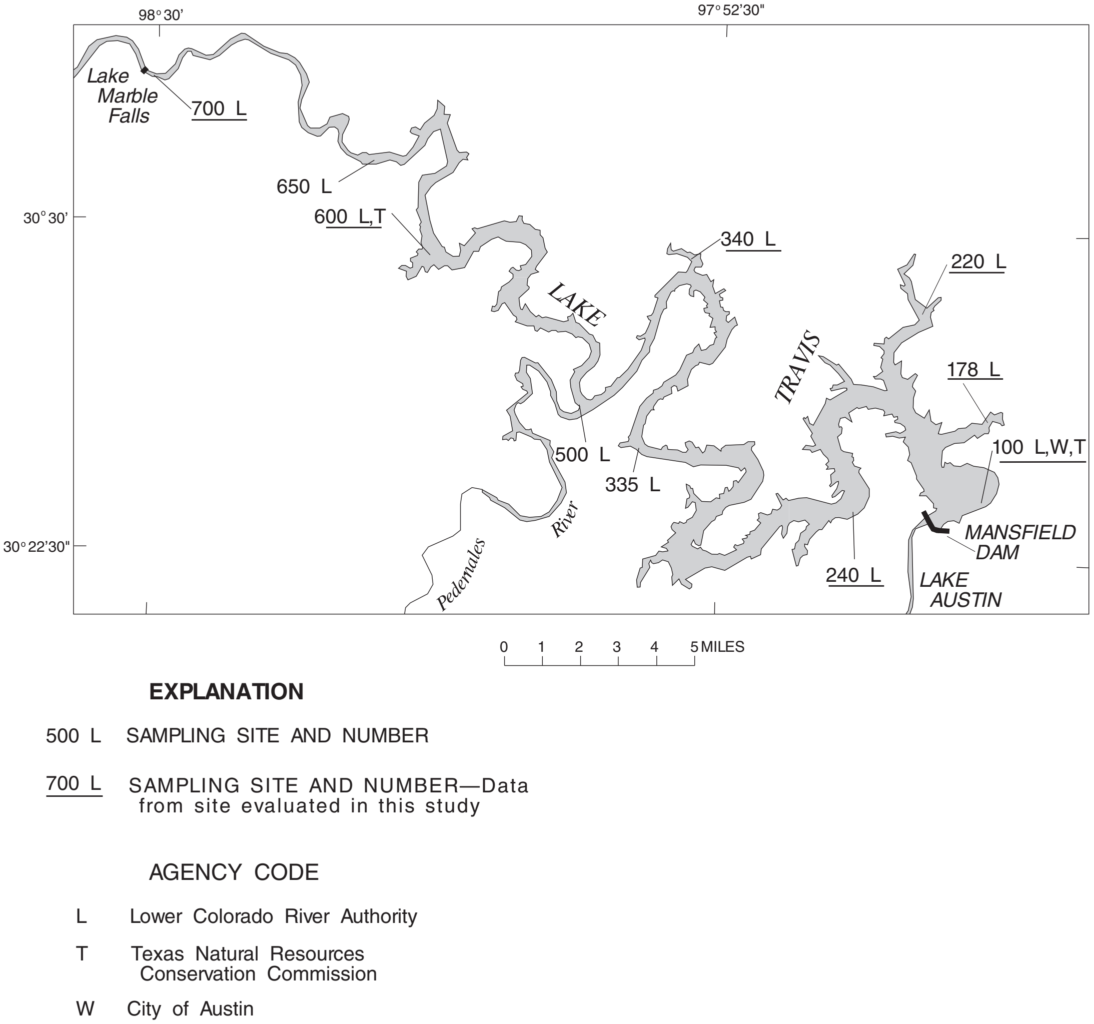

Figure 2. Location of sampling sites in Lake Travis for Lower Colorado River Authority monitoring program.

Table 2. Sampling sites in Lake Travis, near Austin, Texas

Sampling site no.	Sampling site location	Initial sampling date
700	Lake Travis at headwaters	February 1984
[1]650	Lake Travis near Spicewood	February 1984
600	Lake Travis at Turkey Bend	November 1982
[1]500	Lake Travis at Carpenter Bend	November 1982
340	Lake Travis at Pace Bend	February 1982
[1]335	Lake Travis at Baldwin Bend	April 1984
240	Lake Travis at Arkansas Bend	February 1984
[2]220	Lake Travis at confluence of Big Sandy and Lime Creeks	February 1984
[2]178	Lake Travis at Cypress Creek	November 1982
100	Lake Travis at Mansfield Dam	November 1982

[1] Sampled for field measurements only (specific conductance, pH, temperature, dissolved oxygen, and Secchi-disk depth); other sites sampled for field and laboratory measurements.

[2] Cove sites; other sites are in-lake sites.

Table 3. Summary of water-quality properties and constituents sampled in Lake Travis, near Austin, Texas

Water-quality property or constituent
SPECIFIC CONDUCTANCE[1]—measure of dissolved solids (ionized salts) concentration
pH[1]—measure of hydrogen ion activity
TEMPERATURE[1]—measure of thermal content of water
DISSOLVED OXYGEN[1]—measure of gaseous oxygen concentration
SECCHI-DISK DEPTH[1]—measure of water clarity
TOTAL ALKALINITY—measure of acid-neutralizing capacity of water
TOTAL SUSPENDED SOLIDS—measure of suspended particles retained on a glass-fiber filter
NUTRIENTS:
Nitrate nitrogen, nitrite nitrogen, ammonia nitrogen—inorganic forms of nitrogen readily utilized by phytoplankton
Total Kjeldahl nitrogen—sum of organic and ammonia nitrogen
Total phosphorus—sum of particulate and dissolved phosphorus
Orthophosphate phosphorus—inorganic form of phosphorus readily utilized by phytoplankton
TOTAL ORGANIC CARBON—phytoplankton nutrient; also used as a measure of concentration of organic matter
CHLOROPHYLL-a—primary phytoplankton pigment necessary for photosynthesis; often used as a measure of phytoplankton biomass

[1] Field measurements; all others measured in the laboratory.

made at the surface and at about 10-ft intervals. Secchi-disk depth was measured only at the surface during both periods. Water-quality samples for laboratory analyses were collected about 1 ft below the water surface, 1 ft above the thermocline, and 1 ft above the bottom during the thermally stratified period. During the mixed period, samples were collected about 1 ft below the surface and 1 ft above the bottom. A summary of the field measurements and selected laboratory analyses for Lake Travis is listed in table 3.

Methods of Analysis

The approach used in this study was to determine selected water-quality constituents in the field and laboratory using the analytical methods listed in table 4. The data subsequently were analyzed using graphical procedures to define water-quality conditions and using statistical comparisons to identify sampling sites with statistically similar water-quality data.

Data tend to cluster around the middle of a range of measured values (Zar, 1974). This normal distribution of data is statistically important because it indicates what value, among all possible values, an individual variable is most likely to have. The central tendency of the data is indicated by the mean and median of a data set. Water-quality data often do not exhibit normal distribution but instead exhibit log-normal distribution in which common logarithms (base 10) of the data exhibit normal distribution. In log-normal distribution of data, the central tendency of water-quality data is indicated by the median.

The data initially were screened for the means, medians, standard deviations, and 25- and 75-percent interquartiles. Because the depth of Lake Travis changes from a shallow, upstream end to a deep, downstream end, the water column at each sampling site contained a different number of sampling depths. Only data from the surface and bottom sampling depths at each site were selected for subsequent statistical analyses because (1) the surface and bottom depths were the only depths sampled at all sampling sites and (2) the number of intermediate sampling depths differed at each sampling site.

Concentrations of some water-quality constituents in Lake Travis were smaller than the method reporting limit (table 4). These data were replaced with estimated values for the subsequent statistical analyses.

The log-probability regression method (Gilliom and Helsel, 1986) was used to generate values to replace data that were less than the reporting limit. This method was shown by Gilliom and Helsel (1986) to have the smallest error in estimating means and standard deviations for water-quality constituents. The technique defines “less-than detection limit” values on the basis of the statistical distribution of data larger than the

Table 4. Summary of analytical methods used for water-quality properties and constituents in Lake Travis, near Austin, Texas

[STORET, Storage and retrieval system; µS/cm, microsiemens per centimeter at 25 °C; °C, degrees Celsius; mg/L, milligrams per liter; ft, feet; --, not applicable; µg/L, micrograms per liter]

Water-quality property or constituent	STORET code	Analytical method[1]	Method reporting limit
Specific conductance (µS/cm)	00095	FI	1
pH (standard units)	00400	FI	1
Temperature (°C)	00010	FI	1
Dissolved oxygen[2] (mg/L)	00300	FI	.1
Secchi-disk depth (ft)	00077	Secchi-disk depth	--
Total alkalinity (mg/L, as $CaCO_3$)	00410	E310.2	1
Total suspended solids (mg/L)	00530	E160.2	1
Nitrate nitrogen (mg/L)	00620	E353.2	.01
Nitrite nitrogen (mg/L)	00615	E353.2	.01
Ammonia nitrogen (mg/L)	00610	E350.1	.01
Total Kjeldahl nitrogen (mg/L)	00625	E351.2	.01
Total phosphorus (mg/L)	00665	E365.4	.01
Orthophosphate phosphorus (mg/L)	00671	E365.1	.01
Total organic carbon (mg/L)	00680	E415	1
Chlorophyll-a (µg/L)	32230	SM10200H	[3].001

[1] FI, in-situ field-electrode measurement apparatus; E, U.S. Environmental Protection Agency (1983); SM, American Public Health Association and others (1989).

[2] Dissolved oxygen concentrations smaller than 0.1 mg/L were rounded to 0.

[3] Expressed here in mg/L, as is shown in figure 7.

detection limit. This distribution is assumed to describe the data smaller than the laboratory reporting limit. The estimated values were combined with the measured data to produce a complete data set for a sampling site.

Data for boxplots and multiple-comparison tests were grouped on the basis of the most and least biologically productive periods annually for most temperate-zone water bodies. Data for these two periods included (1) the thermally stratified period—all of the data (measured and estimated) from May through November and (2) the mixed period—all of the data (measured and estimated) from December through April.

The water column temperature-profile data indicate that Lake Travis is thermally stratified from about May through November. A similar stratification period for Lake Travis was reported by Cleveland and Armstrong (1987). This is considerably longer than the 3- to 4-month, summer thermal-stratification period typical of natural lakes in the temperate zone. On the basis of mean water temperatures, thermal stratification extended upstream nearly to site 600 (fig. 2), although the stratification was most pronounced from site 340 to site 100 (near Mansfield Dam).

The two data groups were analyzed separately for surface and bottom sampling depths. Thus, the multiple-comparison tests were applied to four different combinations of sampling depths and periods (surface thermally stratified, bottom thermally stratified, surface mixed, and bottom mixed). However, no comparison tests were applied to data from surface and bottom sampling depths or to data from stratified and mixed data sets. The multiple-comparison tests were conducted using field and laboratory data for the five in-lake sites and the two cove sites.

One data set was obtained from each sampling site for the given water-quality constituents. The data for each surface and bottom sampling depth at each sampling site represent a subset of the full data set for the sampling site. Statistical comparisons were made between data from the surface and bottom sampling depths at each sampling site to determine if the surface and bottom data for a given water-quality constituent were statistically similar. The surface and bottom data sets for all water-quality constituents were statistically different (95-percent confidence level) at all sites. Therefore, the surface and bottom sampling depths were analyzed separately in subsequent statistical-comparison tests.

Multiple-comparison tests then were used to determine if there were statistical differences at the 95-percent confidence level in the data sets of each water-quality constituent for the two depths at each sampling site. The advantage of a multiple-comparison test is that it allows a simultaneous, pairwise comparison of data for all possible combinations of sampling sites. Two nonparametric tests, Kruskal-Wallis and Dunn (Hollander and Wolfe, 1973), were used to evaluate the data sets. Nonparametric tests are recommended when the number of observations for a given water-quality constituent is different between sampling sites. In addition, nonparametric tests do not require a normal distribution of the data set (Zar, 1974).

EVALUATION OF WATER-QUALITY DATA

All 10 sampling sites analyzed have water-quality field data (table 2). However, only the five in-lake sites and two cove sites that also have laboratory data will be presented in this report. The data available for nitrite nitrogen and dissolved orthophosphate phosphorus were insufficient for boxplot analysis. Data from the bottom were not collected at site 700 (fig. 2) because the shallow bottom was commonly above the thermocline. “Interquartile range” in the following discussions refers to the difference in constituent values between the 25th and 75th percentiles.

Field Measurements

Specific conductance—The specific conductance interquartile ranges for bottom samples are larger than the ranges for surface samples at most sites during the thermally stratified period (fig. 3a). The ranges and medians generally decrease from upstream to downstream sites. Data for the two cove sites are not substantially different from data for the in-lake sites.

During the mixed period, the specific conductance interquartile ranges for surface and bottom samples are similar at most sites (fig. 3b). As indicated during the thermally stratified period, the interquartile range generally decreases from upstream to downstream sites. The largest data values for bottom samples are generally during the thermally stratified period rather than during the mixed period.

pH—During the thermally stratified period, pH interquartile ranges for surface and bottom samples varied greatly (fig. 4a). The ranges for surface samples are relatively small in contrast to the larger ranges for bottom samples. The interquartile ranges for surface samples are relatively constant along the reservoir, while ranges for bottom samples generally decrease from upstream to downstream sites, except for cove sites 220 and 178. The 25th percentiles were not less than 7.1 standard units.

During the mixed period, differences in pH interquartile ranges between surface and bottom samples are smaller (fig. 4b) than during the thermally stratified period. The interquartile ranges for surface samples are relatively constant along the reservoir. The 25th percentiles were not less than 7.6 standard units.

Temperature—During the thermally stratified period, 75th percentile temperatures are 28 °C or larger for surface samples but markedly smaller for bottom samples (fig. 5a). The median temperatures for surface samples, except at site 100, are larger than 25 °C and generally are constant from upstream to downstream sites. Except at the cove sites, median temperatures for bottom samples decrease from upstream to downstream sites, indicating cooler temperatures as depths increase in downstream direction. Bottom samples for sites 240 and 100, the two most downstream in-lake sites, have the smallest interquartile ranges and medians.

The water temperature typically is lower during the mixed period (fig. 5b) than during the thermally stratified period. Differences in temperature interquartile ranges between surface and bottom samples also are smaller during the mixed period than during the thermally stratified period. Data for surface and bottom samples at the cove sites are similar to data at in-lake sites during the mixed period.

Dissolved oxygen—During the thermally stratified period, dissolved oxygen interquartile ranges are substantially different between surface and bottom samples (fig. 6a). The smaller dissolved oxygen concentrations for the bottom samples are consistent with oxygen depletion at greater depths caused by bacterial consumption of biodegradable materials (for example, dead phytoplankton cells).

The water is colder during the mixed period and generally contains larger dissolved oxygen concentrations than the warmer water of the thermally stratified period. The differences in interquartile ranges between surface and bottom samples are much smaller during the mixed period (fig. 6b) than during the thermally strati-

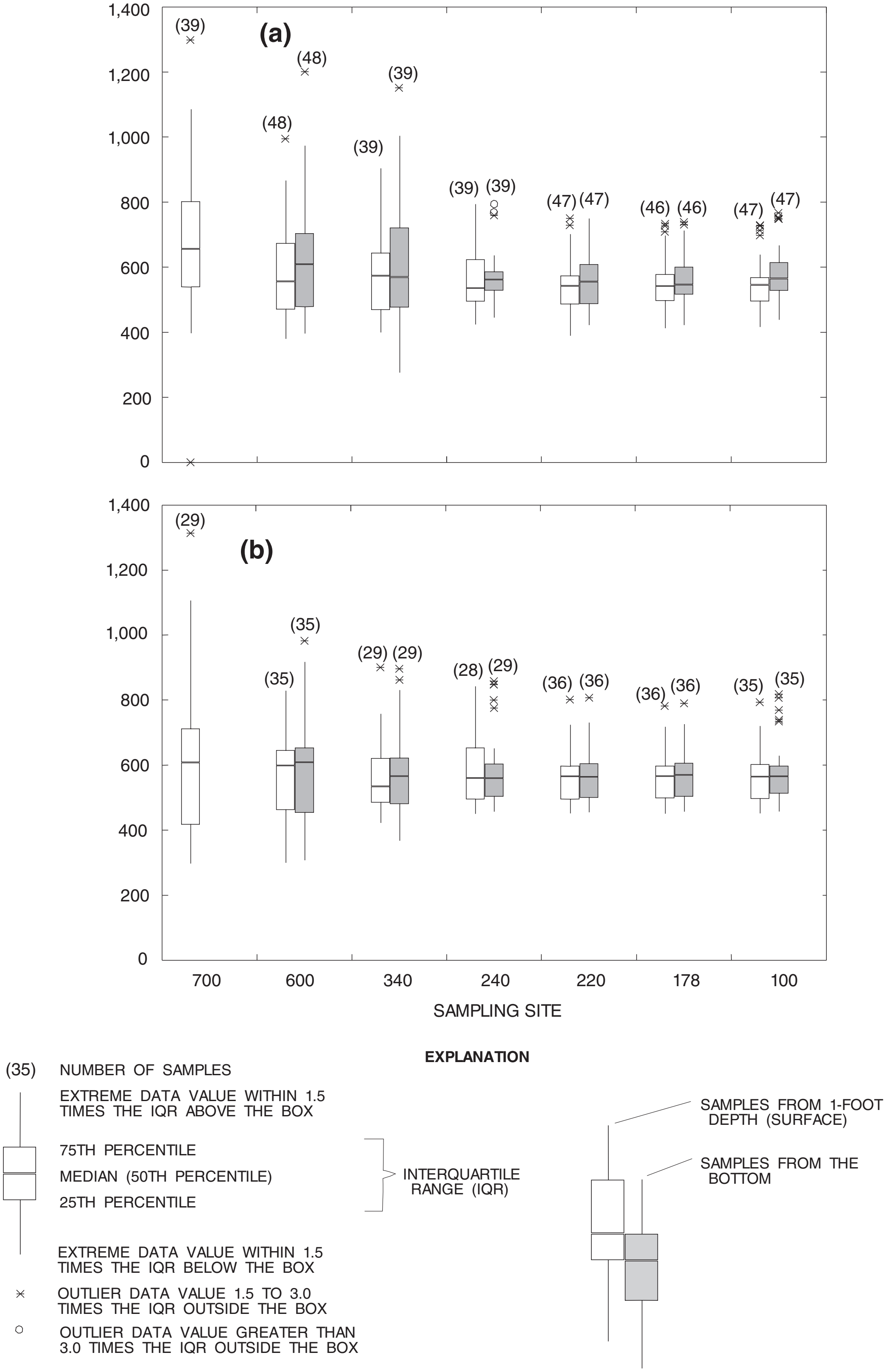

Figure 3. Range and distribution of specific conductance at selected sites in Lake Travis, near Austin, Texas, during (a) thermally stratified period and (b) mixed period.

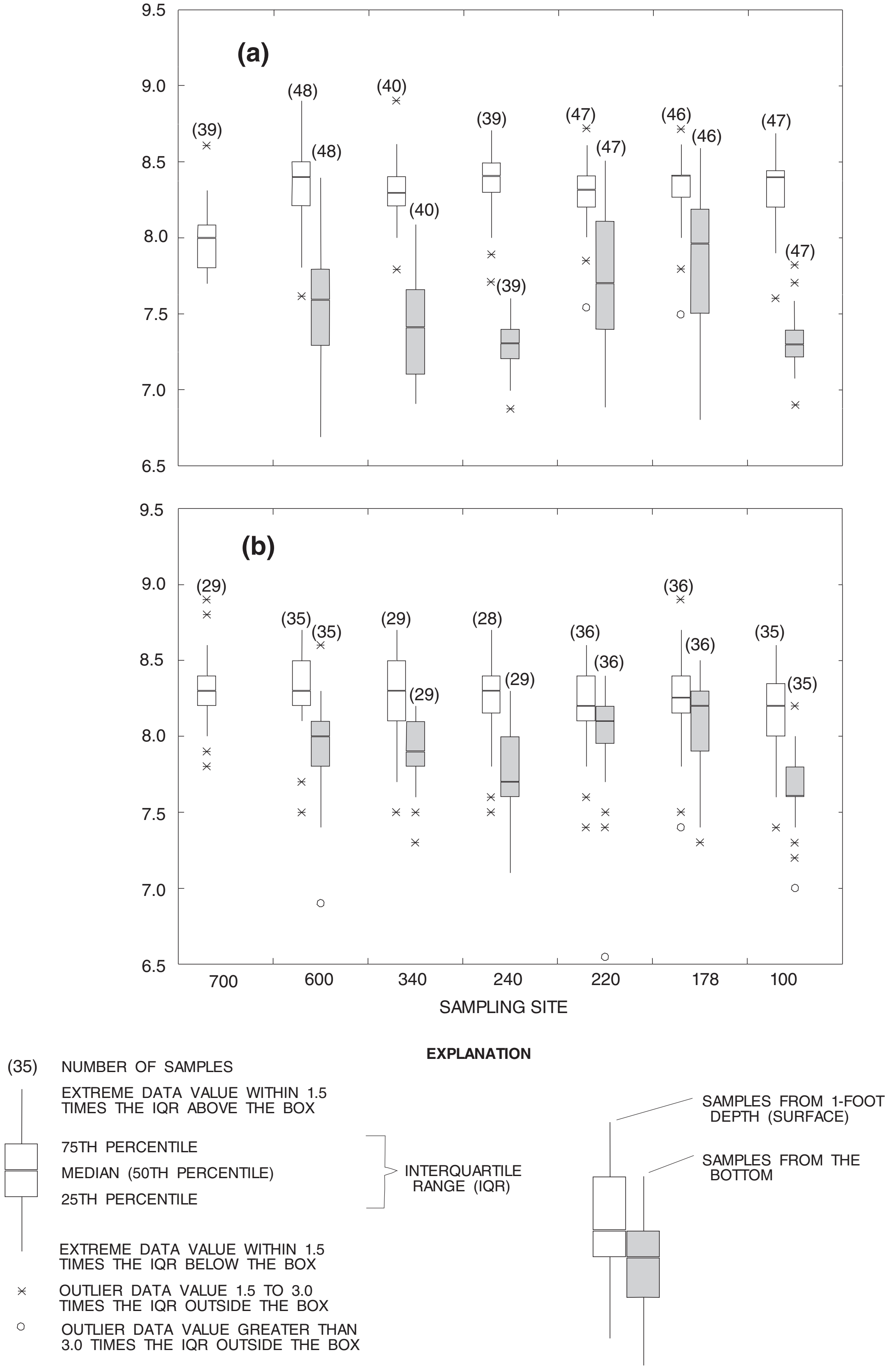

Figure 4. Range and distribution of pH at selected sites in Lake Travis, near Austin, Texas, during (a) thermally stratified period and (b) mixed period.

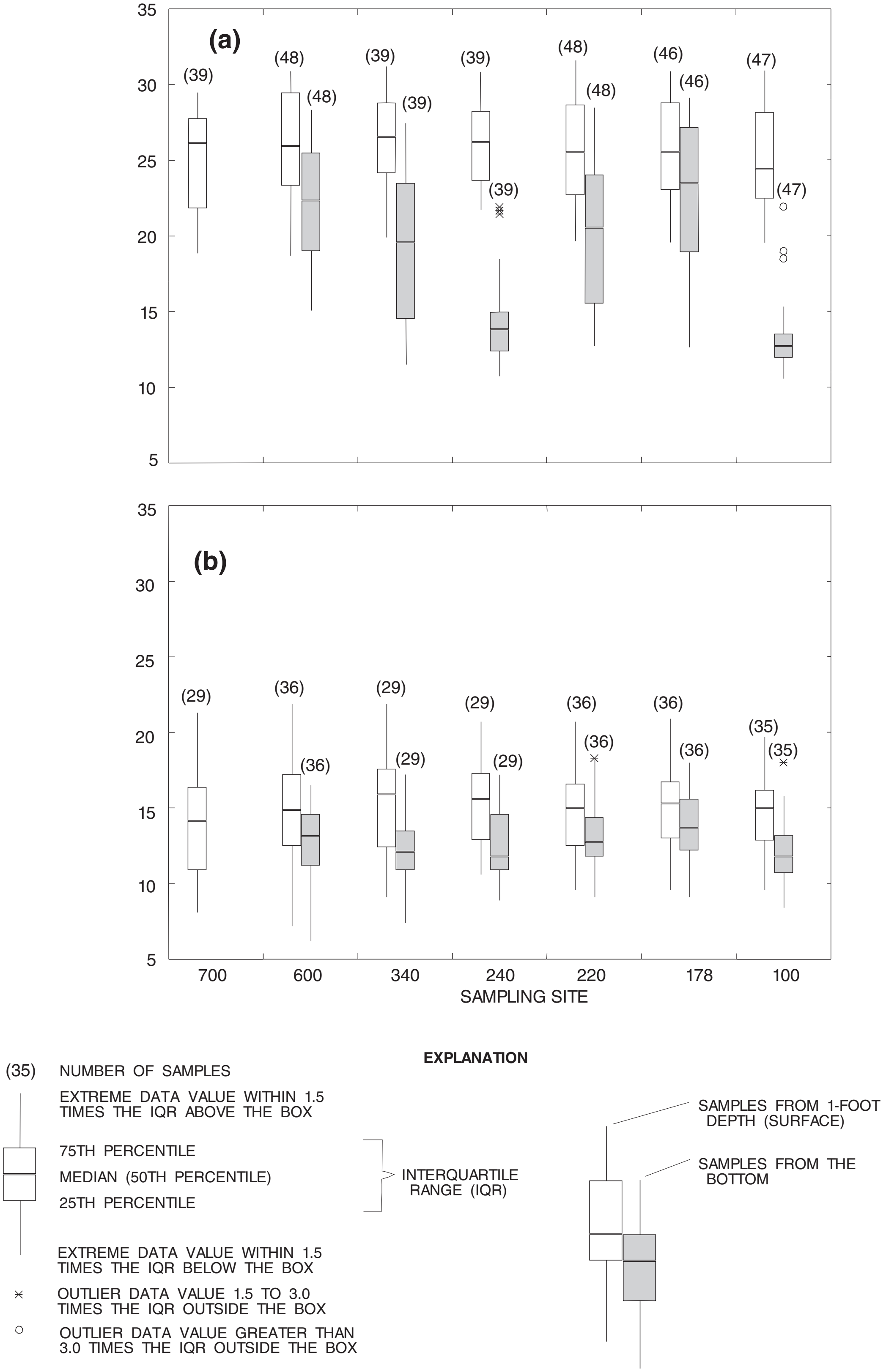

Figure 5. Range and distribution of temperature at selected sites in Lake Travis, near Austin, Texas, during (a) thermally stratified period and (b) mixed period.

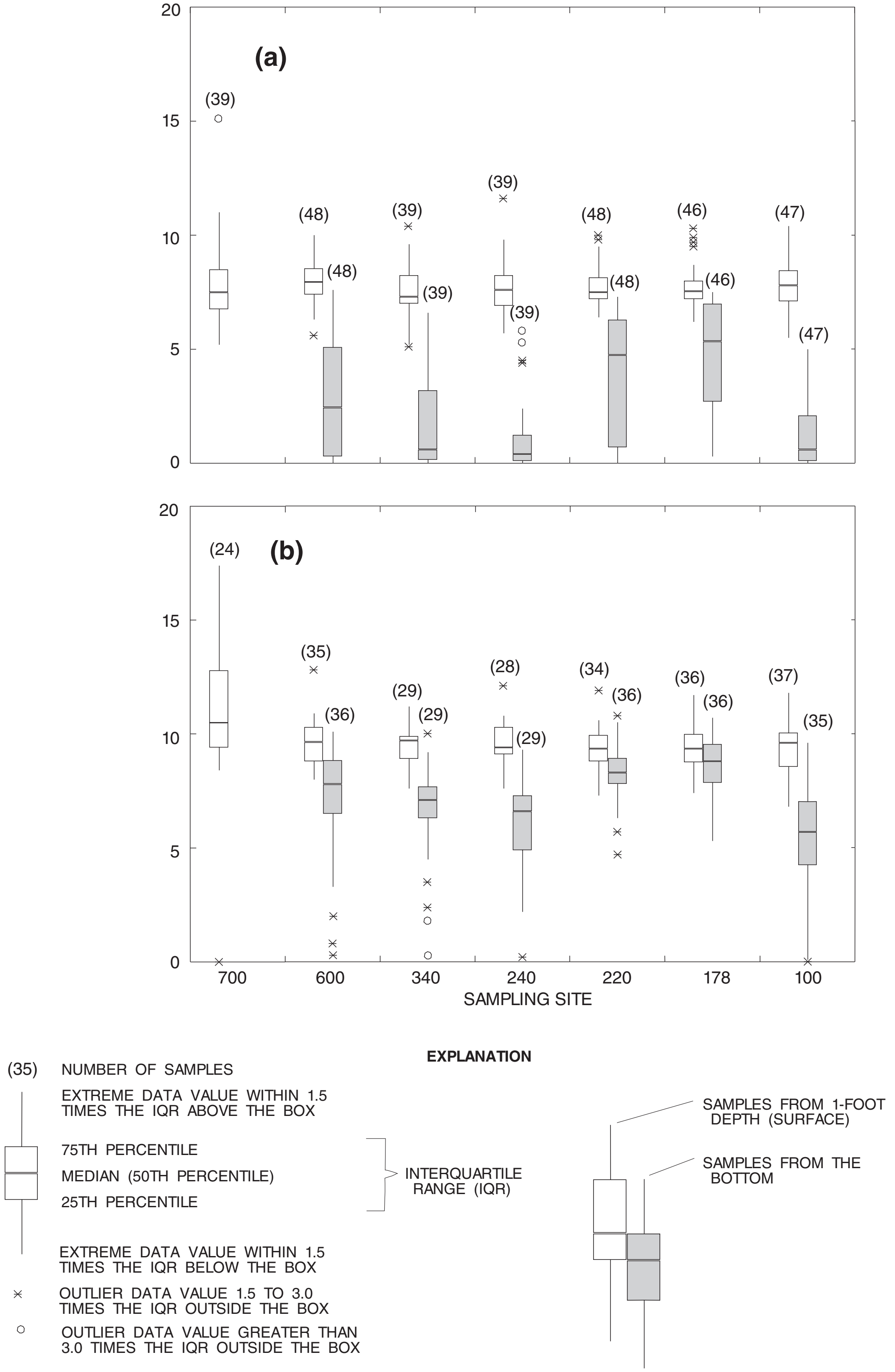

Figure 6. Range and distribution of dissolved oxygen at selected sites in Lake Travis, near Austin, Texas, during (a) thermally stratified period and (b) mixed period.

fied period. The ranges for surface samples are small and relatively constant along the length of the reservoir compared to slightly larger ranges and decreasing concentrations (except at the cove sites) for bottom samples. Data for bottom samples indicate fewer occurrences of anoxic conditions during the mixed period than during the thermally stratified period.

Chlorophyll-a and Secchi-disk depth—Because phytoplankton are a major factor influencing water transparency in most water bodies, chlorophyll-a concentrations (indicative of phytoplankton production) are discussed with Secchi-disk depth instead of in the "Laboratory Measurements" section. Chlorophyll-a and Secchi-disk depth were measured only at the surface during the thermally stratified and mixed periods (fig. 7a, b).

During the thermally stratified period, chlorophyll-a concentrations gradually decrease from upstream to downstream sites, except at site 600 (fig. 7a). The small chlorophyll-a interquartile ranges at most sites indicate a relatively small average annual phytoplankton biomass. Secchi-disk depth increases substantially from the upstream sites to the most downstream site during the thermally stratified period (fig. 7a). The increases in Secchi-disk depth generally correspond to decreases in chlorophyll-a, except at the cove sites. The decreases in chlorophyll-a corresponding to the decreases in Secchi-disk depth at the cove sites could be attributed to inorganic turbidity. The interquartile ranges for Secchi-disk depth increase slightly from upstream to downstream sites.

During the mixed period, chlorophyll-a concentrations show decreases and small interquartile ranges (fig. 7b) similar to those during the thermally stratified period. Secchi-disk depth shows a substantial increase from the upstream sites to the most downstream site, similar to that for the thermally stratified period. The interquartile ranges for Secchi-disk depth are larger for the mixed period than for the thermally stratified period and also increase from upstream to downstream sites, except at the cove sites. During the mixed period as during the thermally stratified period, Secchi-disk depths for the cove sites decrease even though chlorophyll-a concentrations (a potential causative factor) are not substantially larger.

Laboratory Measurements

Total alkalinity as $CaCO_3$—In terms of similar intersite data, total alkalinity is one of the most consistent constituents measured for Lake Travis. During the thermally stratified period, the total alkalinity interquartile ranges for surface samples and for bottom samples are similar (fig. 8a). The 25th and 75th percentiles and the medians for bottom samples are mostly larger than those for the surface samples. Bottom samples at sites 240 and 178 show concentrations exceeding 200 mg/L. The large alkalinity concentrations in Lake Travis, attributed to the abundant limestone in the drainage basin, should negate any effects of acid precipitation.

During the mixed period, total alkalinity interquartile ranges and medians for surface samples are similar (fig. 8b). The interquartile ranges and medians for bottom samples (except at cove site 178) also are similar. More outlier values less than 120 mg/L are shown for the mixed period than for the thermally stratified period.

Total suspended solids—During the thermally stratified period, interquartile ranges of total suspended solids for surface and bottom samples infer larger concentrations of particulate materials at greater depths in the reservoir (fig. 9a). Interquartile ranges, medians, and especially largest data values generally are smaller for surface samples than for bottom samples. The general decrease in medians for surface and bottom samples from upstream to downstream sites indicates settling of particulate matter along the length of the reservoir.

During the mixed period, interquartile ranges and medians of total suspended solids for surface and bottom samples (fig. 9b) are similar to those for the thermally stratified period. However, the smallest data values tend to be less for the mixed period than for the thermally stratified period.

Nitrate nitrogen—During the thermally stratified period, nitrate nitrogen 75th percentiles generally decrease for surface samples and increase for bottom samples from the upstream to downstream sites (fig. 10a). The largest data values for bottom samples tend to be greater than those for surface samples. The smallest data values for surface and bottom samples are less than the reporting limit for this constituent (0.01 mg/L, table 4); therefore, the log-probability regression method of Gilliom and Helsel (1986) was used to estimate those concentrations.

During the mixed period, interquartile ranges and medians of nitrate nitrogen for surface and bottom samples are mostly larger (fig. 10b) than during the thermally stratified period. Furthermore, the interquartile ranges for surface and bottom samples during the mixed

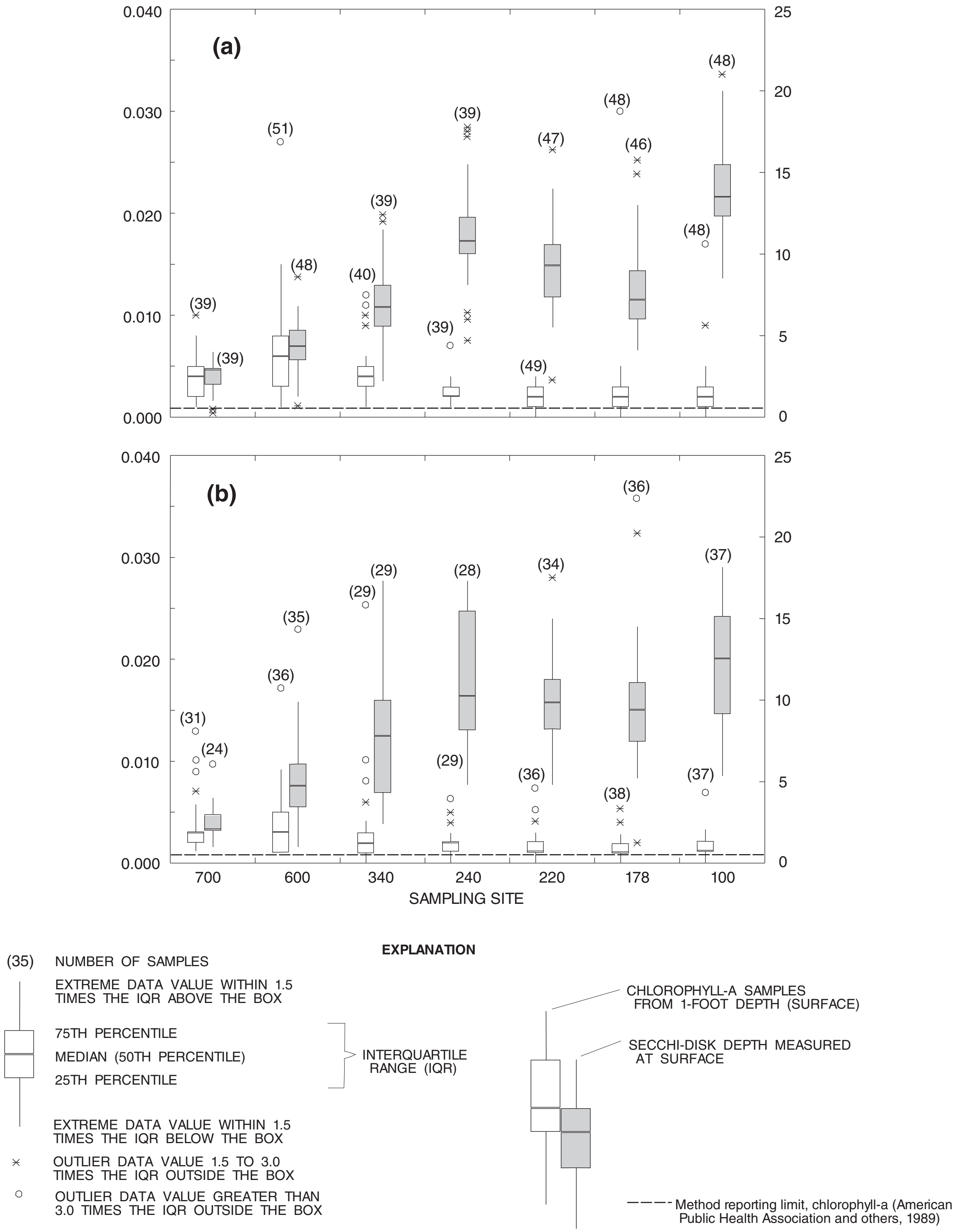

Figure 7. Range and distribution of chlorophyll-a and Secchi-disk depth, surface samples only, at selected sites in Lake Travis, near Austin, Texas, during (a) thermally stratified period and (b) mixed period.

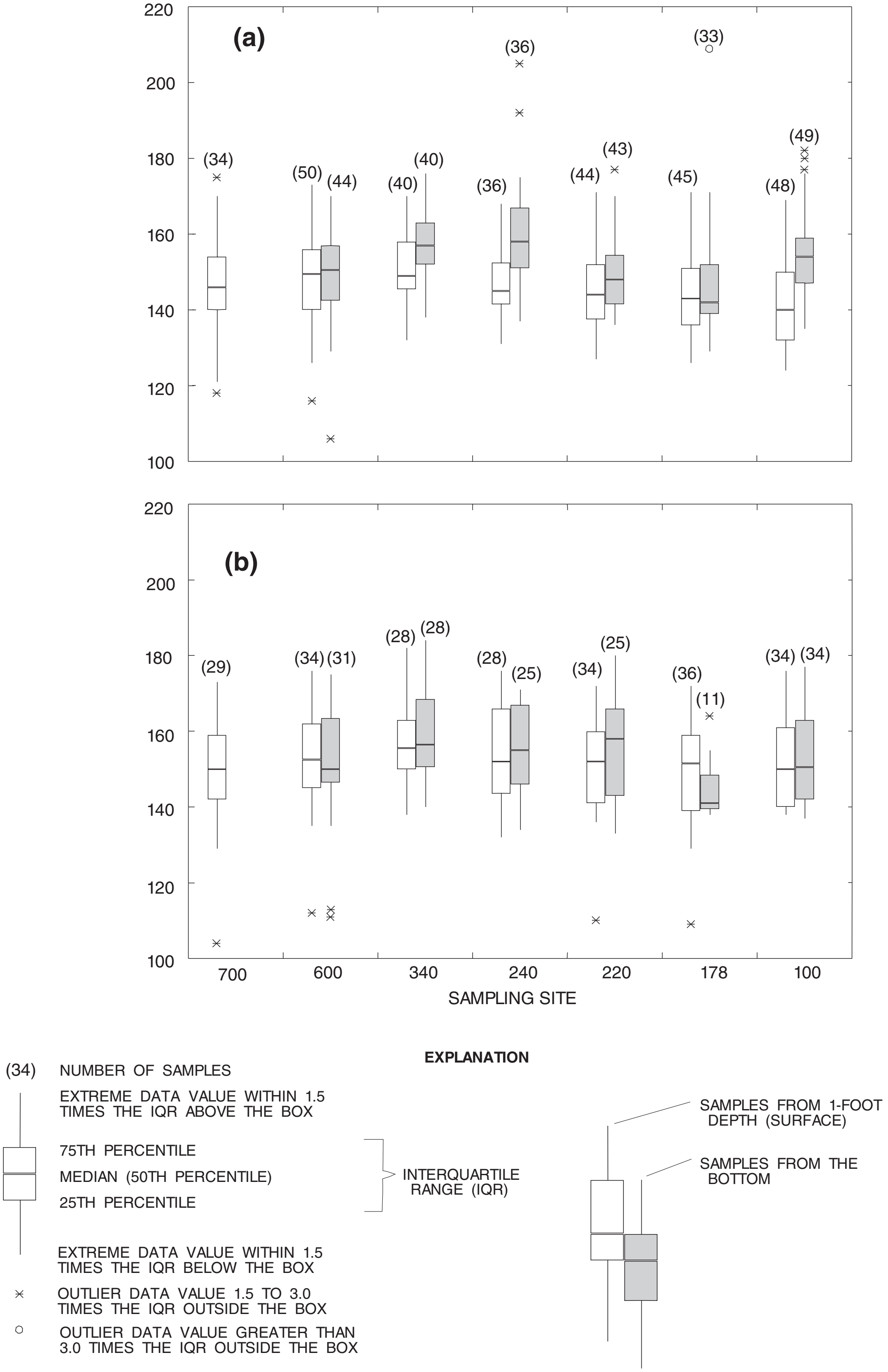

Figure 8. Range and distribution of total alkalinity as $CaCO_3$ at selected sites in Lake Travis, near Austin, Texas, during (a) thermally stratified period and (b) mixed period.

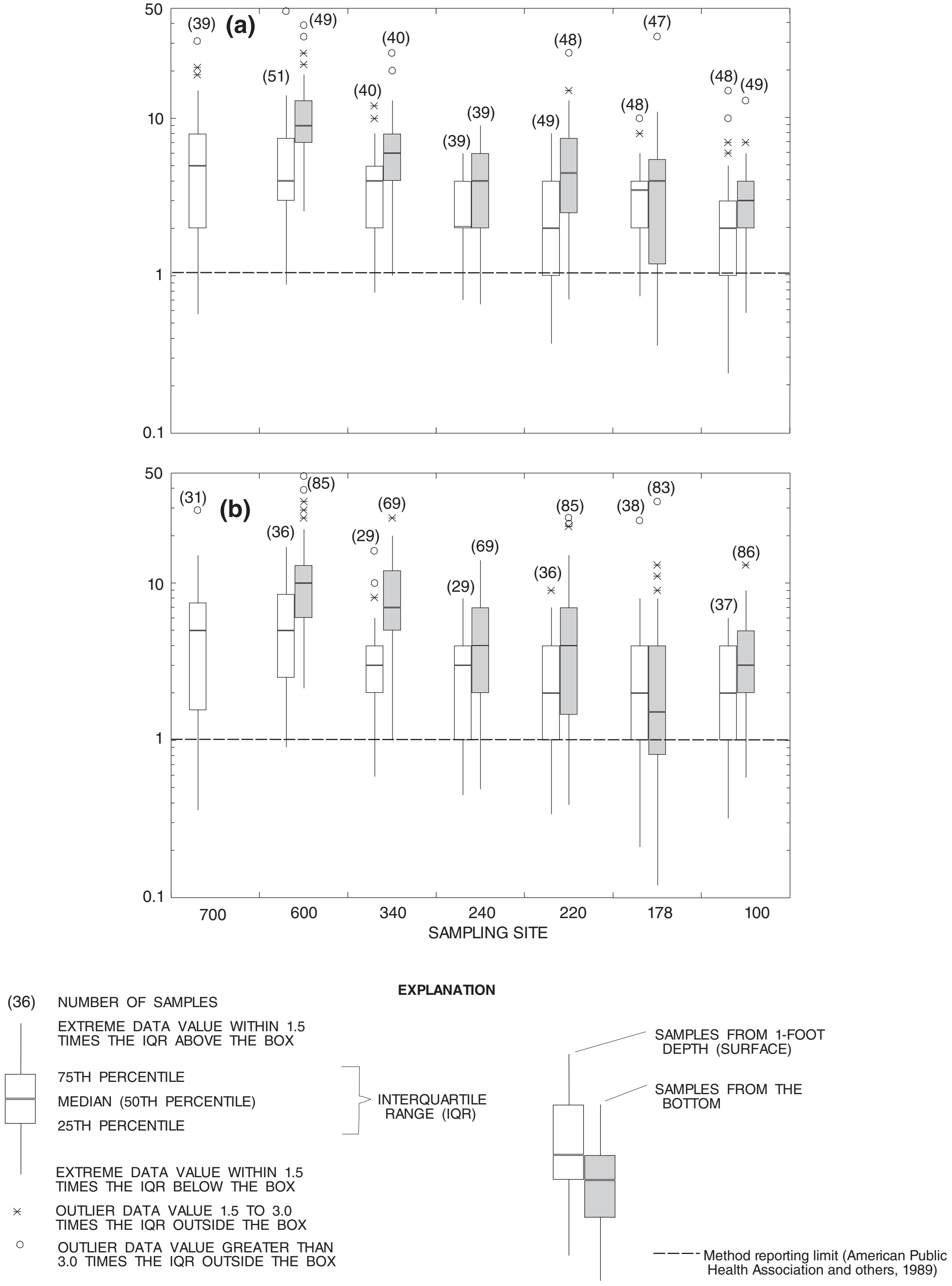

Figure 9. Range and distribution of total suspended solids at selected sites in Lake Travis, near Austin, Texas, during (a) thermally stratified period and (b) mixed period.

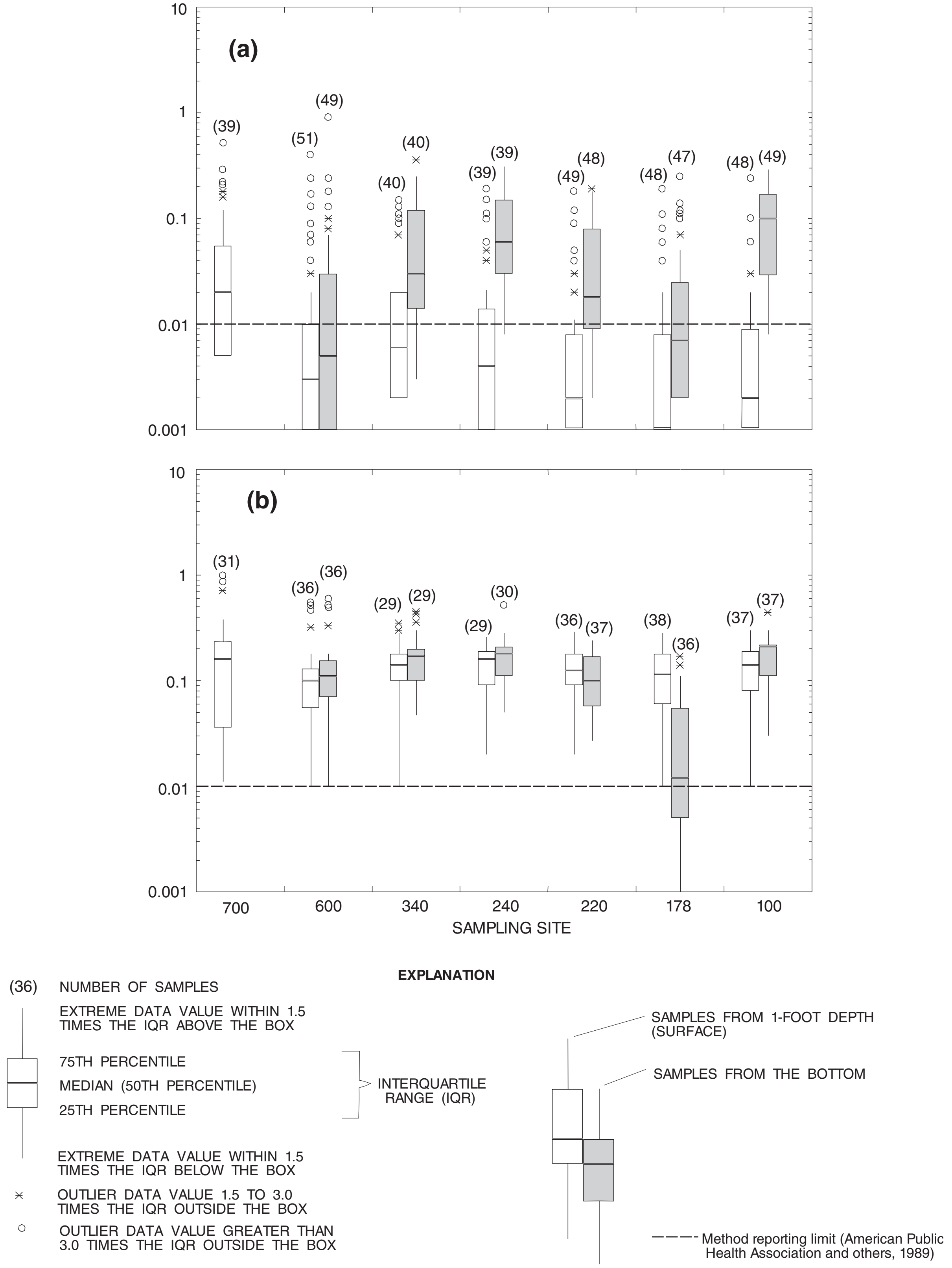

Figure 10. Range and distribution of nitrate nitrogen at selected sites in Lake Travis, near Austin, Texas, during (a) thermally stratified period and (b) mixed period.

period are similar along the length of the reservoir, except for the bottom sample at cove site 178. Boxplots for the mixed period show fewer outlier values above the box than those for the thermally stratified period. Nitrate nitrogen concentrations are mostly larger during the mixed period.

Nitrite nitrogen—Most nitrite nitrogen concentrations are smaller than the reporting limit (0.01 mg/L, table 4). Because it is not technically valid to generate the majority of the values in a data set using the log-probability regression method, boxplots were not prepared for this constituent.

Ammonia nitrogen—During the thermally stratified period, ammonia nitrogen concentrations are small and interquartile ranges for surface and bottom samples are similar at most sites (fig. 11a). The 25th percentiles for most surface samples and one-half of the bottom samples are less than 0.01 mg/L, the reporting limit for this constituent (table 4). Therefore, the log-probability regression method was used to estimate those concentrations.

During the mixed period, ammonia nitrogen interquartile ranges for surface and bottom samples (fig. 11b) are similar to those during the thermally stratified period. However, the differences between the interquartile ranges for surface samples and those for bottom samples at individual sites are smaller during the mixed period than during the thermally stratified period. These differences between interquartile ranges for surface and bottom samples at individual sites, as also noted for the thermally stratified period, could indicate increased biological action. Boxplots for the mixed period show outlier values above the box to be less than 0.4 mg/L.

Total Kjeldahl nitrogen—During the thermally stratified period, Kjeldahl nitrogen interquartile ranges for surface and bottom samples are relatively small and are similar except for the bottom sample at cove site 178 (fig. 12a). The smallest data value of the boxplot for the surface sample at site 340 is about 0.01 mg/L, the reporting limit for total Kjeldahl nitrogen (table 4).

During the mixed period, Kjeldahl nitrogen interquartile ranges for surface and bottom samples are relatively small and are similar except for the bottom sample at cove site 178 (fig. 12b). However, the interquartile ranges are mostly smaller than those during the thermally stratified period. The boxplot for the bottom sample at site 178 and for surface and bottom samples at site 100 show smallest data values of about 0.01 mg/L, the reporting limit for this constituent (table 4).

Total phosphorus—During the thermally stratified period, total phosphorus interquartile ranges for surface and bottom samples are small (fig. 13a). The decrease in medians from upstream to downstream sites most likely is associated with phytoplankton uptake of phosphorus along the length of the reservoir. Using the log-probability regression method, the minimum concentration for most surface samples and two bottom samples was 0.001 mg/L, a growth-limiting level for phytoplankton. The smaller concentrations for surface samples, compared to the bottom samples, also could reflect uptake of this nutrient by phytoplankton in the euphotic zone (Ryding and Rast, 1989).

The most apparent difference in samples for the mixed period, compared to those for the thermally stratified period, is smaller concentrations for bottom samples at the cove sites (fig. 13b). Overall, there is little difference between the total phosphorus data for both periods.

Orthophosphate phosphorus—As with nitrite nitrogen, most data for orthophosphate phosphorus were smaller than the reporting limit. Because it is not technically valid to generate the majority of the values in a data set using the log-probability regression method, boxplots were not prepared for this constituent.

Total organic carbon—During the thermally stratified period, total organic carbon interquartile ranges for the surface sample at site 700 and surface and bottom samples at sites 600 and 340 were 3 to 4 mg/L (fig. 14a). Site 100 had an interquartile range of 2 to 3 mg/L for the bottom sample. Total organic carbon concentrations decreased slightly from upstream to downstream sites.

During the mixed period, total organic carbon interquartile ranges for surface and bottom samples were small (fig. 14b).

Summary of Water-Quality Conditions

Lake Travis is a biologically unproductive reservoir with acceptable water quality for virtually all current water uses, on the basis of criteria highlighted by Ryding and Rast (1989). Because of its location in a subtropical climatic zone, the reservoir generally exhibits greater mean temperatures than water bodies in a temperate climatic zone. The nutrient (nitrogen, phosphorus) concentrations tend to be small in Lake Travis throughout the year, indicating nutrient limitation of maximum phytoplankton biomass. This is consistent

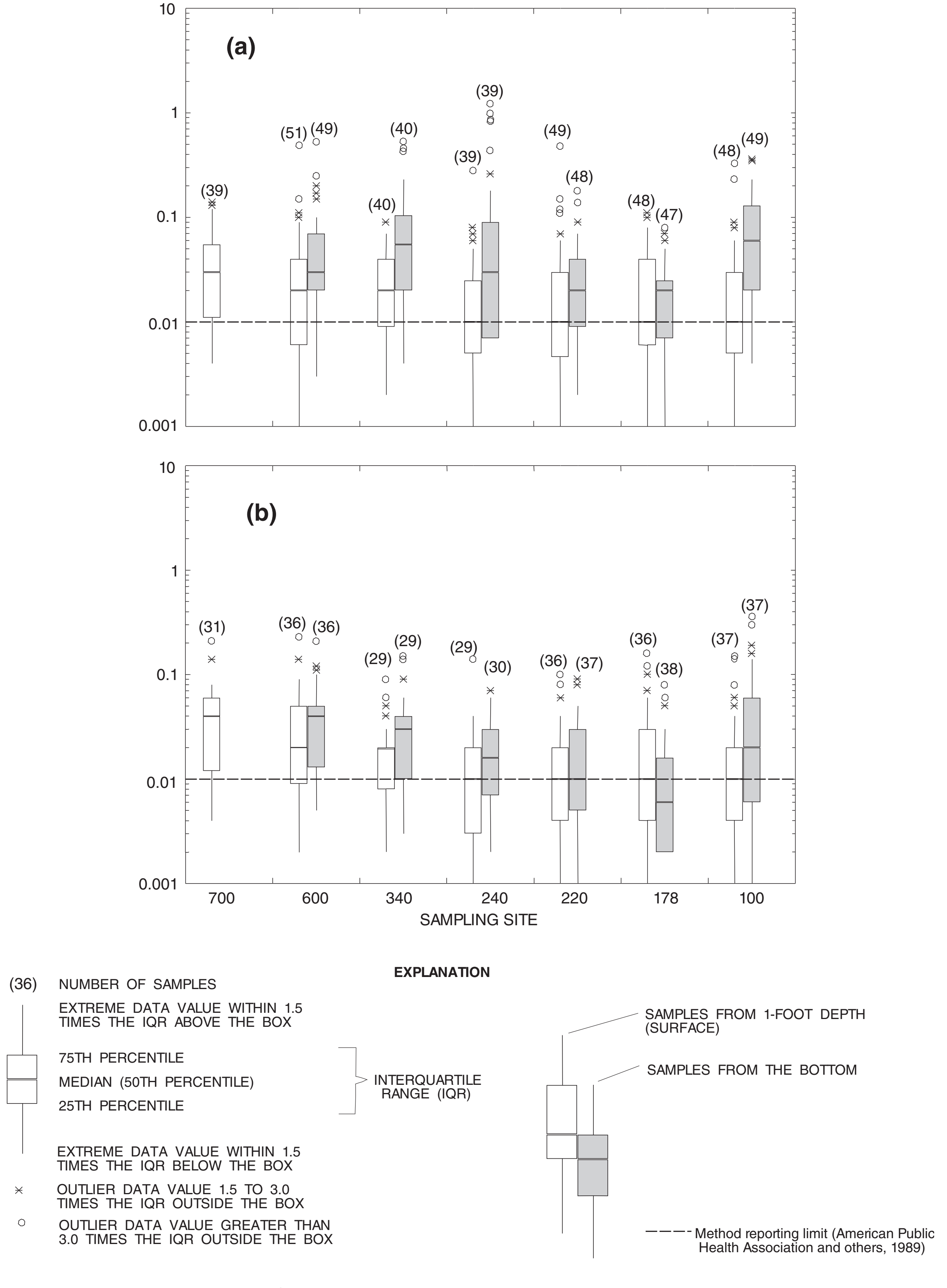

Figure 11. Range and distribution of ammonia nitrogen at selected sites in Lake Travis, near Austin, Texas, during (a) thermally stratified period and (b) mixed period.

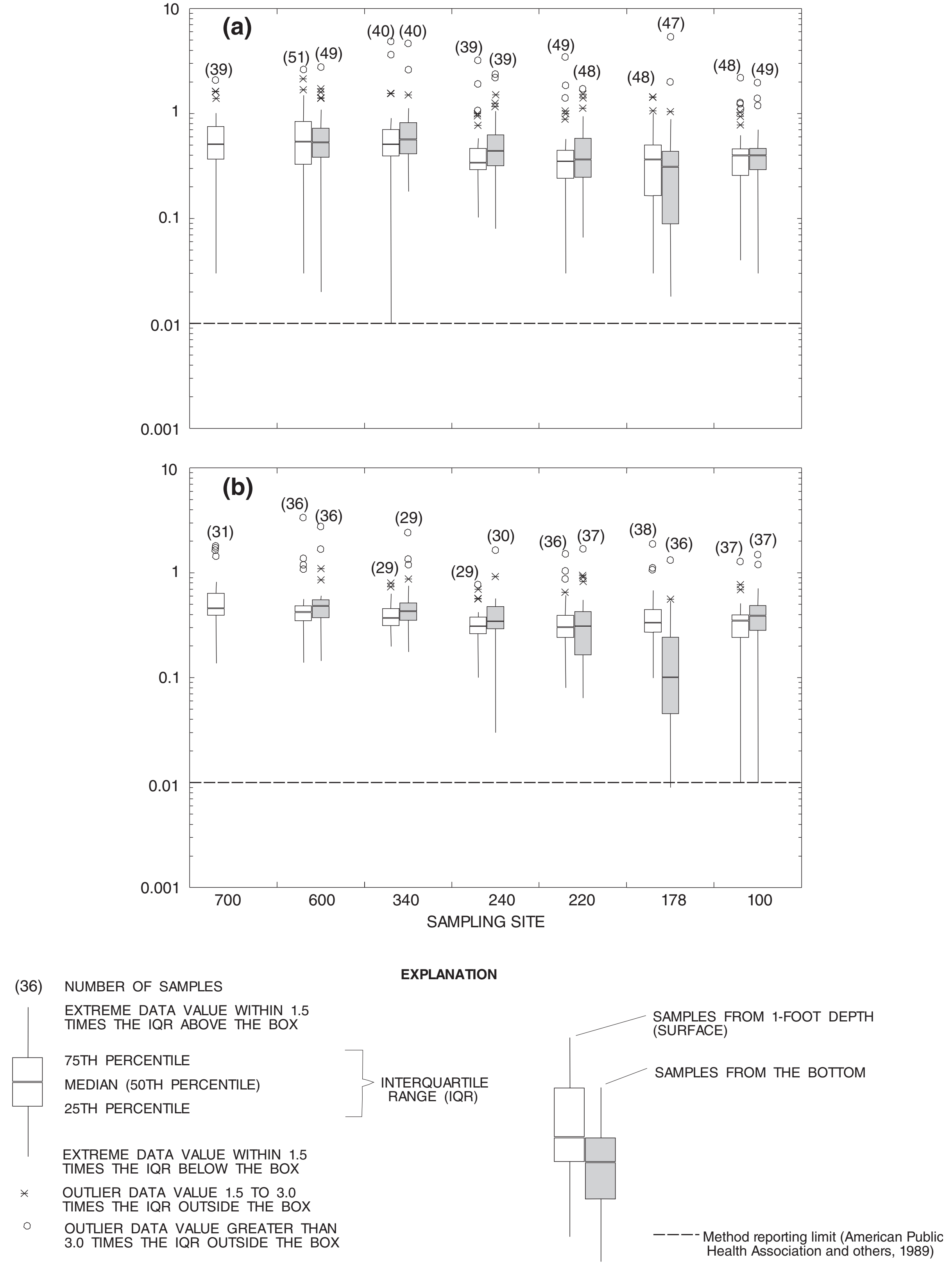

Figure 12. Range and distribution of total Kjeldahl nitrogen at selected sites in Lake Travis, near Austin, Texas, during (a) thermally stratified period and (b) mixed period.

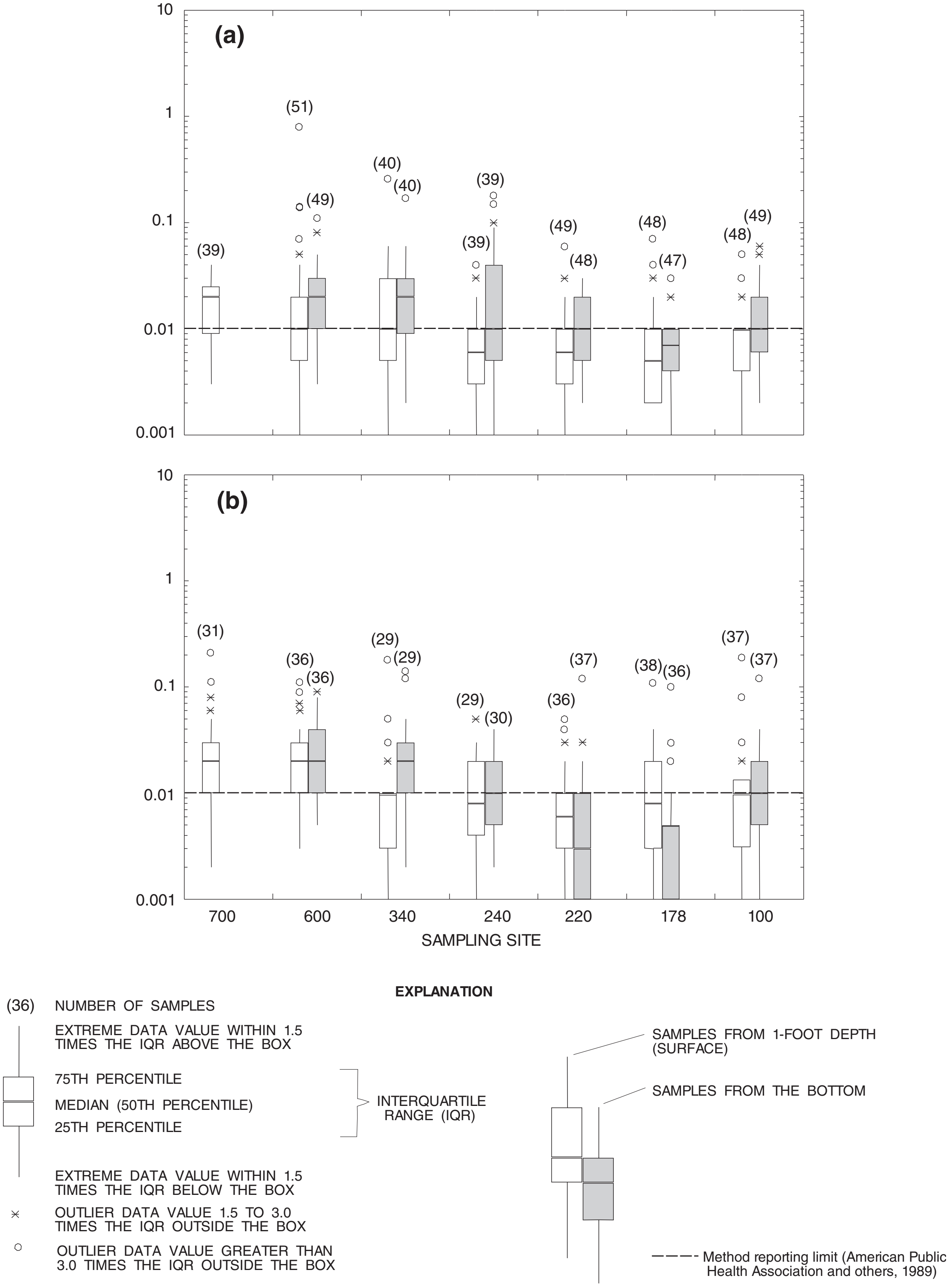

Figure 13. Range and distribution of total phosphorus at selected sites in Lake Travis, near Austin, Texas, during (a) thermally stratified period and (b) mixed period.

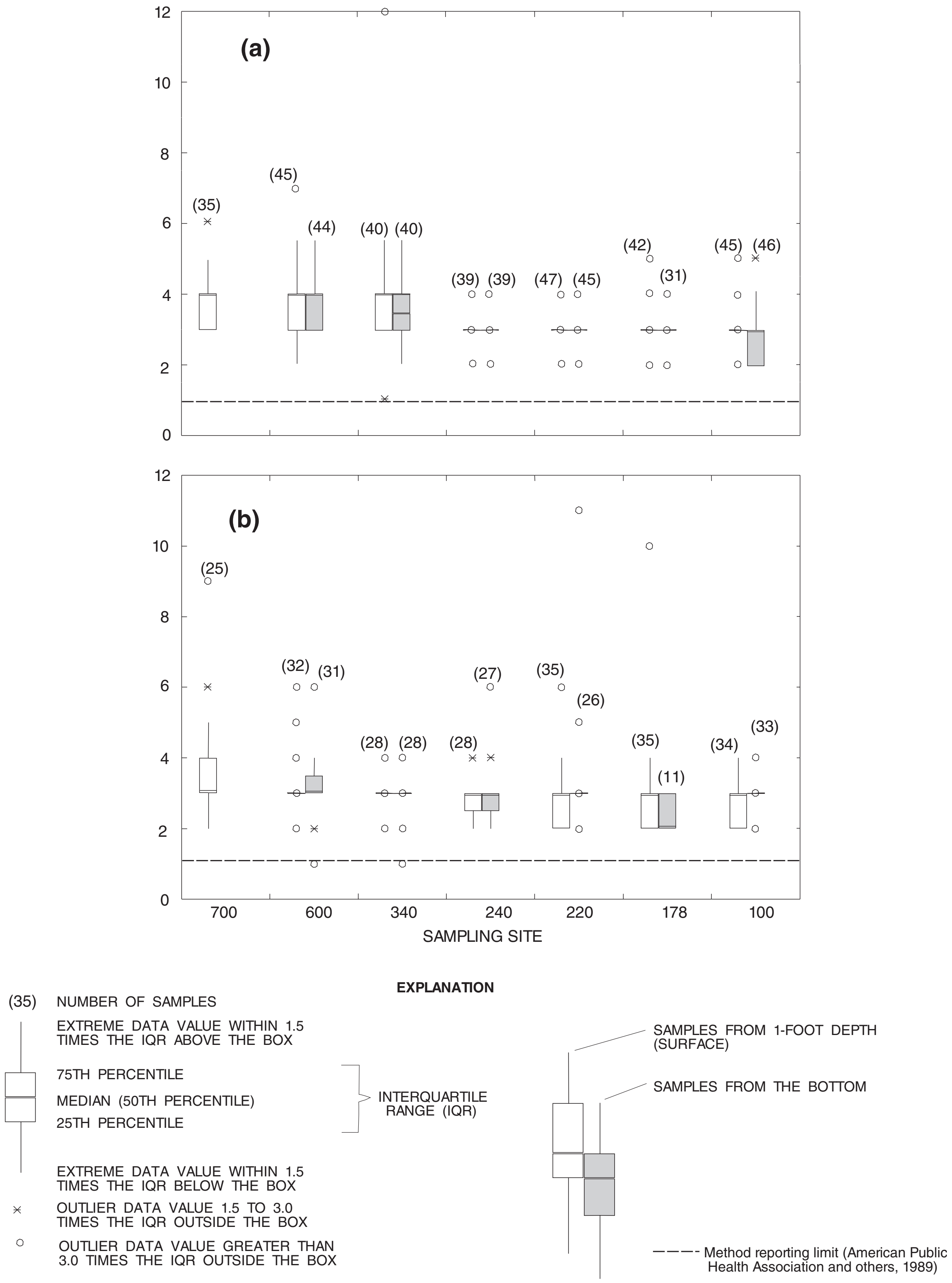

Figure 14. Range and distribution of total organic carbon at selected sites in Lake Travis, near Austin, Texas, during (a) thermally stratified period and (b) mixed period.

Table 5. Summary of criteria for selected water-quality properties and constituents in Lake Travis, near Austin, Texas

[mg/L, milligrams per liter; °C, degrees Celsius]

Property or constituent	Criteria[1]
pH	5.0 to 9.0 standard units for domestic water supply 6.5 to 9.0 standard units for freshwater aquatic life
Temperature	Variable, based primarily on effects on growth of sensitive species
Dissolved oxygen	5 mg/L or more to maintain good fish populations
Total alkalinity, as $CaCO_3$	20 mg/L or more for freshwater aquatic life, except where natural concentrations are less
Total suspended solids	Concentration that will not reduce depth of compensation point for photosynthesis activity by more than 10 percent from the seasonally established norm for aquatic life
Nitrate and nitrite nitrogen	10 mg/L or less for domestic water supply
Ammonia nitrogen	0.02 mg/L or less (as un-ionized ammonia) for freshwater aquatic life (for comparison, an equivalent concentration of ammonia nitrogen at pH 8.0 and 20 °C is approximately 0.52 mg/L)
Total phosphorus	0.025 mg/L or less during spring overturn on a volume-weighted basis

[1] U.S. Environmental Protection Agency, 1986.

with the relatively great Secchi-disk depths, especially at the downstream end of the reservoir.

On the basis of traditional limnological properties, Lake Travis exhibits little biological productivity and exceptional water transparency. However, dissolved oxygen concentrations for bottom samples often decrease to less than 5 mg/L, and even smaller concentrations are measured throughout the reservoir, especially during the thermally stratified period.

The measured water-quality data can be compared to other water-quality criteria. The criteria published by the U.S. Environmental Protection Agency (1986) for constituents examined in this study are summarized in table 5. The recommended limits for pH, temperature, total alkalinity, total suspended solids, and nitrate nitrogen were not exceeded in Lake Travis. Total phosphorus concentrations exceeded the recommended limit of 0.025 mg/L at some sites, but median concentrations were less than 0.025 mg/L at all sites during the thermally stratified and mixed periods.

EVALUATION OF MONITORING PROGRAM

Multiple-comparison tests were performed to determine if monitoring sites produced data statistically similar to that produced at one or more sites. The sites were restricted to seven sites with both field and chemical data (700, 600, 340, 240, 220, 178, and 100). Because of unequal numbers of samples for the different sampling sites, the estimated data were not directly used in the multiple-comparison tests. Instead, the ranks of the data (smallest to largest, 1 to n values) were used in this analysis, which is a common procedure with nonparametric statistical tests (Hollander and Wolfe, 1973).

Statistical Comparisons Between Sampling Sites

The results from the multiple-comparison tests are listed in table 6. Sites with statistically similar (95-percent confidence level) data for surface samples are indicated by the same letter for surface samples in table 6; also, sites with statistically similar data for bottom samples are indicated by the same letter for bottom samples. Sampling sites with statistically similar data are thus grouped in table 6 to indicate the minimum number of sites needed to adequately characterize individual water-quality constituents in either shallow (surface samples) or deep (bottom samples) Lake Travis water during either the thermally stratified period or the mixed period. For example, specific conductance data for surface samples at all sites are statistically similar during the mixed period—one site might characterize specific conductance in shallow Lake Travis water during the mixed period (table 6). Temperature data for bottom samples during the thermally stratified period indicate two statistically similar groupings (table 6)—one site from each group might adequately characterize temperature in deep Lake Travis water during the thermally stratified period.

Table 6. Sampling sites in Lake Travis, near Austin, Texas, with statistically similar concentrations of constituents or properties during thermally stratified period (May to November) and during mixed period (December to April)

[Same-letter designations indicate statistical similarity.]

Constituent or property	Stratified or mixed period	Surface or bottom samples	Sampling site number						
			700	600	340	240	220	178	100
Specific conductance	Stratified	Surface	A	B	B	B	B	B	B
Specific conductance	Stratified	Bottom	(1)	A	A	A	A	A	A
Specific conductance	Mixed	Surface	A	A	A	A	A	A	A
Specific conductance	Mixed	Bottom	(1)	A	A	A	A	A	A
pH	Stratified	Surface	A	B	B	B	B	B	B
pH	Stratified	Bottom	(1)	A/B	A/C	C	B/D	D	C
pH	Mixed	Surface	A	A	A	A	A	A	A
pH	Mixed	Bottom	(1)	A/B	A/B	B/C	A	A	C
Temperature	Stratified	Surface	A	A	A	A	A	A	A
Temperature	Stratified	Bottom	(1)	A	A	B	A	A	B
Temperature	Mixed	Surface	A	A	A	A	A	A	A
Temperature	Mixed	Bottom	(1)	A	B	A/B	A	A	B
Dissolved oxygen	Stratified	Surface	A	A	A	A	A	A	A
Dissolved oxygen	Stratified	Bottom	(1)	A/B	A/C	C	B/D	D	C
Dissolved oxygen	Mixed	Surface	A	B	B	B	B	B	B
Dissolved oxygen	Mixed	Bottom	(1)	A/B	B/C	C	A	A	C
Secchi-disk depth	Stratified	Surface	A	B	C	D	C	C	D
Secchi-disk depth	Stratified	Bottom[2]							
Secchi-disk depth	Mixed	Surface	A	A	B	B/C	B/C	B/C	C
Secchi-disk depth	Mixed	Bottom[2]							
Total alkalinity	Stratified	Surface	A/B/C	B/C	B	A/B/C	A/B/C	A/C	A
Total alkalinity	Stratified	Bottom	(1)	A/B	C	C	A/B	A	B/C
Total alkalinity	Mixed	Surface	A	A	A	A	A	A	A
Total alkalinity	Mixed	Bottom	(1)	A/B	A	A/B	A/B	B	A/B
Total suspended solids	Stratified	Surface	A	A	A/B	B/C/D	C/D	B/C	D
Total suspended solids	Stratified	Bottom	(1)	A	A/D	B/C	B/D	B/C	C
Total suspended solids	Mixed	Surface	A/B	A	A/B/C	B/C	C	C	C
Total suspended solids	Mixed	Bottom	(1)	A	A/B	B/C	C	D	C
Nitrate nitrogen	Stratified	Surface	A	B	A/B	B	B	B	B
Nitrate nitrogen	Stratified	Bottom	(1)	A	B/C	B	A/C	A	B
Nitrate nitrogen	Mixed	Surface	A	A	A	A	A	A	A
Nitrate nitrogen	Mixed	Bottom	(1)	A	A	B	B	B	A
Nitrite nitrogen	Stratified	Surface	A	B	B	A	A	A	B
Nitrite nitrogen	Stratified	Bottom	(1)	A/B	C	A/B	A	(3)	B/C
Nitrite nitrogen	Mixed	Surface	A	A	A	A/B	B	B	B
Nitrite nitrogen	Mixed	Bottom	(1)	A	A	A	A/B	C	B
Ammonia nitrogen	Stratified	Surface	A	A/B	A/B	B	B	B	B
Ammonia nitrogen	Stratified	Bottom	(1)	A	A	A/C	C	C	A
Ammonia nitrogen	Mixed	Surface	A	A/B	A/B	C	C	B/C	C
Ammonia nitrogen	Mixed	Bottom	(1)	A	A	B	B	B	A

Footnotes at end of table.

Table 6. Sampling sites in Lake Travis, near Austin, Texas, with statistically similar concentrations of constituents or properties during thermally stratified period (May to November) and during mixed period (December to April)—Continued

Constituent or property	Stratified or mixed period	Surface or bottom samples	Sampling site number						
			700	600	340	240	220	178	100
Total Kjeldahl nitrogen	Stratified	Surface	A/B	A/B	A	B/C	C	C	B/C
Total Kjeldahl nitrogen	Stratified	Bottom	(1)	A	A	B	B/C	C	B/C
Total Kjeldahl nitrogen	Mixed	Surface	A	A/B	A/B/C	B/C	C	B/C	B/C
Total Kjeldahl nitrogen	Mixed	Bottom	(1)	A	A	B	B	C	A/B
Total phosphorus	Stratified	Surface	A	A/B	A/B/C	C/D	D	D	B/C/D
Total phosphorus	Stratified	Bottom	(1)	A	A	A/B	B/C	C	B/C
Total phosphorus	Mixed	Surface	A	A	B	B	B	B	B
Total phosphorus	Mixed	Bottom	(1)	A	A/B	B	C	C	B
Orthophosphate phosphorus	Stratified	Surface	A	B	B	C	D	D	B
Orthophosphate phosphorus	Stratified	Bottom	(1)	A	A	A	B	B	A
Orthophosphate phosphorus	Mixed	Surface	A	A/B	B	C	D	A/B	B/C
Orthophosphate phosphorus	Mixed	Bottom	(1)	A	A	A	B	C	A
Total organic carbon	Stratified	Surface	A	A	A	B	B	B	B
Total organic carbon	Stratified	Bottom	(1)	A	A/B	C	C	B/C	C
Total organic carbon	Mixed	Surface	A	A/B	A/B	B	B	B	B
Total organic carbon	Mixed	Bottom	(1)	A	A/B	A/B	A/B	B	A/B
Chlorophyll-a	Stratified	Surface	A	A	A	B	B	B	B
Chlorophyll-a	Stratified	Bottom[2]							
Chlorophyll-a	Mixed	Surface	A	A	A/B	A/B/C	B/C	B/C	C
Chlorophyll-a	Mixed	Bottom[2]							

[1] No bottom samples were taken at site 700 because the shallow bottom was commonly above the thermocline.

[2] Not measured at bottom depths.

[3] Data were insufficient for site 178.

Field Measurements

Specific conductance—The surface-sample data (table 6) indicate that two sampling sites might adequately characterize the specific conductance of shallow water in Lake Travis during the thermally stratified period—site 700 and any one downstream site—and that any single site might characterize shallow water during the mixed period. The bottom-sample data indicate that any single site might characterize the specific conductance of deep water during either period.

pH—The surface-sample data (table 6) indicate that two sites might adequately characterize the pH of shallow water in Lake Travis during the thermally stratified period—site 700 and any one downstream site—and that any single site might characterize shallow water during the mixed period. The data for bottom samples are more heterogeneous than the data for surface samples. Five sites might characterize the pH of deep water in Lake Travis during the thermally stratified period—site 600, site 340, site 240 or 100, site 220, and site 178—and four sites might characterize deep water during the mixed period—site 600 or 340, site 240, site 220 or 178, and site 100.

Temperature—The lake surface temperature primarily is controlled by the intensity of sunlight reaching the surface, a consistent factor for all surface samples. Water temperatures at the surface, therefore, are assumed to be similar throughout the reservoir as confirmed by the surface samples in table 6—any single site might adequately characterize the temperature of shallow water in Lake Travis during either period.

The sunlight energy penetrates to different water-column depths at different locations in Lake Travis.

The bottom-sample temperature data therefore exhibit a more heterogeneous distribution. Two sites might adequately characterize the temperature of deep water in Lake Travis during the thermally stratified period—site 240 or 100 and one remaining site. Although two groups of sites with statistically similar bottom-sample data were determined for the mixed period, three sites might be needed—site 600, 220, or 178; site 340 or 100; and site 240.

Dissolved oxygen—The dissolved oxygen concentrations for surface samples primarily result from phytoplankton photosynthesis and atmospheric exchange. Accordingly, the dissolved oxygen data for surface samples (table 6) are relatively homogeneous during the thermally stratified period (normally the period of maximum phytoplankton photosynthesis)—any single site might characterize the dissolved oxygen of shallow water in Lake Travis. During the mixed period two sites might characterize shallow water—site 700 and one downstream site.

Dissolved oxygen data for bottom samples during the stratified period need five sites—site 600, site 340, site 240 or 100, site 220, and site 178. For the mixed period, dissolved oxygen for bottom samples needs four sites—site 600, site 340, site 240 or 100, and site 220 or 178.

Secchi-disk depth—Secchi-disk depth was measured at the surface only. Water clarity is a function of many factors, including phytoplankton density, inorganic turbidity, and other light-absorbing or scattering components. These factors typically vary along the length of a reservoir system. For example, water transparency typically increases toward the downstream end of a reservoir as inorganic turbidity (suspended solids) aggregates and settles to the bottom of the reservoir. Furthermore, phytoplankton pigment (chlorophyll-a) is a major light-absorbing component in the water column. Therefore, Secchi-disk depth and phytoplankton density (expressed as chlorophyll-a) are assumed to be inversely related in a reservoir.

Because its causative factors can change along the downstream length of a reservoir, Secchi-disk depth exhibits large variability (table 6). The data indicate that four sites might characterize Secchi-disk depths for Lake Travis during the thermally stratified period—site 700; site 600; site 340, 220 or 178; and site 240 or 100. During the mixed period, phytoplankton growth usually is minimal. Four sites might adequately characterize Secchi-disk depths for Lake Travis during the mixed period—site 700 or 600; site 340; site 240, 220, or 178; and site 100.

Laboratory Measurements

Total alkalinity as $CaCO_3$—The surface-sample data (table 6) indicate that five sites might characterize the total alkalinity of shallow water in Lake Travis during the thermally stratified period—site 700, 240 or 220; site 600; site 340; site 178; and site 100—and any single site might adequately characterize shallow water during the mixed period.

Total alkalinity data for bottom samples are slightly more heterogeneous than for surface samples. Four sites might characterize the total alkalinity of deep water in Lake Travis during the thermally stratified period—site 600 or 220, site 340 or 240, site 178, and site 100—and three sites might characterize deep water during the mixed period—site 600, 240, 220 or 100; site 340; and site 178.

Total suspended solids—The surface-sample data (table 6) indicate that six sites might adequately characterize the total suspended solids of shallow water in Lake Travis during the thermally stratified period—site 700 or 600, site 340, site 240, site 220, site 178, and site 100. Five sites might adequately characterize shallow water during the mixed period—site 700, site 600, site 340, site 240, and site 220, 178, or 100.

The bottom-sample data indicate that five sites might adequately characterize the total suspended solids of deep water in Lake Travis—site 600, site 340, site 240 or 178, site 220, and site 100 during the thermally stratified period and site 600, site 340, site 240, site 220 or 100, and site 178 during the mixed period.

Nitrate nitrogen—The surface-sample data for nitrate nitrogen, a primary phytoplankton nutrient, are relatively homogeneous (table 6). Three sites might characterize the nitrate of shallow water in Lake Travis during the thermally stratified period—site 700, site 340, and one other site. Any single site might adequately characterize the nitrate of shallow water during the mixed period.

Reduced phytoplankton photosynthesis is represented by the more heterogeneous nitrate data for bottom samples, compared to that for surface samples. Four sites might adequately characterize the nitrate of deep water in Lake Travis during the thermally stratified period—site 600 or 178, site 340, site 240 or 100, and site 220—and two sites might characterize deep water during the mixed period—site 600, 340, or 100; and site 240, 220, or 178.

Nitrite nitrogen—Surface-sample data (table 6) indicate that two sites might characterize the nitrite of shallow water in Lake Travis during the thermally stratified period—site 700, 240, 220, or 178; and site 600, 340, or 100. Three sites might characterize shallow water during the mixed period—site 700, 600, or 340; site 240; and site 220, 178, or 100.

The data for bottom samples are more heterogeneous than for surface samples. Four sites might characterize the nitrite of deep water in Lake Travis during the thermally stratified period—site 600 or 240, site 340, site 220, and site 100. Because no detectable nitrite concentrations were measured at cove site 178, sampling at this site also might be needed. Four sites might characterize deep water during the mixed period—site 600, 340, or 240; site 220; site 178; and site 100.

Ammonia nitrogen—Ammonia nitrogen is a bioavailable form of nitrogen, and in-lake concentrations typically are smaller than nitrate or nitrite nitrogen concentrations. Median concentrations often are at the reporting limit during both periods. Surface-sample data (table 6) indicate that three sites might characterize the ammonia nitrogen of shallow water in Lake Travis during the stratified period—site 700; site 600 or 340; and site 240, 220, 178, or 100. Four sites might characterize shallow water during the thermally mixed period—site 700; site 600 or 340; site 240, 220, or 100; and site 178.

Bottom-sample data indicate that three sites might characterize the ammonia nitrogen of deep water in Lake Travis during the thermally stratified period—site 600, 340, or 100; site 240; and site 220 or 178—and two sites might characterize deep water during the mixed period—site 600, 340, or 100; and site 240, 220, or 178.

Total Kjeldahl nitrogen—The surface-sample data (table 6) indicate that four sites might adequately characterize the total Kjeldahl nitrogen of shallow water in Lake Travis during the thermally stratified period—site 700 or 600, site 340, site 240 or 100, and site 220 or 178. Five sites might characterize shallow water during the mixed period—site 700; site 600; site 340; site 240, 178, or 100; and site 220.

The bottom-sample data indicate that four sites might adequately characterize the total Kjeldahl nitrogen of deep water in Lake Travis during the thermally stratified period—site 600 or 340, site 240, site 220 or 100, and site 178. Four sites also might characterize deep water during the mixed period—site 600 or 340, site 240 or 220, site 178, and site 100.

Orthophosphate phosphorus—Most of the orthophosphate phosphorus data were generated by the log-probability regression method of Gilliom and Helsel (1986). Therefore, the results of the multiple-comparison tests should be used with caution. During the thermally stratified period, the period of presumed maximal phytoplankton biomass, surface-sample data (table 6) indicate that four sites might characterize the orthophosphates of shallow water in Lake Travis—site 700; site 600, 340, or 100; site 240; and site 220 or 178. Six sites might characterize shallow water during the mixed period—site 700, site 600 or 178, site 340, site 240, site 220, and site 100.

Phytoplankton photosynthesis typically is minimal for bottom samples and is reflected in the more homogeneous data patterns, compared to surface samples. Two sites might characterize the orthophosphates of deep water in Lake Travis during the thermally stratified period—site 600, 340, 240, or 100; and site 220 or 178. The same general pattern is indicated during the mixed period, except that both cove sites (220 and 178) might require sampling.

Total phosphorus—Total phosphorus is the summation of the dissolved (readily bioavailable) and particulate forms of phosphorus. Because it is a primary phytoplankton and aquatic plant nutrient, it often is at or below the detection limit in many bodies of water. The surface-sample data (table 6) exhibit a relatively homogeneous distribution during the thermally stratified period, typically the period of maximal phytoplankton growth (and presumed phosphorus depletion). Six sites might adequately characterize the total phosphorus of shallow water in Lake Travis during the thermally stratified period—site 700, site 600, site 340, site 240, site 220 or 178, and site 100. Two sites might characterize shallow water during the mixed period—site 700 or 600, and one downstream site.

Because phytoplankton photosynthesis is reduced at the bottom of the reservoir, the total phosphorus data for bottom samples differ from data for surface samples. Four sites might adequately characterize the total phosphorus of deep water in Lake Travis during the thermally stratified period—site 600 or 340, site 240, site 220 or 100, and site 178. Four sites also might characterize deep water during the mixed period—site 600, site 340, site 240 or 100, and site 220 or 178.

Total organic carbon—Total organic carbon sometimes is used as an indirect measure of

Table 7. Statistically similar water-quality properties and constituents (95-percent confidence level) at in-lake sampling sites in Lake Travis, near Austin, Texas

Property or constituent	Statistically similar, thermally stratified period (May to November)		Statistically similar, mixed period (December to April)	
	Surface	Bottom	Surface	Bottom
Specific conductance	......	Yes	Yes	Yes
pH	......	......	Yes	......
Temperature	Yes	......	Yes	......
Dissolved oxygen	Yes	......	......	......
Secchi-disk depth	......	......	......	......
Total alkalinity	......	......	Yes	......
Total suspended solids	......	......	......	......
Nitrate nitrogen	......	......	Yes	......
Nitrite nitrogen	......	......	......	......
Ammonia nitrogen	......	......	......	......
Total Kjeldahl nitrogen	......	......	......	......
Total phosphorus	......	......	......	......
Orthophosphate phosphorus	......	Yes	......	Yes
Total organic carbon	......	......	......	......
Chlorophyll-a	......	......	......	......

phytoplankton biomass. Because total Kjeldahl nitrogen also is used for this purpose, these two constituents often exhibit similar patterns in lakes and reservoirs. The surface-sample data (table 6) indicate that two sites might characterize the total organic carbon of shallow water in Lake Travis during the thermally stratified period—site 700, 600, or 340; and site 240, 220, 178, or 100. Three sites might characterize shallow water during the mixed period—site 700; site 600 or 340; and site 240, 220, 178, or 100.

The pattern of bottom-sample data for total organic carbon is similar to that of surface-sample data. Four sites might characterize the total organic carbon of deep water in Lake Travis during the thermally stratified period—site 600; site 340; site 240, 220, or 100; and site 178. Three sites might characterize deep water during the mixed period—site 600; site 340, 240, 220, or 100; and site 178.

Chlorophyll-a—Chlorophyll-a concentrations generally are measured only at or near surface to provide an indication of phytoplankton biomass, which requires sunlight as the energy source for photosynthesis. Because total Kjeldahl nitrogen and total organic carbon often are used as indirect indicators of phytoplankton biomass, chlorophyll-a data can exhibit patterns similar to the patterns for these two constituents. The surface-sample data (table 6) indicate that two sites might adequately characterize the chlorophyll-a of shallow water in Lake Travis during the thermally stratified period—site 700, 600, or 340; and one downstream site. Five sites might characterize shallow water during the mixed period—site 700 or 600, site 340, site 240, site 220 or 178, and site 100.

Statistical Comparisons Between In-Lake and Cove Sites

In addition to seasonal periods, the data were evaluated on the basis of location in Lake Travis, specifically, in-lake sites versus cove sites. For example, at the in-lake sites (700, 600, 340, 240, and 100), only temperature data were statistically similar for all surface samples during both periods; similarly only specific conductance and orthophosphate phosphorus data were statistically similar for all bottom samples during both periods (table 7). The data also can be evaluated on the basis of season and location. For example, during the thermally stratified period, temperature and dissolved oxygen data were statistically similar for all surface samples at all in-lake sites; and specific conductance and orthophosphate phosphorus data were statistically similar for all bottom samples at all in-lake sites. More properties and constituents were statistically similar at all in-lake sites during the mixed period because of the more homogeneous nature of the water column.

Table 8. Statistically similar water-quality properties and constituents (95-percent confidence level) at cove sampling sites in Lake Travis, near Austin, Texas

Property or constituent	Statistically similar, thermally stratified and mixed periods	
	Surface	Bottom
Specific conductance	Yes	Yes
pH	Yes	......
Temperature	Yes	Yes
Dissolved oxygen	Yes	......
Secchi-disk depth	Yes	......
Total alkalinity	......	......
Total suspended solids	......	......
Nitrate nitrogen	Yes	......
Nitrite nitrogen	Yes	......
Ammonia nitrogen	......	Yes
Total Kjeldahl nitrogen	......	......
Total phosphorus	Yes	......
Orthophosphate phosphorus	......	......
Total organic carbon	Yes	......
Chlorophyll-a	Yes	......

Data for the cove sites (220 and 178) also were evaluated. Table 6 indicates that the data for cove sites are more homogeneous than the data for in-lake sites, probably because of smaller water and contaminant input from the smaller watersheds of the coves and smaller volume of the coves. The properties and constituents that were statistically similar at the cove sites during both periods are listed in table 8 for surface samples and for bottom samples. The data indicate more similarity of water-quality properties and constituents between the cove sites than between the in-lake sites.

Limitations of Statistical Comparisons Between Sampling Sites

The results of the multiple-comparison tests indicate that, for some constituents, a single sampling site for a constituent or property might adequately characterize the water quality of the reservoir for that constituent or property. However, multiple-sampling sites might be required to provide information of sufficient temporal and spatial resolution to accurately evaluate other water-quality constituents for the reservoir, particularly with respect to spatial differences in development of the drainage basin. The challenge is identifying the minimum number of sampling sites required to provide adequate water-quality information for Lake Travis.

One approach to identifying the minimum number of sampling sites required is to adhere to the statistical results, sampling only those sites identified as being statistically distinct from other sites in Lake Travis. The data in table 9 indicate that only temperature can be sampled at the surface at any site during any time of the year and still provide statistically similar data for all sampling sites in Lake Travis. This is consistent with the observation that sunlight intensity should be essentially similar and hence produce the same temperature at the surface at all Lake Travis sites. The data in table 9 also indicate that only specific conductance can be sampled at the bottom at any site during any time of the year and still provide statistically similar data for all sampling sites in the reservoir. This observation is expected because inflowing water with the largest density (most saline) typically sinks to the bottom layers of a lake or reservoir.

Another approach to identifying the minimum number of sampling sites required is to consider the need for consistency of the data base over time. If statistical results were strictly followed, an inconsistent monitoring program for Lake Travis would result. Some sites would be sampled for only one or a few water-quality constituents while others would be sampled for many or all of the constituents. For those constituents where only one site is needed to characterize Lake Travis (on the basis of the multiple-comparison tests),

Table 9. Statistically similar water-quality properties and constituents (95-percent confidence level) at all sampling sites in Lake Travis, near Austin, Texas

Property or constituent	Statistically similar, thermally stratified period (May to November)		Statistically similar, mixed period (December to April)	
	Surface	Bottom	Surface	Bottom
Specific conductance	......	Yes	Yes	Yes
pH	......	......	Yes	......
Temperature	Yes	......	Yes	......
Dissolved oxygen	Yes	......	......	......
Secchi-disk depth	......	......	......	......
Total alkalinity	......	......	Yes	......
Total suspended solids	......	......	......	......
Nitrate nitrogen	......	......	Yes	......
Nitrite nitrogen	......	......	......	......
Ammonia nitrogen	......	......	......	......
Total Kjeldahl nitrogen	......	......	......	......
Total phosphorus	......	......	......	......
Orthophosphate phosphorus	......	......	......	......
Total organic carbon	......	......	......	......
Chlorophyll-a	......	......	......	......

the inference is that the data measured at the one site will accurately describe the entire water body, or at least large parts of it. Thus, in analyzing Lake Travis data over the long term, it would be necessary to combine data for some constituents at some sites with the data for some or all constituents at other sites. Because of the dynamic nature of reservoir ecosystems, this practice would prove to be logistically cumbersome over time. Furthermore, data obtained in this manner would require continuous reassessment of their adequacy over time to determine if data groupings different from these results evolved as the reservoir aged. Some constituents can be measured easily, especially specific conductance, pH, temperature, and dissolved oxygen (typically all measured in place with a multi-probe sensor), as well as Secchi-disk depth. This means that the same effort required to measure all four constituents is used to measure only one or a few.

Addition of New Sampling Sites

In addition to identifying sampling sites with statistically similar water-quality data, the analytical results also can be used to determine if additional sampling sites are needed to more accurately characterize water-quality conditions in the reservoir. Several techniques are available to determine the minimum number of sampling sites to define water-quality conditions in reservoirs exhibiting water-quality gradients from the upstream to the downstream end. These techniques are based on the natural variability of the water-quality constituent and the desired precision of the mean value (Thornton and others, 1982; and Ryding and Rast, 1989). However, the data base is not sufficiently large enough, or of adequate duration, to provide an accurate representation of the natural variability of the water-quality constituents at all the sampling sites over an extended period. Furthermore, the data available are not sufficient to appropriately characterize the climatic and hydrologic conditions in Lake Travis.

The data in table 6 indicate that nutrients (nitrogen, phosphorus) might require additional sampling sites for a more accurate characterization of their in-lake dynamics. This is especially true for the reservoir surface area between sites 600 and 340 and between sites 340 and 240. The large number of statistically distinct data sets for many nutrient constituents is indicative of the influence of biochemical uptake and utilization of these constituents. The fact that related constituents, such as Secchi-disk depth (affected by in-lake phytoplankton biomass) and total organic carbon (a measure of in-lake biomass), also exhibit this pattern supports the possible need for additional in-lake sampling sites to more accurately characterize the

Table 10. Water-quality properties and constituents from surface samples that are significantly different statistically between adjacent sites in the main body of Lake Travis, near Austin, Texas

[Constituents significantly different statistically listed between respective sampling sites.]

Period	Sampling site no.				
	700	600	340	240	100
Thermally stratified	Specific conductance	....	....	....	
	pH	....	....	....	
	Secchi-disk depth	Secchi-disk depth	Secchi-disk depth	....	
	Total alkalinity	Total alkalinity	Total alkalinity	Total alkalinity	
	....	Total suspended solids	Total suspended solids	Total suspended solids	
	Nitrate nitrogen	Nitrate nitrogen	Nitrate nitrogen	....	
	Nitrite nitrogen	....	Nitrite nitrogen	Nitrite nitrogen	
	Ammonia nitrogen	....	Ammonia nitrogen	....	
	....	Total Kjeldahl nitrogen	Total Kjeldahl nitrogen	....	
	Total phosphorus	Total phosphorus	Total phosphorus	Total phosphorus	
	Orthophosphate phosphorus	....	Orthophosphate phosphorus	Orthophosphate phosphorus	
	....	....	Total organic carbon	....	
	....	....	Chlorophyll-a	....	
Mixed	Dissolved oxygen	....	....	....	
	....	Secchi-disk depth	Secchi-disk depth	Secchi-disk depth	
	Total suspended solids	Total suspended solids	Total suspended solids	Total suspended solids	
	....	....	Nitrite nitrogen	Nitrite nitrogen	
	Ammonia nitrogen	....	Ammonia nitrogen	....	
	Total Kjeldahl nitrogen	Total Kjeldahl nitrogen	Total Kjeldahl nitrogen	....	
	....	Total phosphorus	....	....	
	Orthophosphate phosphorus	Orthophosphate phosphorus	Orthophosphate phosphorus	Orthophosphate phosphorus	
	Total organic carbon	....	Total organic carbon	....	
	....	Chlorophyll-a	Chlorophyll-a	Chlorophyll-a	

dynamics of biologically mediated water-quality constituents in Lake Travis.

The results of the multiple-comparison tests also can be used to assess the need for additional sampling sites in Lake Travis. This was done by identifying differences in generally similar water-quality data between adjacent in-lake sites. These differences, or discontinuities in otherwise similar data, represent statistically significant differences in water quality between adjacent sampling sites. This, in turn, could justify establishment of one or more additional in-lake sampling sites to better characterize the water quality of Lake Travis. The water-quality properties and constituents from surface samples and from bottom samples with statistically significant differences between adjacent sites in the main body of Lake Travis are listed in tables 10–11.

Table 11. Water-quality properties and constituents from bottom samples that are significantly different statistically between adjacent sites in the main body of Lake Travis, near Austin, Texas

[Constituents significantly different statistically listed between respective sampling sites.]

Period	Sampling site no.				
	700	**600**	**340**	**240**	**100**
Thermally stratified	....	pH	pH	....	
	....	....	Temperature	....	
	....	Dissolved oxygen	Dissolved oxygen	....	
	....	Total alkalinity	....	Total alkalinity	
	....	Total suspended solids	Total suspended solids	Total suspended solids	
	....	Nitrate nitrogen	Nitrate nitrogen	....	
	....	Nitrite nitrogen	Nitrite nitrogen	Nitrite nitrogen	
	....	....	Ammonia nitrogen	Ammonia nitrogen	
	....	....	Total Kjeldahl nitrogen	Total Kjeldahl nitrogen	
	....	....	Total phosphorus	Total phosphorus	
	....	Total organic carbon	Total organic carbon	....	
Mixed	....	....	pH	pH	
	....	Temperature	Temperature	Temperature	
	....	Dissolved oxygen	Dissolved oxygen	....	
	....	Total alkalinity	Total alkalinity	....	
	....	Total suspended solids	Total suspended solids	Total suspended solids	
	....	....	Nitrate nitrogen	Nitrate nitrogen	
	....	....	....	Nitrite nitrogen	
	....	....	Ammonia nitrogen	Ammonia nitrogen	
	....	....	Total Kjeldahl nitrogen	Total Kjeldahl nitrogen	
	....	Total phosphorus	Total phosphorus	....	
	....	Total organic carbon	....	....	

SUMMARY

Selected water-quality constituents were analyzed to provide a description of water-quality conditions in Lake Travis. Some water-quality constituents were present in Lake Travis in concentrations too small to be detected by currently used laboratory methods, and “less than detection limit” data were estimated for subsequent statistical analyses. A technique called the log-probability regression method was used to estimate these values.

Boxplots were used to illustrate the water-quality characteristics of the selected constituents. For the boxplots and the multiple-comparison tests, the data were grouped on the basis of the most and least biologically productive annual periods for most temperate-zone water bodies. These two periods include the thermally stratified period (May through November), and the mixed period (December through April).

Statistical comparisons were made with the data for surface and bottom sampling depths at seven sampling sites to determine statistical similarities. The available data were insufficient to make comparisons for nitrite nitrogen and dissolved orthophosphate phosphorus. In addition, no bottom data were available at site 700 because the shallow bottom was commonly above the thermocline.

Lake Travis is a biologically unproductive reservoir with acceptable water quality for virtually all current water uses. Nutrient (nitrogen, phosphorus) concentrations tend to be small in the reservoir throughout the year, indicating nutrient limitation of maximum phytoplankton biomass. On the basis of traditional limnological properties, Lake Travis exhibits small biological productivity and exceptional water transparency. However, dissolved oxygen concentrations for bottom samples often decrease to values below 5 mg/L, especially during the thermally stratified period.

The multiple-comparison tests indicated that, for some constituents, a single sampling site for a constituent or property might adequately characterize water quality of the reservoir for that constituent or property. However, multiple-sampling sites are required to provide information of sufficient temporal and spatial resolution to accurately evaluate other water-quality constituents for Lake Travis.

The results of the multiple-comparison tests also can be used to assess the need for additional sampling sites in Lake Travis. This was done by identifying differences in generally similar water-quality data between adjacent in-lake sites. These differences in otherwise similar data represent statistically significant differences in water quality between the sites. The water-quality data from surface samples and from bottom samples indicate that nutrients (nitrogen, phosphorus) might require additional sampling sites for a more accurate characterization of their in-lake dynamics.

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