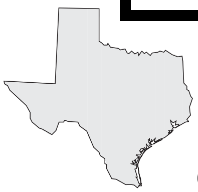
LIGHT ATTENUATION IN A SHALLOW, TURBID RESERVOIR, LAKE HOUSTON, TEXAS

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 97–4064



Prepared in cooperation with the
CITY OF HOUSTON

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

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By Roger W. Lee and Walter Rast

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U.S. DEPARTMENT OF THE INTERIOR

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VERTICAL DATUM, ABBREVIATIONS, AND ACRONYMS

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

Abbreviations:

cm, centimeter
°C, degree Celsius
ha, hectare
km, kilometer
km/hr, kilometer per hour
km^2, square kilometer
m, meter
m^3, cubic meter
mg/L, milligram per liter
μg/L, microgram per liter
nm, nanometer
ntu, nephelometric turbidity unit
Pt-Co, platinum-cobalt

Acronyms:

ISS, inorganic suspended solids
PAR, photosynthetically active radiation
TOC, total organic carbon
TSS, total suspended solids
VSS, volatile suspended solids

Light Attenuation in a Shallow, Turbid Reservoir, Lake Houston, Texas

By Roger W. Lee *and* Walter Rast

Abstract

Results of measurements of light penetration at sites in Lake Houston near Houston, Texas, indicate that light-extinction coefficients during 1989–90 range from about 2.49 to 7.93 meters^{-1} and euphotic zone depth ranges from about 0.61 to 1.85 meters. The coefficients are largest near the inflow site of West Fork San Jacinto River (upstream) and decrease slightly toward the dam (downstream). Total suspended solids and total organic carbon concentrations also are largest at the upstream end. Chlorophyll a+b concentrations are smallest near the dam, increase slightly upstream, and are largest during growing-season months. Color and turbidity show the strongest correlations with light-extinction coefficients in Lake Houston. Dissolved phosphorus and nitrogen concentrations are greater than growth-limiting concentrations during the study period, indicating that nutrient availability did not limit primary productivity or the phytoplankton biomass in Lake Houston.

Light-extinction coefficients in relation to selected water-quality constituents indicate that more than one constituent affects the light-attenuating properties of Lake Houston. Attenuation of light in water depends on total suspended solids for predominant light scattering and on dissolved organic matter (color) and chlorophyll a+b for absorption of light.

A statistical analytical model using Spearman rank order correlation shows that color and turbidity are the most useful water-quality constituents sampled to determine light-attenuating properties of water in Lake Houston. Multiple-regression analysis of measured light-extinction coefficients as the dependent variable and measured color and turbidity as independent variables for water from Lake Houston produced the relation:

$$\text{light-extinction coefficient } (\eta) = 2.78 + 0.007 \times \text{color} + 0.036 \times \text{turbidity},$$

with an average error of the computed coefficient to measured value of ±13 percent. The model can be useful in computing the thickness of the euphotic zone to determine primary productivity in the reservoir.

INTRODUCTION

Reservoirs are a major part of the usable surface-water resources in the southern and southwestern United States. They are used for multiple purposes, including water supply, recreation, flood control, sports fishery, industrial purposes, and hydroelectric-power generation. In spite of the considerable ecological and economic importance of reservoirs, however, considerably less is known about the limnological structure and function of reservoirs than of natural lakes. A better understanding of characteristics of reservoir systems such as physical and chemical properties of water and hydraulics is essential to sustain these important freshwater resources.

Much limnological knowledge used for management of reservoir water quality has been obtained from studies of natural lakes in the north-central and upper-midwestern United States. Present understanding of natural lakes does not completely justify the extrapolation of limnological principles to reservoirs, or from waterbodies in the northern, temperate climatic zones to waterbodies in the semiarid climatic conditions of the southwestern United States.

Sunlight is a major factor controlling eutrophication of lakes and reservoirs, as it represents the fundamental energy for photosynthesis. Accurate prediction of the effects of light intensity on the biological productivity and chemical characteristics of waterbodies is difficult, mainly because of the complex interactions of sunlight with constituents in the water column. Various constituents within the water column can absorb and scatter light, affecting chemical and biological reactions in reservoirs. These effects are observed in reservoir ecosystems, many of which exhibit high inorganic turbidity, an important component contributing to light attenuation. Little evidence is available from the literature to quantify and assess light attenuation in the turbid reservoirs characteristic of the southern and southwestern United States.

The purpose of this report is to describe light attenuation in Lake Houston, a shallow, turbid, water-supply reservoir near Houston, Texas, by examining measured profiles of photosynthetically active radiation (PAR; 400 to 900 nm) (Wetzel, 1983); computing light-extinction coefficients; and determining which factors significantly affect light attenuation and the relations of those factors to light attenuation. A secondary purpose is to develop a statistical model to determine the effects of mixing water from Lake Houston with water from sources outside the San Jacinto River Basin. The investigation by the U.S. Geological Survey, in cooperation with the City of Houston, was accomplished by

1. Measuring light attenuation in Lake Houston at six sites during an annual cycle (July 1989 through September 1990);
2. Determining light-extinction coefficients;
3. Measuring organic and inorganic constituents and physical properties of the water column influencing the light-extinction coefficient;
4. Relating organic and inorganic constituents and physical properties to the temporal and spatial characteristics of light attenuation in Lake Houston water; and
5. Providing a statistical model to predict light attenuation in Lake Houston water.

Characteristics of Light Attenuation in Surface Waterbodies

Sunlight (PAR) is the primary energy source for the photosynthesis reaction of all chlorophyll-containing organisms, including phytoplankton (free-floating algae), periphyton (attached algae), and macrophytes (aquatic plants). As sunlight descends through the water column, it is (1) scattered by particulate matter in the water column, and (2) absorbed by phytoplankton pigments (chlorophyll a+b) and color in the water column (Baker and Smith, 1982; Kirk, 1983; Smith and others, 1983; Kishimo and others, 1984; Effler and others, 1987). Although water itself can absorb light, the amount of absorption is small and negligible in turbid waterbodies such as Lake Houston. The cumulative effect of the scattering and absorption processes is attenuation of light with depth, eventually to a level no longer able to sustain photosynthesis (less than 1 percent of initial sunlight intensity). The upper zone of a waterbody capable of transmitting more than 1 percent of the initial sunlight intensity is referred to as the euphotic zone.

The depth that sunlight penetrates a waterbody is a combination of the effects of the light-scattering and absorption processes in the water column, which together define a waterbody's light-attenuation capacity. In many studies, light penetration is measured by lowering a Secchi disc into the water and recording the depth at which visual contact is lost (French and others, 1982). Secchi-depth transparency is a qualitative evaluation of the depth of light penetration and might not accurately represent penetration of 1 percent of initial sunlight intensity.

Light-attenuation capacity can be expressed quantitatively by the light-extinction coefficient, which is a measure of (1) the light-attenuation process in the water column, and (2) the rate at which light energy is depleted as it descends through the water column (Jerlov, 1976; Williams and others, 1980; Kirk, 1983). The light-extinction coefficient describes the decrease in light intensity with depth in the water column.The light intensity at any given depth in a waterbody is computed by:

$$I_{(z)} = I_{(o)} e^{-\eta z} , \qquad (1)$$

where:

$I_{(z)}$ = light intensity at depth z (percent);

$I_{(o)}$ = light intensity at water surface (100 percent);

η = light-extinction coefficient or light-attenuation coefficient (meters^{-1}); and

z = depth of euphotic zone (meters).

As previously noted, the decreasing light intensity with depth is a function of the concentration of light-scattering and light-absorbing constituents in the water column. The larger the light-extinction coefficient (expressed as meters^{-1}), the greater the loss of light intensity with depth. By measuring light intensity at a specified depth in the euphotic zone, the light-extinction coefficient can be computed from eq. 1. The depth of the euphotic zone (z) can be computed directly from:

$$z = \frac{\ln I_{(o)} - \ln I_{(z)}}{\eta} , \qquad (2)$$

where:

$I_{(o)} = l;$

$I_{(z)} = 0.0l;$

$\ln I_{(o)} - \ln I_{(z)} = 4.6;$ and

$$z = \frac{4.6}{\eta} . \qquad (3)$$

The light-extinction coefficient in eq. 1 is based on the composite of all the wavelengths of light penetrating the water column (PAR, 400 to 900 nm). Direct measurement of the light-extinction coefficient (by a quantum sensor) provides a quantitative expression of the light-attenuation capacity over the entire PAR wavelength range at a given depth and location within the euphotic zone of the waterbody.

Verduin and others (1976, p. 1) expressed the Lambert-Beer law relating light attenuation to depth of the euphotic zone (z) and concentrations (c) of light-absorbing and scattering constituents in the water column, as follows:

$$I_{(z)} = I_{(o)} e^{-\eta z c} . \qquad (4)$$

The light-extinction coefficient (η) can be replaced by terms that describe the concentrations of light-scattering and light-absorbing constituents and their light-attenuation capacity. Light-scattering and absorbing constituents in the water column include phytoplankton (algae) chlorophyll (a+b), organic and inorganic particulate matter, and color. Accordingly, eq. 4 can be rewritten:

$$I_{(z)} = I_{(o)} e^{-(\eta_s S + \eta_p + \eta_a) z} , \qquad (5)$$

where:

η_s = light-extinction coefficient per gram dry weight per cubic meter particulate matter (S);

S = concentration of particulate matter in water column (grams per cubic meter);

η_p = light-extinction coefficient of color (meters^{-1}); and

η_a = light-extinction coefficient of pure water (meters^{-1}).

The particulate matter content can be further differentiated into (1) a chlorophyll a+b constituent (Schl); (2) an organic particulate constituent (So); and (3) an inorganic particulate constituent (Si). Thus, eq. 5 can be rewritten as:

$$I_{(z)} = I_{(o)} e^{-(\eta_s [Schl + So + Si] + \eta_p + \eta_a) z} , \qquad (6)$$

The concentrations of the relevant constituents for eq. 6 can be measured and used to compute the relative contribution of each constituent to the total light-extinction coefficient (Verduin and others, 1976). Because these constituents vary in quantity in a waterbody annually, the light-extinction coefficient (and its causative constituents) also can vary during the annual cycle. Further details on the theoretical background for light attenuation in natural waters are provided elsewhere (Jerlov, 1976; Kirk, 1983; Wetzel, 1983).

Effects of Constituents Contributing to Light Attenuation on Surface Waterbodies

The light-attenuation capacity of a waterbody is important because it affects several fundamental limnological properties including the size (depth) of the euphotic zone (normally the layer of maximum phytoplankton primary productivity) and its total primary production. Primary production defines biological productivity and trophic (nutrients) status of a waterbody and can fundamentally affect water quality as well (Ryding and Rast, 1989). Most predictive equations for primary productivity include light intensity as a variable (Smith, 1980). Other studies (Rast and Lee, 1978; Bukata and others, 1985; Ryding and Rast, 1989) have demonstrated that the optical properties of water can be related quantitatively to other limnological properties often used to assess trophic status, for example, in-lake chlorophyll and nutrient concentrations. Natural cleansing processes such as photolysis of organic chemicals (Rand and Petrocelli, 1985) can be influenced by the light availability in the water column and by the presence of dissolved organic matter (Goldberg and others, 1991).

Previous studies on the optical properties of natural water have focused on phytoplankton chlorophyll and color as the primary components influencing

Table 1. Geometric means of selected characteristics of natural lakes and reservoirs in the United States (modified from Thornton and others, 1980)

[km^2, square kilometers; m, meters; yr, years; mg/L, milligrams per liter; µg/L, micrograms per liter; $(g/m^2)/yr$, grams per square meter per year]

Characteristic	Natural lakes (n = 309)[1]	U.S. Army Corps of Engineers reservoirs (n = 107)[1]
Drainage-basin area (km^2)	222	3,228
Water-surface area (km^2)	5.6	34.5
Maximum depth (m)	10.7	19.8
Mean depth (m)	4.5	6.9
Hydraulic residence time (yr)	.74	.37
Ratio of drainage-basin area to water-surface area	33	93
Secchi-depth transparency (m)	1.4	1.1
Total phosphorus (mg/L)	.054	.039
Chlorophyll-a (µg/L)	14	8.9
Areal phosphorus load ($(g/m^2)/yr$)	.87	1.7
Areal nitrogen load ($(g/m^2)/yr$)	18	28

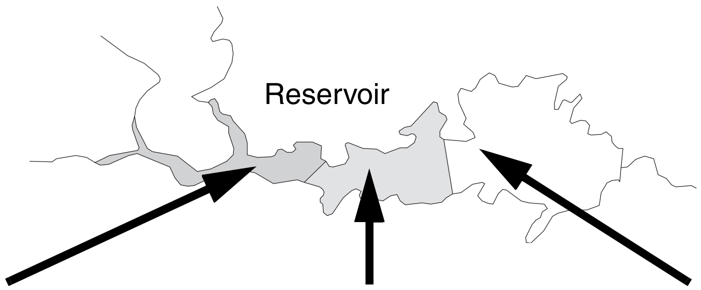
[1] n = number of waterbodies in sample.

light attenuation (Brezonik, 1978; Kirk, 1983; Canfield and others, 1984; Effler and others, 1985). Nonalgal components, especially inorganic sediments, are important in defining the light attenuation in reservoirs (Jewson and Taylor, 1978; Walmsley and others, 1980; Canfield and Bachmann, 1981; Hoyer and Jones, 1983; Grobbelaar, 1985; Lind, 1986; Effler and others, 1987). Lind (1986) reported that moderate amounts of nonalgal turbidity can negate traditional trophic classification systems that incorporate Secchi depth as a primary classification parameter. A distinct characteristic of many southern and southwestern reservoirs is large in-lake concentrations of inorganic turbidity (suspended sediments) (Rast and Lee, 1978). Large suspended-sediment loads can increase phytoplankton biomass concentrations because of increased inputs of sediment-associated plant nutrients. However, the resultant attenuation of light would inhibit phytoplankton photosynthesis, effectively limiting the phytoplankton biomass (Ryding and Rast, 1989). The potential for algal blooms would increase as the water column becomes less turbid.

Reservoirs and Natural Lakes

Some general characteristics distinguish reservoirs from natural lakes in the United States (table 1). Reservoirs have a higher mean annual water temperature and a longer phytoplankton and aquatic plant growing season. In the southwestern United States, evaporation exceeds precipitation. Drainage-basin and water-surface areas and maximum and mean depths typically are greater for reservoirs than for natural lakes. In addition, the morphology of many reservoir basins is dendritic, narrow, and elongated compared to the more rounded basins of natural lakes. Hydraulic, nutrient, and sediment loads typically are larger in reservoirs, and the residence time of water is lower (Thornton and others, 1980; Ryding and Rast, 1989).

Additional distinctions include selective withdrawal or discharge of water from distinct water layers within a reservoir and the possibility of longitudinal water-quality gradients, which can change by a factor of 10 or more from the upstream, riverine end to the downstream, lacustrine end of the reservoir basin. Longitudinal gradients characterize the physical, chemical, and biological properties typical of reservoir ecosystems, as illustrated in figure 1. Additional discussions on the differences between reservoirs and natural lakes are presented in Thornton and others, 1980, 1990; Lind, 1986; Ryding and Rast, 1989; Thornton and Rast, 1993.



Upstream end	Middle	Downstream end
Narrow, channelized basin	Broader, deeper basin	Broad, deep, lake-like basin
Relatively high flow	Reduced flow	Little flow
High suspended solids; low light availability at depth	Reduced suspended solids; light availability at depth	Relatively clear; light more available at depth
Nutrient supply by advection; relatively high nutrient levels	Advective nutrient supply reduced	Nutrient supply by interval recycling; relatively low nutrient levels
Light-limited primary productivity	Primary productivity relatively high	Nutrient-limited primary productivity
Cell losses primarily by sedimentation	Cell losses by sedimentation and grazing	Cell losses primarily by grazing
Organic matter supply primarily allochthonous (transported into basin)	Intermediate between allochthonous and autochthonous	Organic matter supply primarily autochthonous (produced in place)
More eutrophic	Intermediate between eutrophic and oligotrophic	More oligotrophic

Figure 1. Kimmel and Groeger model of reservoir gradients (modified from Kimmel and Groeger, 1984).

Study Area

Lake Houston is a public supply reservoir for the city of Houston, Texas (fig. 2). It is located on the San Jacinto River approximately 40 km northeast of downtown Houston and has a drainage-basin area of approximately 7,324 km^2.

Climate

Annual precipitation in the Lake Houston drainage basin averages 1.3 m and ranges from 0.9 to 1.8 m. Monthly mean temperature typically ranges from a low of about 19 °C in January to a high of about 28.5 °C in July or August. The wind averages about 13 km/hr, with prevailing winds from the south-southeast direction nearly the entire year.

Characteristics of Lake Houston

Lake Houston is a constructed reservoir with a volume of about 180 x 10^6 m^3 and a surface area of about 4,954 ha at its dam spillway crest elevation of 13.4 m above sea level (unadjusted for land-surface subsidence). The reservoir is relatively shallow, with a mean depth of about 3.65 m and a maximum depth of about 15.2 m.

Lake Houston has two main inflow branches (fig. 2). East Fork San Jacinto River drains a nonurbanized watershed with some development. West Fork San Jacinto River drains a watershed containing more development. The East Fork San Jacinto River subbasin drains approximately 2,395 km^2, about one-third of the Lake Houston drainage basin. The West Fork San

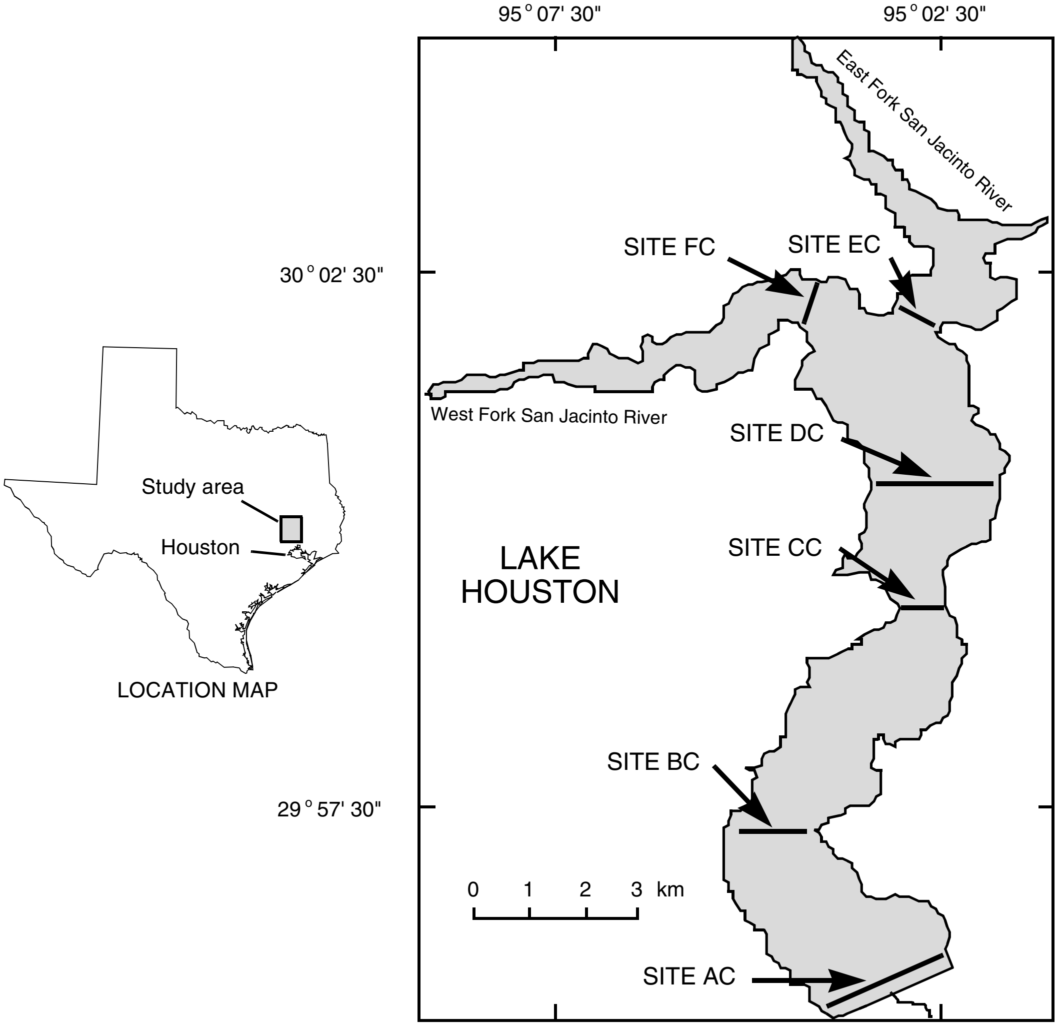


Figure 2. Study area and locations of water-quality sampling sites on Lake Houston.

Jacinto River subbasin drains approximately 4,420 km^2, about two-thirds of the drainage basin.

Land Use in the Drainage Basin

Approximately 73 percent of the Lake Houston drainage basin is forest, and 14 percent is pasture land. Remaining land uses include gravel mining, oil production, agriculture, and highways. Lake Houston receives wastewater discharges directly from 5 municipal wastewater-treatment plants, as well as 31 permitted treatment plants in tributary watersheds. Overall, more than 150 municipal wastewater-treatment plants of various capacities are located in the drainage basin (Bedient and others, 1980).

LIGHT ATTENUATION IN A SHALLOW, TURBID RESERVOIR

Site Selection and Data Collection

Surface-water samples and in-lake light measurements were collected at sites located above the original river channel in the center of each of six transects across the reservoir basin (fig. 2). The transects consist of 1 site at the dam (site AC) and 1 site each at the mouths of East Fork San Jacinto River (site EC) and West Fork San Jacinto River (site FC) where they enter Lake Houston. Influent water from the two forks of the San Jacinto River mix to provide the principal characteristics of water at site DC and downstream of site DC. Sites BC, CC, and DC are located between the dam and the mouths of East Fork and West Fork San Jacinto River.

Light intensity (of PAR) was measured at the time of sample collection with a Li-Cor quantum sensor at depths of 7, 10, 20, 31.5, and 40 cm below the lake surface. The sampling depths were selected on the basis of convenience of marking depths on the quantum sensor frame. If water turbidity was low, additional measurements were made at 10-cm intervals until no changes in light intensity could be detected. In all cases, the maximum depth of light measurements was about 1 m below the surface.

Grab samples were collected 30 cm below the water surface for analysis of total suspended solids (TSS), volatile suspended solids (VSS), total organic carbon (TOC), chlorophyll a+b, color, turbidity, and dissolved phosphorus and nitrogen (the sum of dissolved ammonia, nitrate, and nitrite nitrogen) according to methods in Brown and others (1974). Secchi-depth transparency also was measured at each sampling site according to standard procedures (French and others, 1982; Cole, 1983).

Each site was sampled approximately biweekly from July 1989 to September 1990 and at 4- to 6-week intervals during the remainder of the year. Occasional departures from this sampling schedule were caused by inclement weather or equipment failures. Light-extinction coefficients, concentrations of selected water-quality constituents, and values of selected physical properties of water collected from Lake Houston are listed in table 2 (at end of report).

Light-Extinction Coefficients

Light-extinction coefficients are averages determined from light intensity measured at different depths in the euphotic zone and from eq. 1 for each site, and are summarized graphically in figure 3. Light-extinction coefficients and depth of euphotic zone range from 2.49 to 7.93 m^{-1} and from 0.61 to 1.85 m, respectively, for all sites. Sampling site FC shows the largest light-extinction coefficients, greater than 7.0 m^{-1} (euphotic zone thickness less than 0.66 m, from eq. 3), on 3 of the 15 sampling dates. On the basis of these values, site FC indicates the greatest capacity to attenuate sunlight penetrating the water column compared to the other sampling sites. Site FC also has the largest range in light-extinction coefficients; 2.49 to 7.93 m^{-1} (table 2).

The light-extinction coefficients are aggregated in boxplots by sampling site to illustrate the change in light attenuation from the upstream end of Lake Houston to the dam (fig. 4). The light attenuation tends to be greatest at the upstream end (site FC) and decreases toward the dam (site AC). At site AC, the light-extinction coefficients range from 2.90 to 6.39 m^{-1} (table 2) throughout the sampling period, maintaining relatively high light attenuation.

Secchi Depth

Secchi-depth transparencies were measured in Lake Houston during 1989–90 because of their relation to the light-attenuation capacity of a waterbody (French and others, 1982). Secchi depths do not vary greatly, increasing slightly from median depths of about 0.30 m at site FC, to greater than 0.40 m at site AC (fig. 5), consistent with generally decreasing light-extinction coefficients. The exception is July 10, 1990, when the Secchi depth increases to greater than 1.00 m at all sampling sites (table 2). The reason for this unusual water clarity is not understood. No other water-quality parameter showed substantial change on this sampling date.

Comparison of Secchi-depth measurements with light-extinction coefficients (fig. 6) shows that Secchi depths measured in Lake Houston more closely approximate the depth of penetration of 3-percent initial sunlight intensity rather than the depth of penetration of 1-percent initial sunlight intensity. Secchi depth underestimates the depth of the euphotic zone by as much as 30 percent. Therefore, a more accurate measure of the depth of the euphotic zone should be based on light-extinction coefficient measurements rather than Secchi depth.

Water-Quality Constituents Affecting Light Attenuation

Water-quality constituents related to light attenuation are listed in table 2. TSS, TOC, chlorophyll a+b, color, turbidity, and the nutrients, dissolved phosphorus and nitrogen, were sampled at six sites in Lake Houston from July 1989 to September 1990.

Total Suspended Solids

TSS concentrations for all samples collected range from 1.00 to 186 mg/L (fig. 7) with a mean of 27.0 mg/L. The maximum concentration for most sites was measured during the nongrowing-season winter months. The largest median TSS concentration

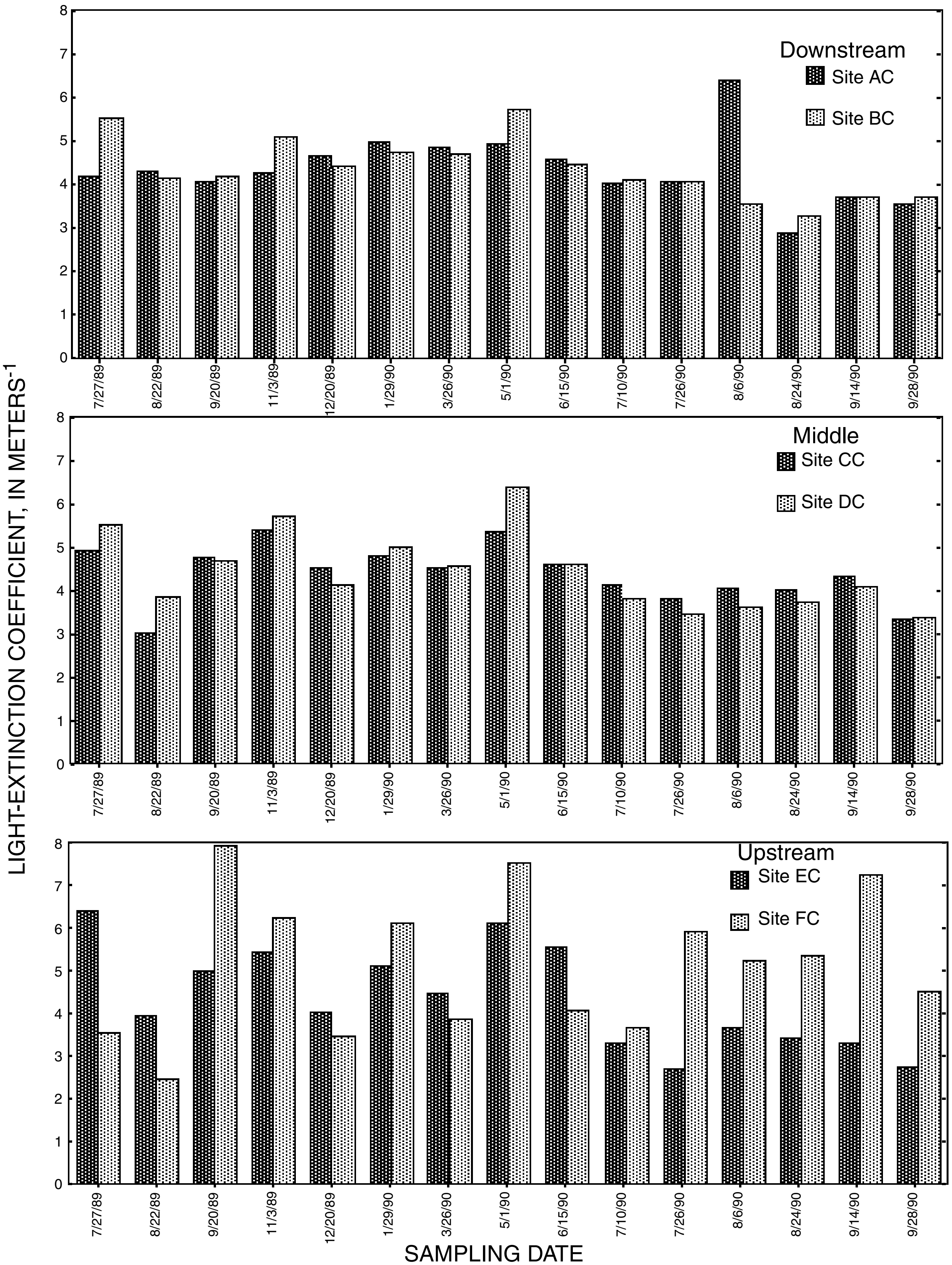


Figure 3. Relation of light-extinction coefficients to sampling date for water at six sites in Lake Houston, 1989–90.

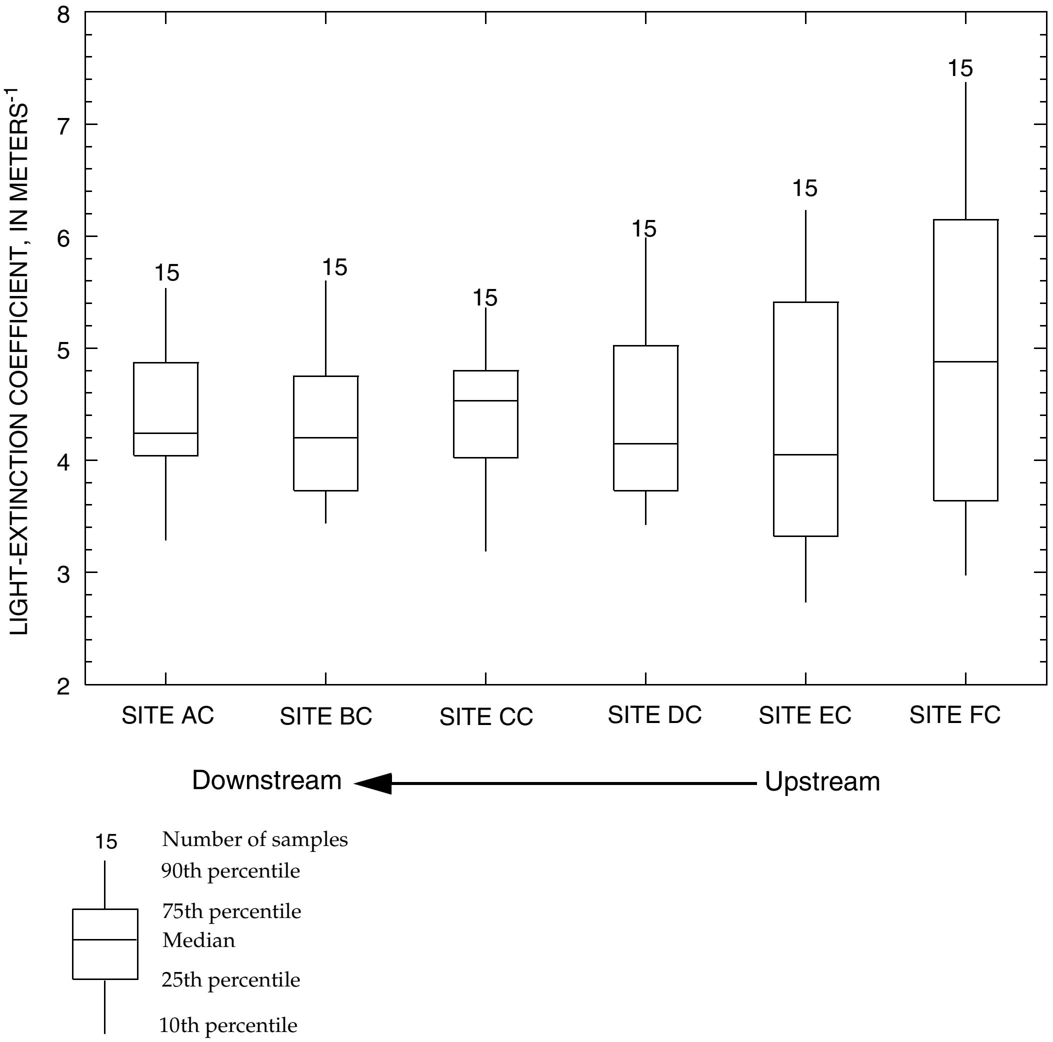


Figure 4. Distribution of light-extinction coefficients for water at six sites in Lake Houston, 1989–90.

(34.0 mg/L) is at sampling site FC (fig. 8). The next largest median concentrations are at sites CC and DC. Maximum concentrations at site FC were mostly larger than maximum concentrations at site EC, indicating the West Fork San Jacinto River as the principal source of TSS concentrations. Median TSS concentrations decrease toward the dam from 34.0 mg/L at site FC to 16.0 mg/L at site AC.

Total Organic Carbon

TOC concentrations for all samples collected range from 6.0 to 18 mg/L, with a mean concentration of 11 mg/L (table 2). All sites indicate a temporal pattern of seasonal trends of minimum concentrations during the nongrowing-season winter months and maximum concentrations during growing-season months (April–September) (fig. 9). The median TOC concentration is largest (11.5 mg/L) at site FC (fig. 10), indicating the West Fork San Jacinto River typically delivers more TOC to Lake Houston than the East Fork San Jacinto River. Although TOC concentrations are variable, median concentrations at sites closer to the dam are consistently about 11 mg/L.

Chlorophyll a+b

The chlorophyll a+b concentrations for all samples collected range from 0.600 to 42.7 µg/L, with a mean of 6.90 µg/L (table 2). All sites indicate seasonal variations of maximum concentrations mostly during the growing-season months and minimum

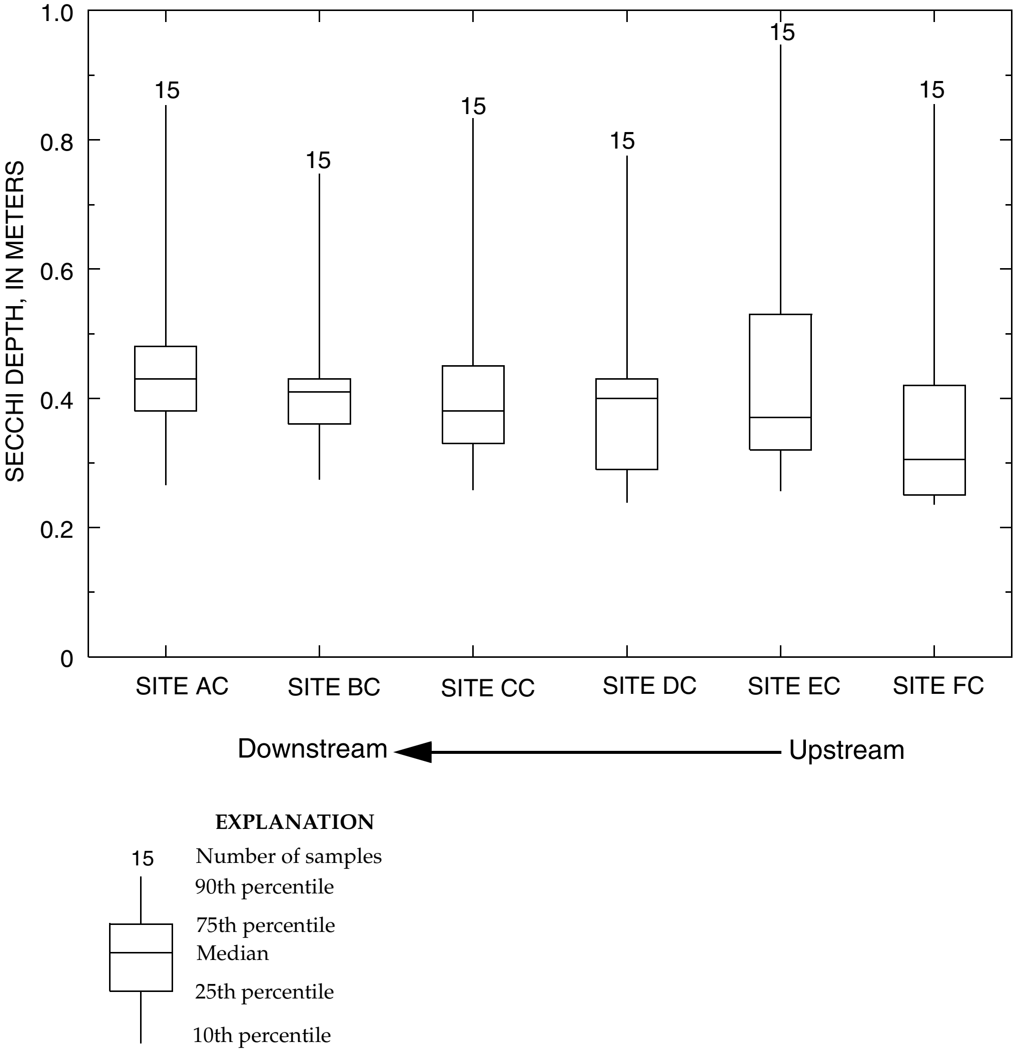


Figure 5. Distribution of Secchi-depth transparency for water at six sites in Lake Houston, 1989–90.

concentrations mostly during the nongrowing-season months (fig. 11). Median concentrations decrease consistently from the upper end of Lake Houston toward the dam (fig. 12). The median concentration is 16.7 µg/L at site FC and 1.60 µg/L at site AC. This pattern indicates that the primary productivity by phytoplankton and the total biomass decrease as water moves through the reservoir.

Color

Color of water for all samples collected ranges from 22 to 220 Pt-Co units, with a mean of 99 Pt-Co units (table 2). The color data indicate seasonal effects of mostly higher colored water (from organic matter) during nongrowing-season months and lower colored water during growing-season months (fig. 13). The exceptions are several samples collected on July 27, 1989. Those samples contain some of the highest color measured during the study (some greater than 200 Pt-Co units) except for site FC. Color shows a greater median and wider variation at site EC than at site FC (fig. 14), indicating that more highly colored water comes from East Fork San Jacinto River than from West Fork San Jacinto River. Color in the reservoir increases toward the dam from a median of 55 Pt-Co units at site FC to about 100 Pt-Co units at sites CC, BC, and AC. The increase in color, therefore, might be caused by processes such as addition of color-producing

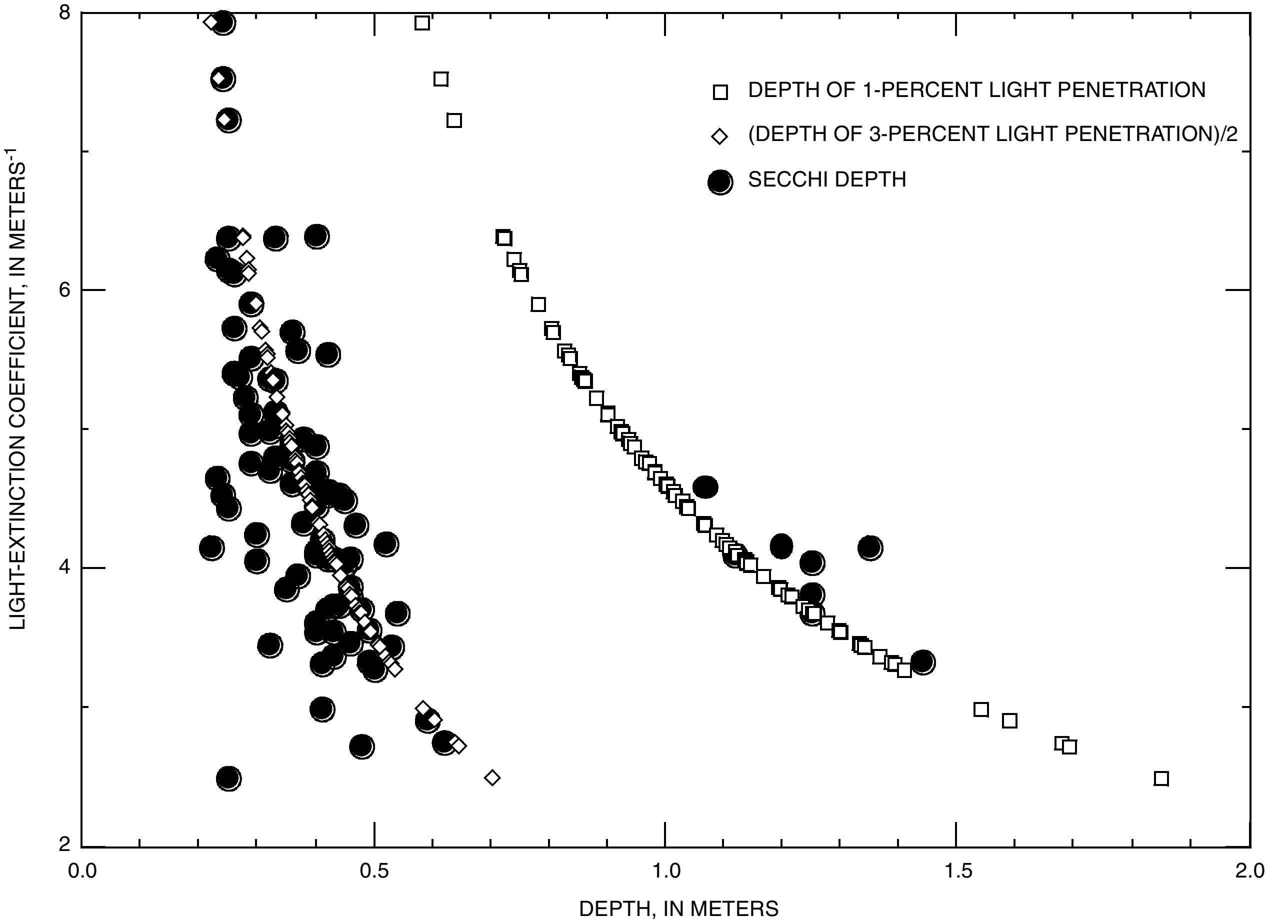


Figure 6. Relation of light-extinction coefficients to computed depths of light penetration and Secchi-depth transparency for water at six sites in Lake Houston, 1989–90.

constituents dissolved from reservoir sediments, chemical maturation of dissolved organic matter, or by biological processes.

Turbidity

Turbidity of water for all samples collected ranges from 10 to 65 ntu, with a mean of 29 ntu (table 2). All sites indicate seasonal trends of greatest turbidity mostly during November and December 1989 and lowest turbidity during August 1990 (fig. 15). A smaller turbidity peak is shown for data from May through June 1990. Turbidity typically is lowest at site FC and EC, although variability of the data is greatest at these sites (fig. 16) owing to the proximity of these sites to river inflows. Medians for turbidity increase toward the dam, reaching the largest median at site CC, then decrease at sites BC and AC. This pattern indicates that turbidity increases in water after entering Lake Houston, probably as a result of resuspension of inorganic and organic matter in the shallow reservoir by wind.

Nutrients

Dissolved phosphorus and nitrogen concentrations in Lake Houston are important if they are greater than the minimum concentrations required to sustain phytoplankton productivity (0.005 mg/L for phosphorus and 0.02 mg/L for nitrogen; Cole, 1983). The concentrations of the dissolved nutrients during periods of high phytoplankton productivity would represent residual nutrients unused by algae populations. If the dissolved phosphorus concentration decreases to less than about 0.005 mg/L during a period of substantial phytoplankton growth, then phosphorus is likely the algal growth-limiting factor during this period (Ryding

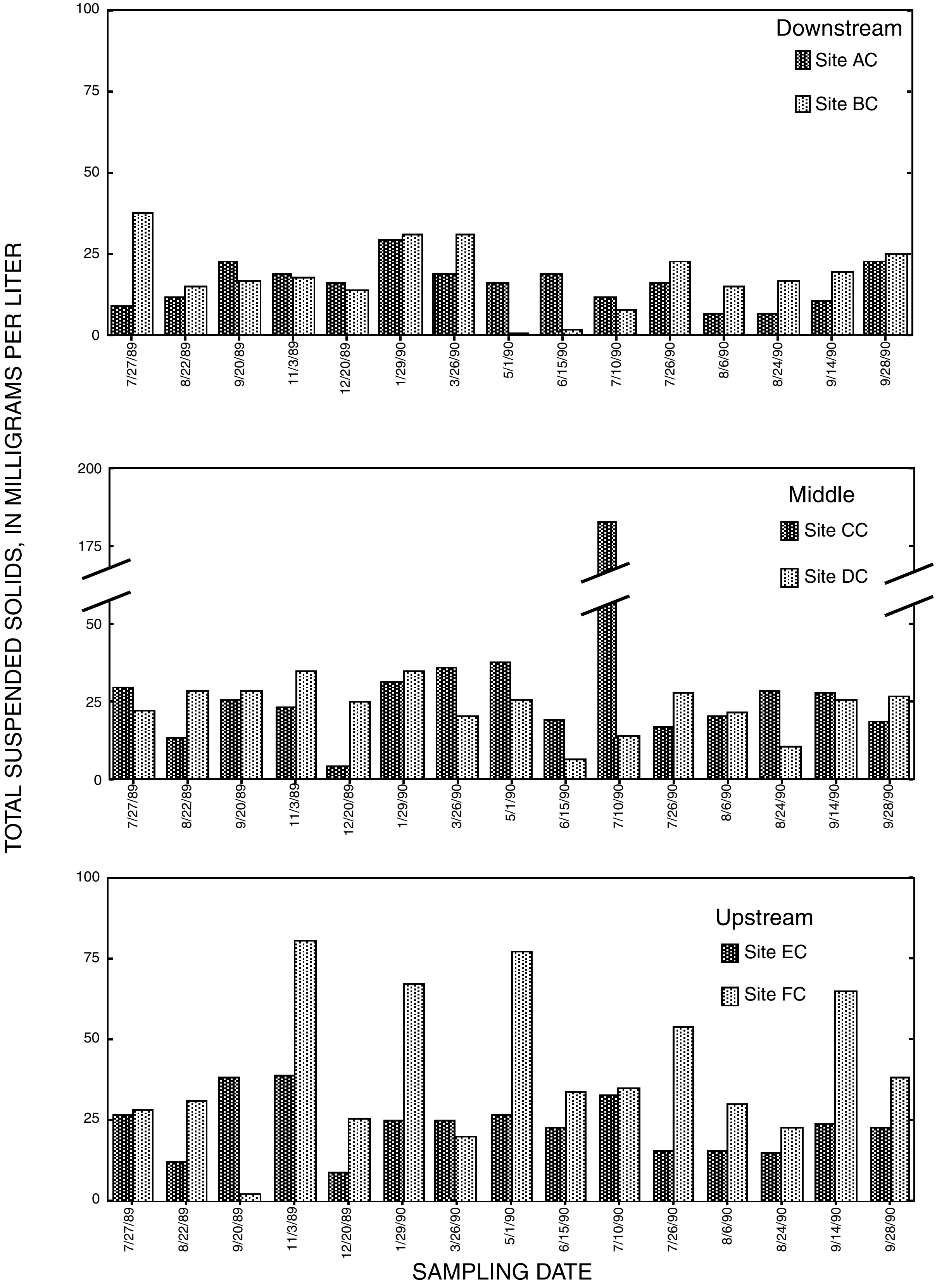


Figure 7. Relation of total suspended solids to sampling date for water at six sites in Lake Houston, 1989–90.

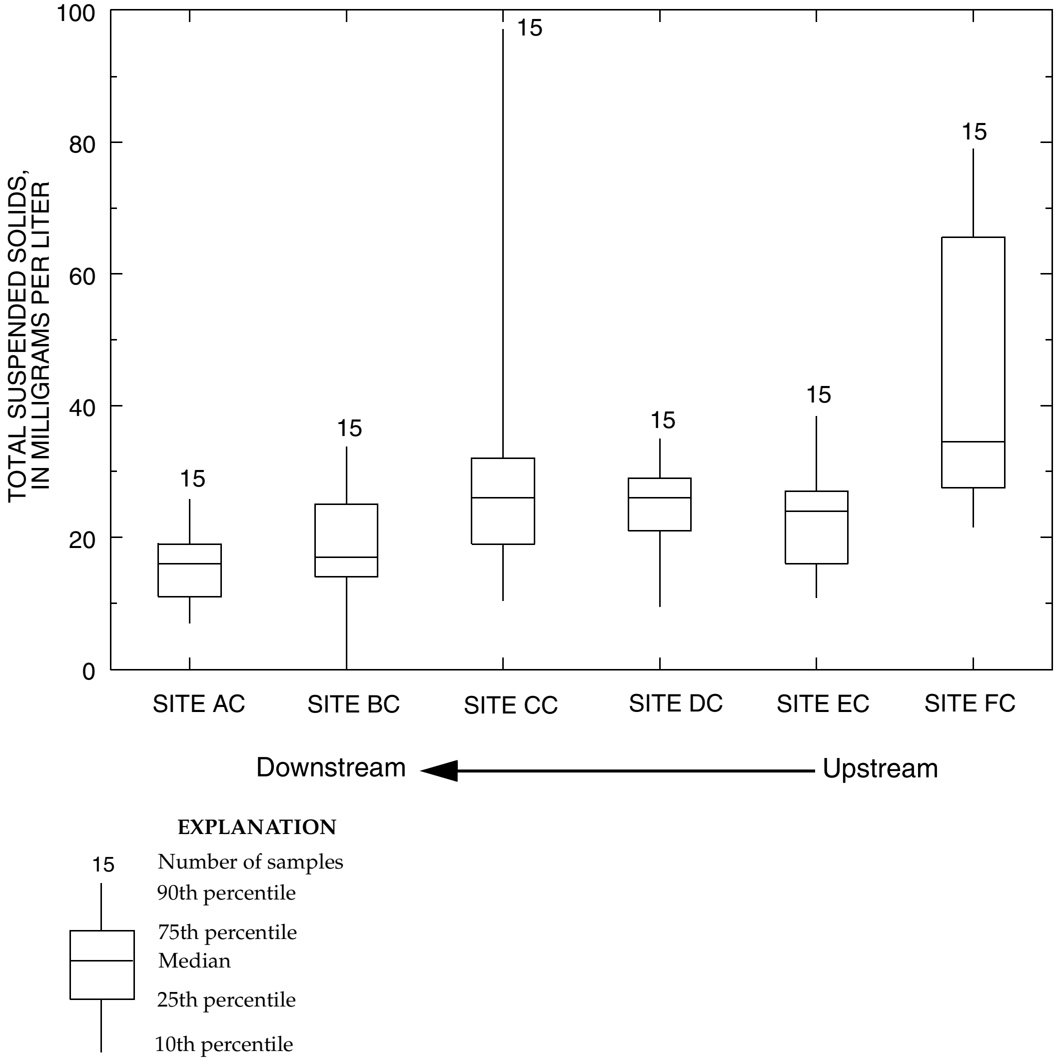


Figure 8. Distribution of total suspended solids for water at six sites in Lake Houston, 1989–90.

and Rast, 1989). Similarly, if the dissolved nitrogen concentration (sum of ammonia, nitrate, and nitrite nitrogen) decreases to less than about 0.02 mg/L, then nitrogen is likely the algal growth-limiting factor. If both nutrients decrease to less than these threshold concentrations, both could be limiting the phytoplankton biomass.

Dissolved Phosphorus

Dissolved phosphorus concentrations for all samples collected range from 0.060 to 1.50 mg/L, with a mean of 0.240 mg/L (table 2). The maximum concentration at most sites was measured during the nongrowing-season winter months. The dissolved phosphorus concentrations are larger than the growth-limiting concentration of 0.005 mg/L at all sampling sites during the sampling period (table 2.). The smallest concentration reported at any sampling site is 0.060 mg/L at site EC on March 26, 1990. Two large concentrations (1.50 and 1.30 mg/L) were measured at site FC on November 3, 1989, and September 14, 1990, respectively, indicating that most of the phosphorus source to Lake Houston enters from West Fork San Jacinto River. Phosphorus concentrations decrease toward the dam (fig. 17), indicating uptake of phosphorus by phytoplankton in the reservoir. Because dissolved phosphorus is not less than the algal growth-limiting concentration in any of the samples, it is not considered

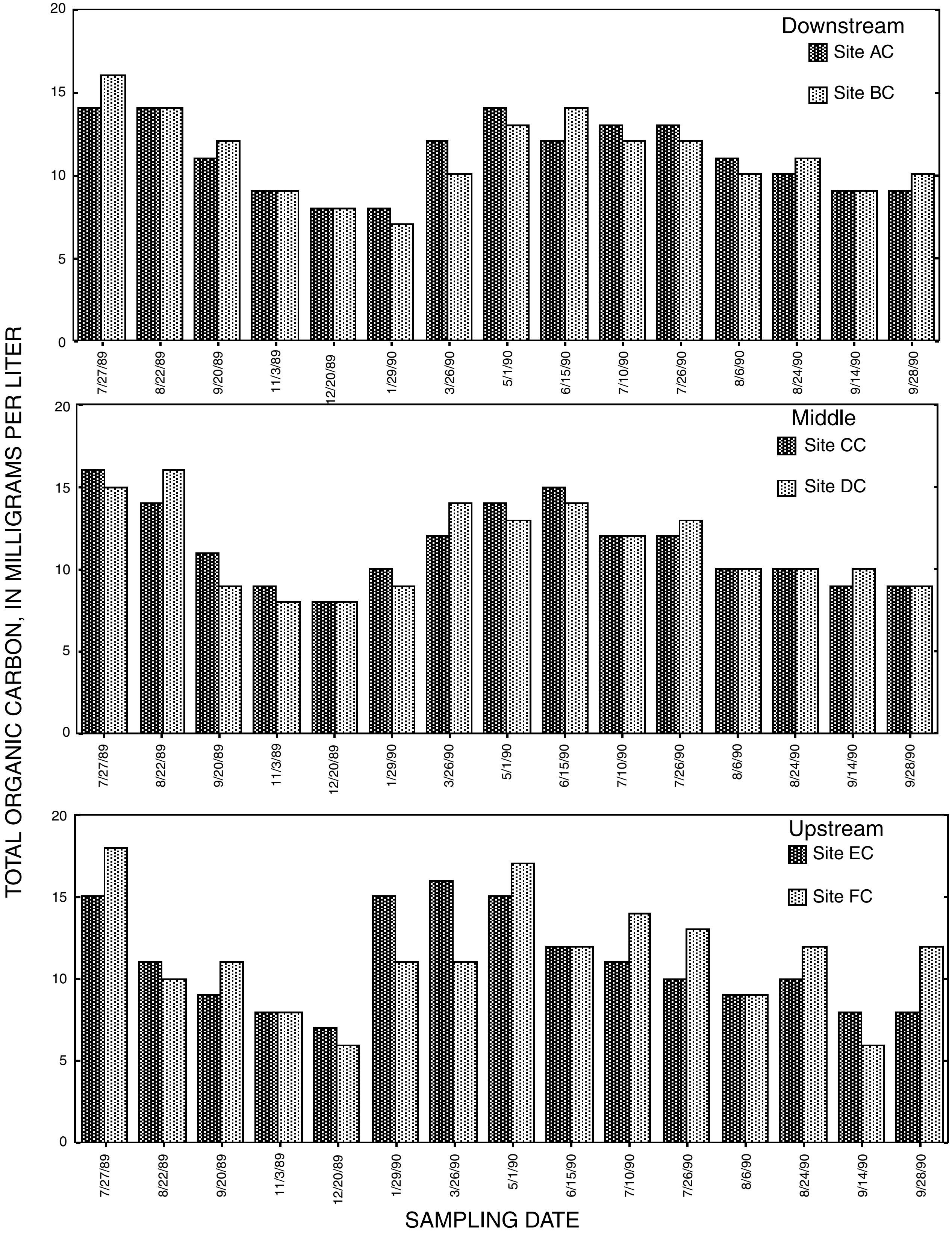


Figure 9. Relation of total organic carbon to sampling date for water at six sites in Lake Houston, 1989–90.

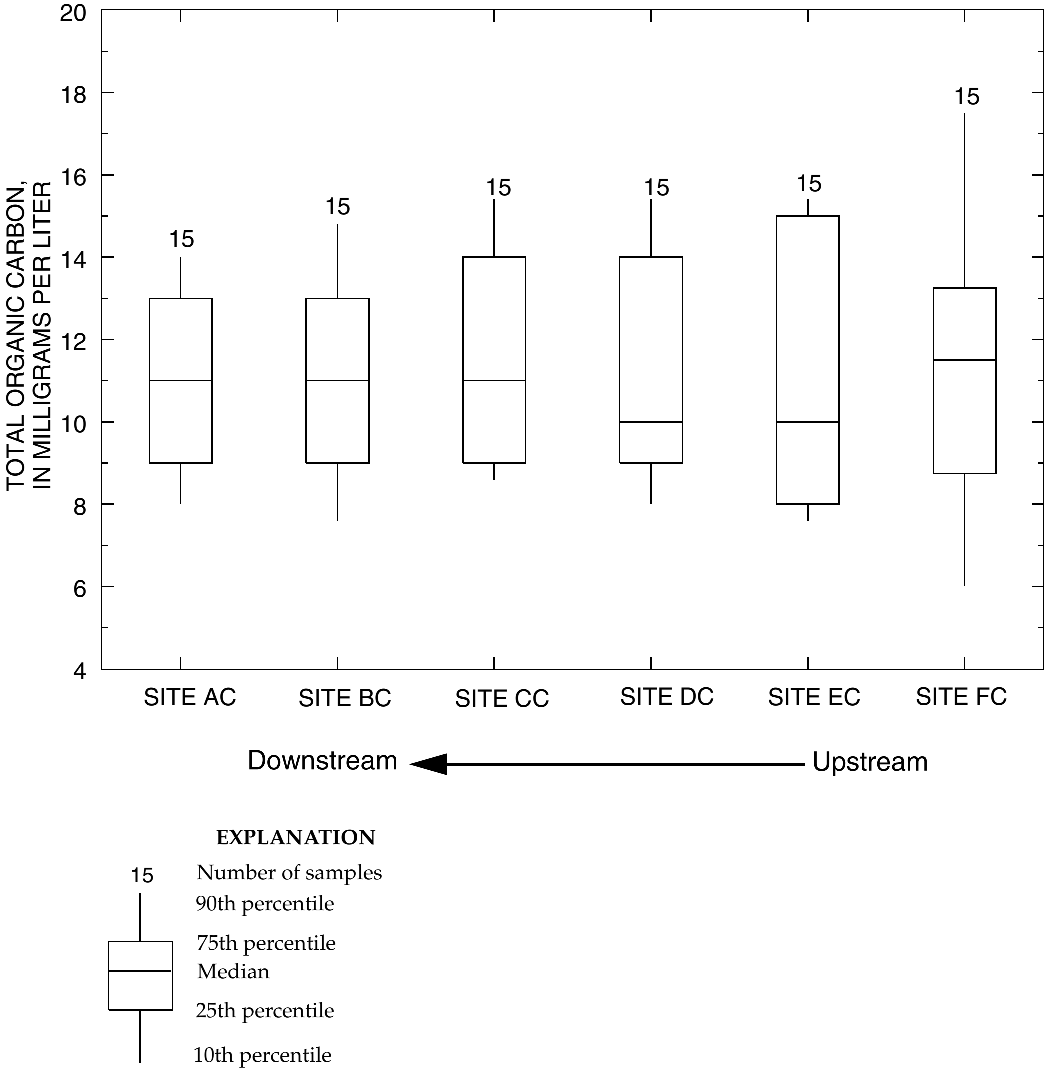


Figure 10. Distribution of total organic carbon for water at six sites in Lake Houston, 1989–90.

a limiting nutrient in Lake Houston during the study period.

Dissolved Nitrogen

Dissolved nitrogen concentrations for all samples collected range from 0.06 to 10 mg/L with a mean of 0.25 mg/L (table 2). The maximum concentration at most sites was measured during the nongrowing-season winter months. In general, dissolved nitrogen concentrations decrease from large influent concentrations into Lake Houston at site FC (West Fork San Jacinto River) toward the dam (fig. 18). Dissolved nitrogen concentrations are greater than the algal growth-limiting concentration of 0.02 mg/L in all samples.

Relation of Relevant Water-Quality Constituents to Light Attenuation

Principal water-quality constituents contributing to light attenuation were presented previously in eq. 5 as suspended matter that scatters light (S) and color (from dissolved organic matter) that absorbs light. TSS measured in Lake Houston actually consists of an organic fraction (VSS, table 2; analogous to So, nonchlorophyll organic component and chlorophyll a+b in eq. 6) and an inorganic fraction (inorganic suspended solids (ISS), table 2; analogous to Si, nonchlorophyll inorganic component, in eq. 6). TSS minus VSS equals ISS. VSS, ISS, and color are independent variables contributing to

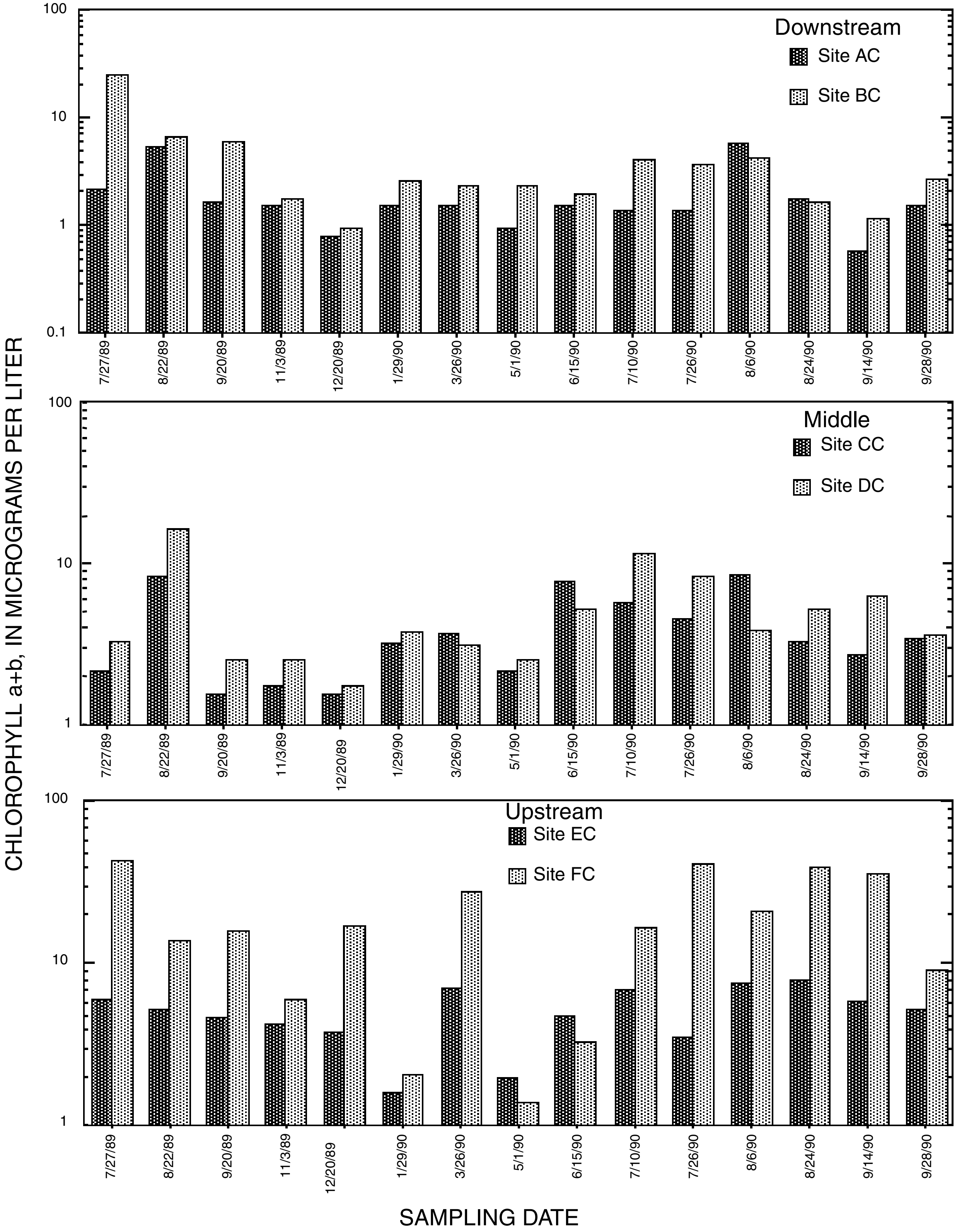


Figure 11. Relation of chlorophyll a+b to sampling date for water at six sites in Lake Houston, 1989–90.

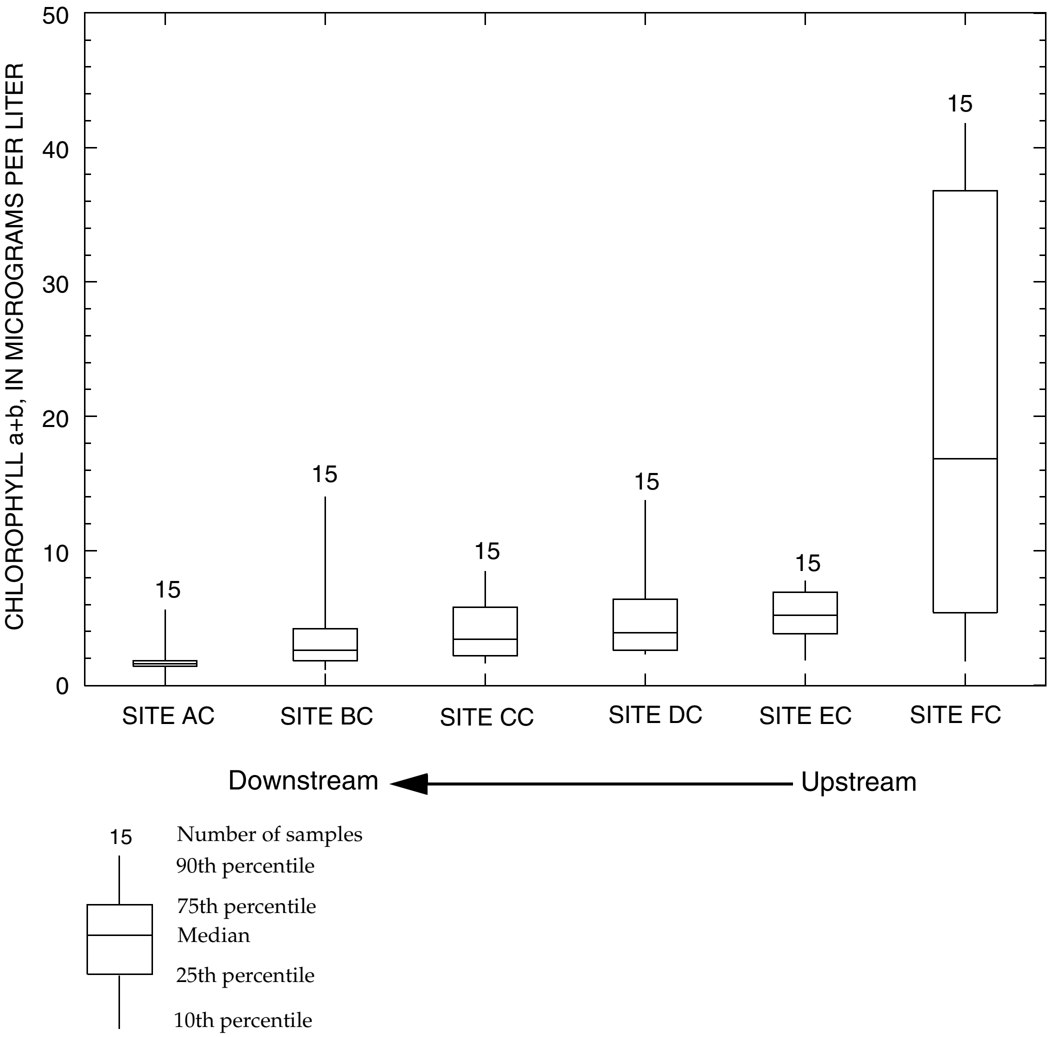


Figure 12. Distribution of chlorophyll a+b for water at six sites in Lake Houston, 1989–90.

light attenuation, and phytoplankton biomass, as measured by chlorophyll a+b concentrations, is a component of VSS.

Water-Quality Constituents Contributing to Light Attenuation

The four principal water-quality constituents that determine light attenuation in a waterbody are VSS, ISS, chlorophyll a+b, and color. Chlorophyll a+b, although a component of VSS, will be treated as an independent variable to have an indicator of the relative contribution of phytoplankton biomass to light extinction. A linear combination of these parameters (analogous to the linear combination in the exponent of eq. 6) should provide some correlation with measured light-extinction coefficients assuming that light extinction from pure water (η_a) is negligible.

Statistical analysis using multiple regression of the four water-quality constituents produced the coefficients for the relation illustrated in figure 19:

$$\begin{aligned}\eta = {} & 0.00225 \times \mathrm{VSS} + 0.0120 \times \mathrm{ISS} \\ & + 0.020 \times (\text{chlorophyll a+b}) \\ & + 0.00113 \times \text{color} + 2.99. \end{aligned} \tag{7}$$

The fit of data is relatively poor, however, with r^2 of 0.338 (fig. 19).

Large variations and apparent inconsistencies of the data in relating VSS, ISS, chlorophyll a+b, and color to light attenuation limit the ability to determine

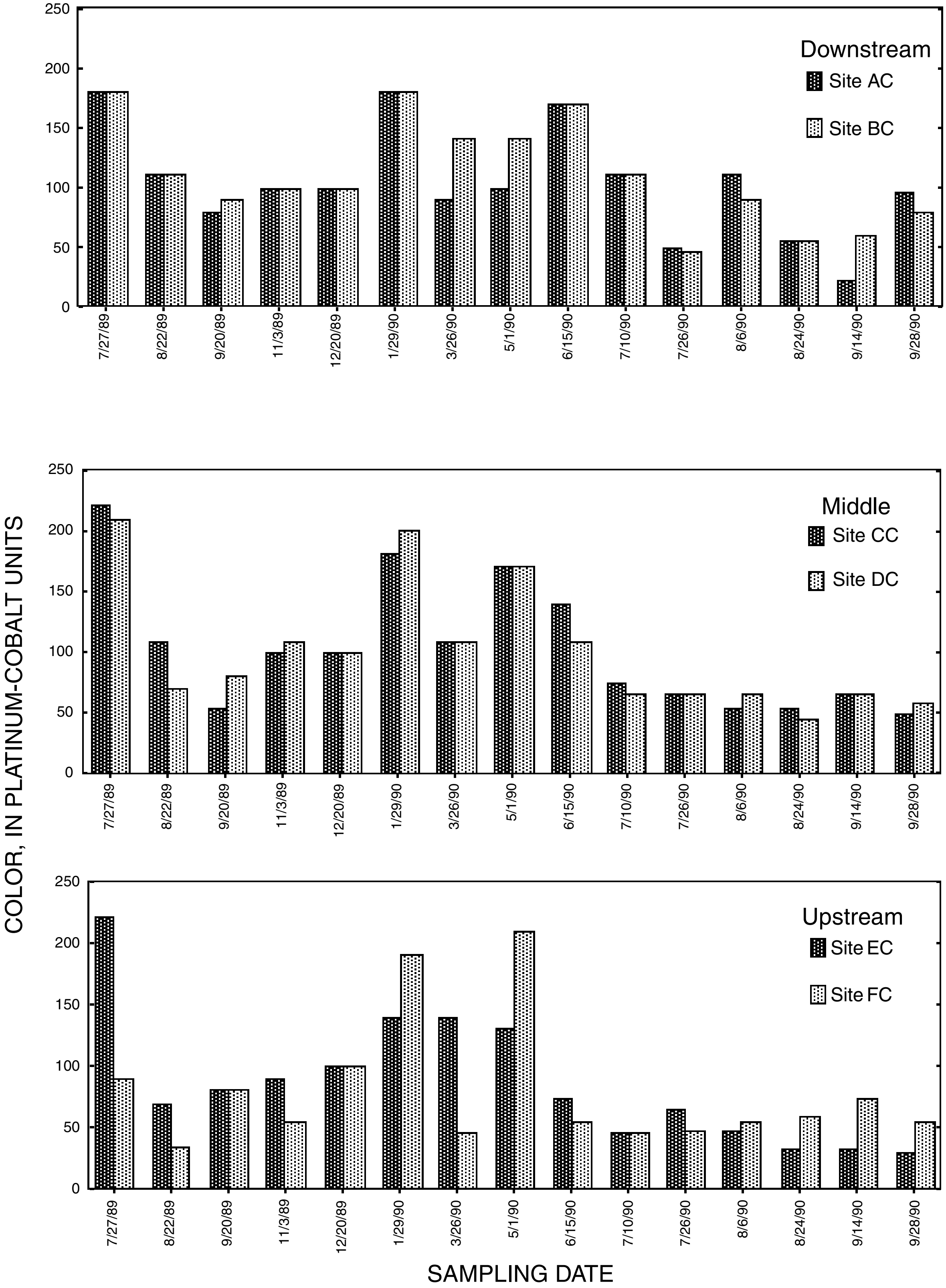


Figure 13. Relation of color to sampling date for water at six sites in Lake Houston, 1989–90.

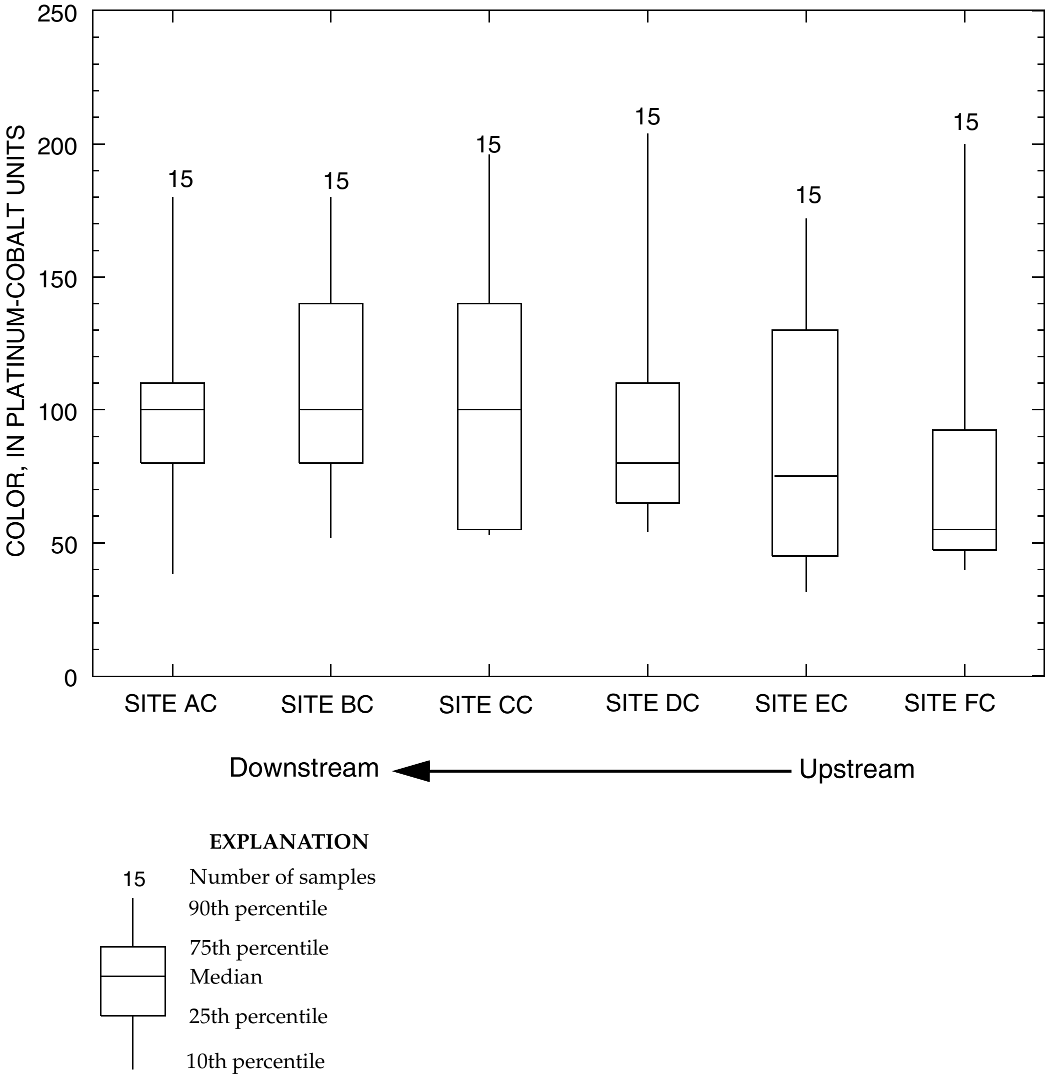


Figure 14. Distribution of color for water at six sites in Lake Houston, 1989–90.

light-extinction coefficients directly from these water-quality constituents. One possible explanation for the high degree of variability is that the water-quality data were obtained from grab samples rather than from depth-integrated samples. Because the measured light-extinction coefficients were averaged over a range of depths at each site, a better representation of possible vertical gradients of light extinction in the euphotic zone was obtained.

Water-Quality Data Significant to Light Attenuation

A statistical method to determine the relation of a dependent variable to one or more independent variables in a data set is the Spearman rank order correlation (Ott, 1993). This method was applied to the Lake Houston data to relate the dependent variable, light-extinction coefficient, to the selected independent variables, TSS, VSS, ISS, TOC, chlorophyll a+b, color, turbidity, and Secchi-depth transparency (fig. 20). Positive correlation coefficients indicate a direct relation to the dependent variable, and negative correlation coefficients indicate an inverse relation to the dependent variable. Spearman rank order correlation coefficients and probabilities for light-extinction coefficients as related to the water-quality constituents and physical properties are listed in table 3 (at end of report). The

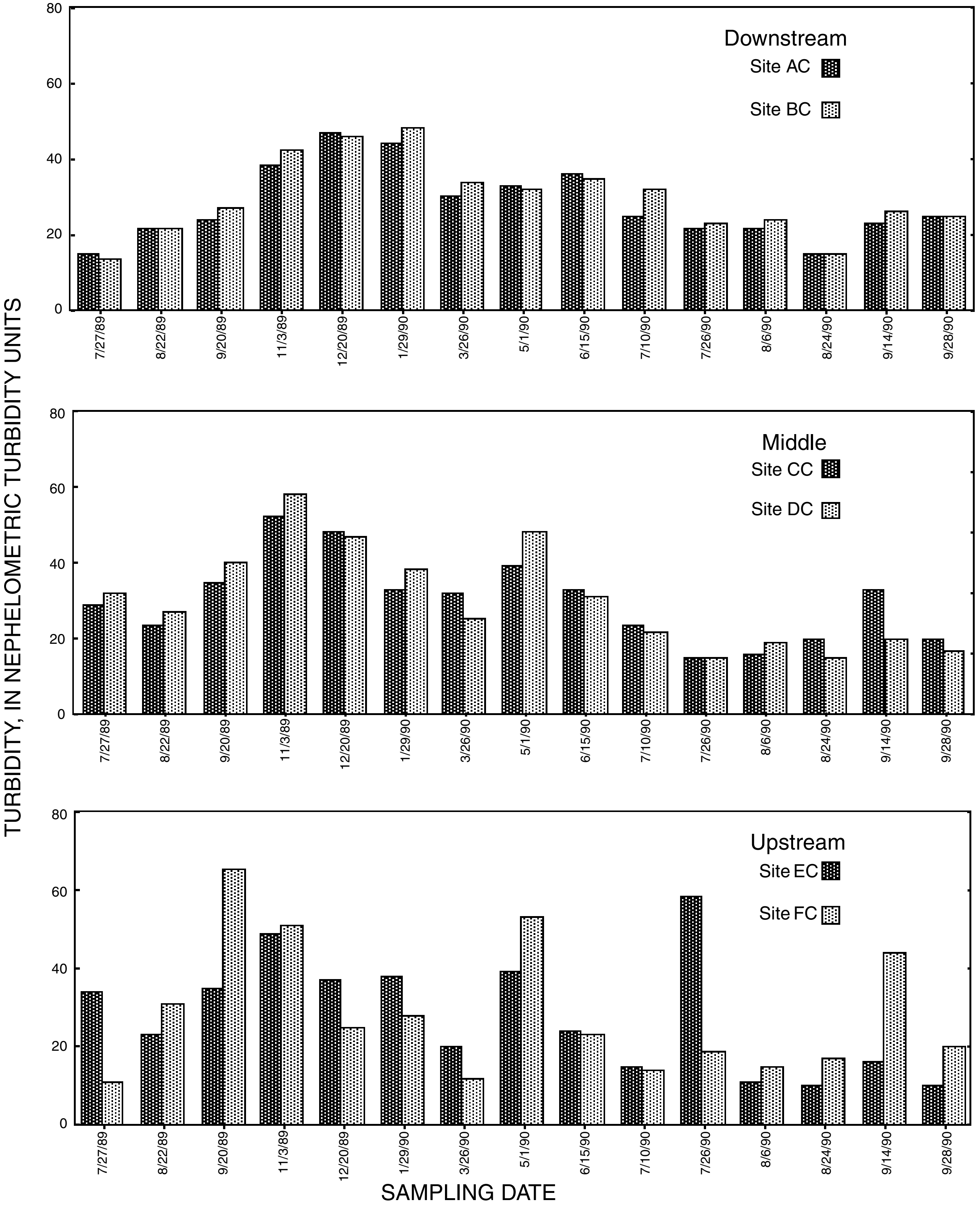


Figure 15. Relation of turbidity to sampling date for water at six sites in Lake Houston, 1989–90.

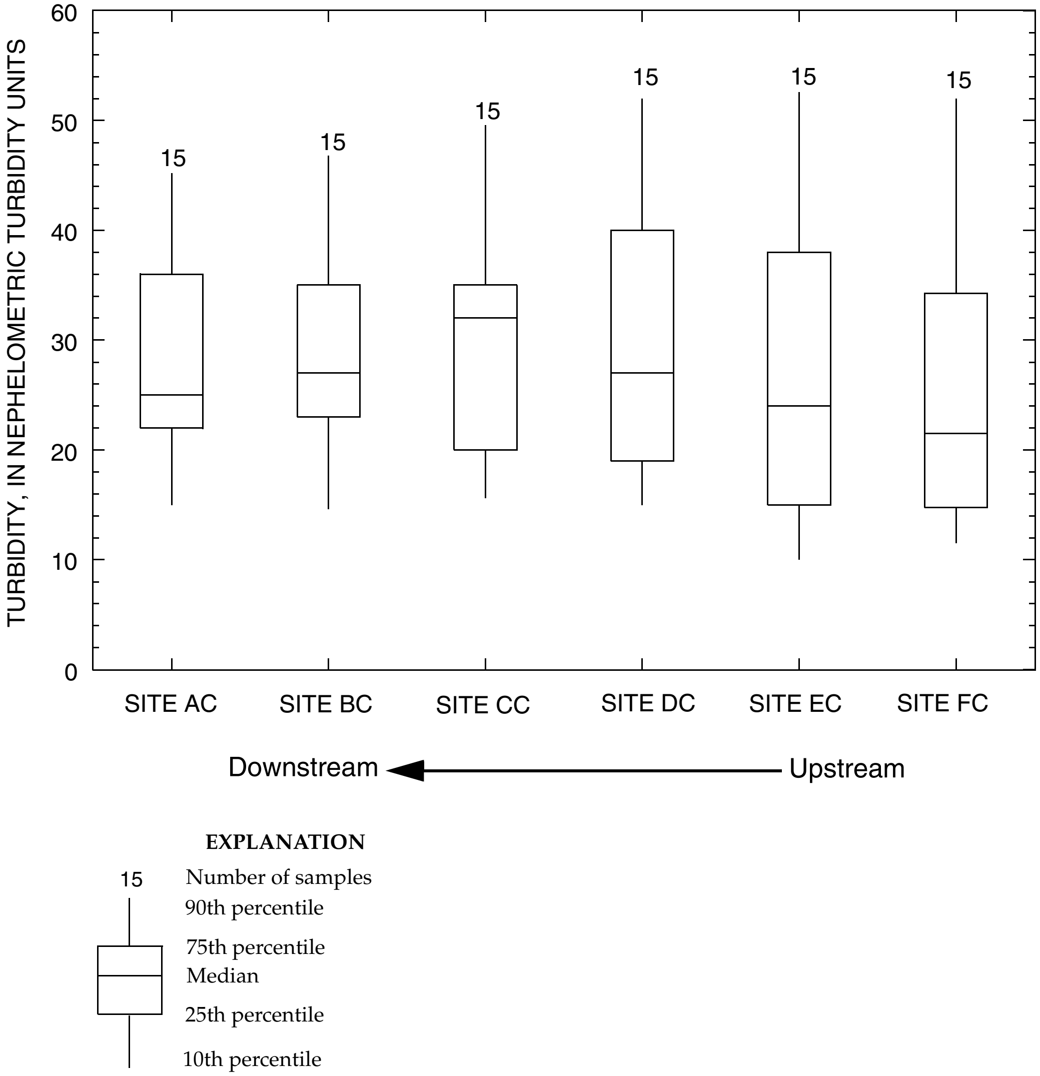


Figure 16. Distribution of turbidity for water at six sites in Lake Houston, 1989–90.

independent variables range from poor to acceptable correlation rank to light-extinction coefficients, with VSS having a slightly negative correlation rank for all sites. Secchi-depth transparency is another measure of light attenuation and shows strong negative correlation, as expected, indicative of its inverse relation to the light-extinction coefficient. Most noteworthy, color and turbidity show the strongest positive correlation in relation to the light-extinction coefficients. Color and turbidity measurements, which include the principal light-attenuating constituents from eq. 6, should provide the best estimates of the light-extinction coefficients by using multiple-regression analysis.

Multiple-Regression Analysis

A multiple-regression analysis of measured light-extinction coefficients to color and turbidity was performed on the complete data set and produced the relation:

$$\text{light-extinction coefficient } (\eta) = 2.78 + 0.007 \times \text{color (Pt-Co units)} + 0.036 \times \text{turbidity (ntu)}, \qquad (8)$$

with an average error of computed coefficient in relation to measured value of ±13 percent. Fit of data to eq. 8 ($r^2 = 0.401$) was better than to eq. 7 (fig. 21).

Thus, the statistically-based model of eq. 8 calculates light-extinction coefficients from measured color

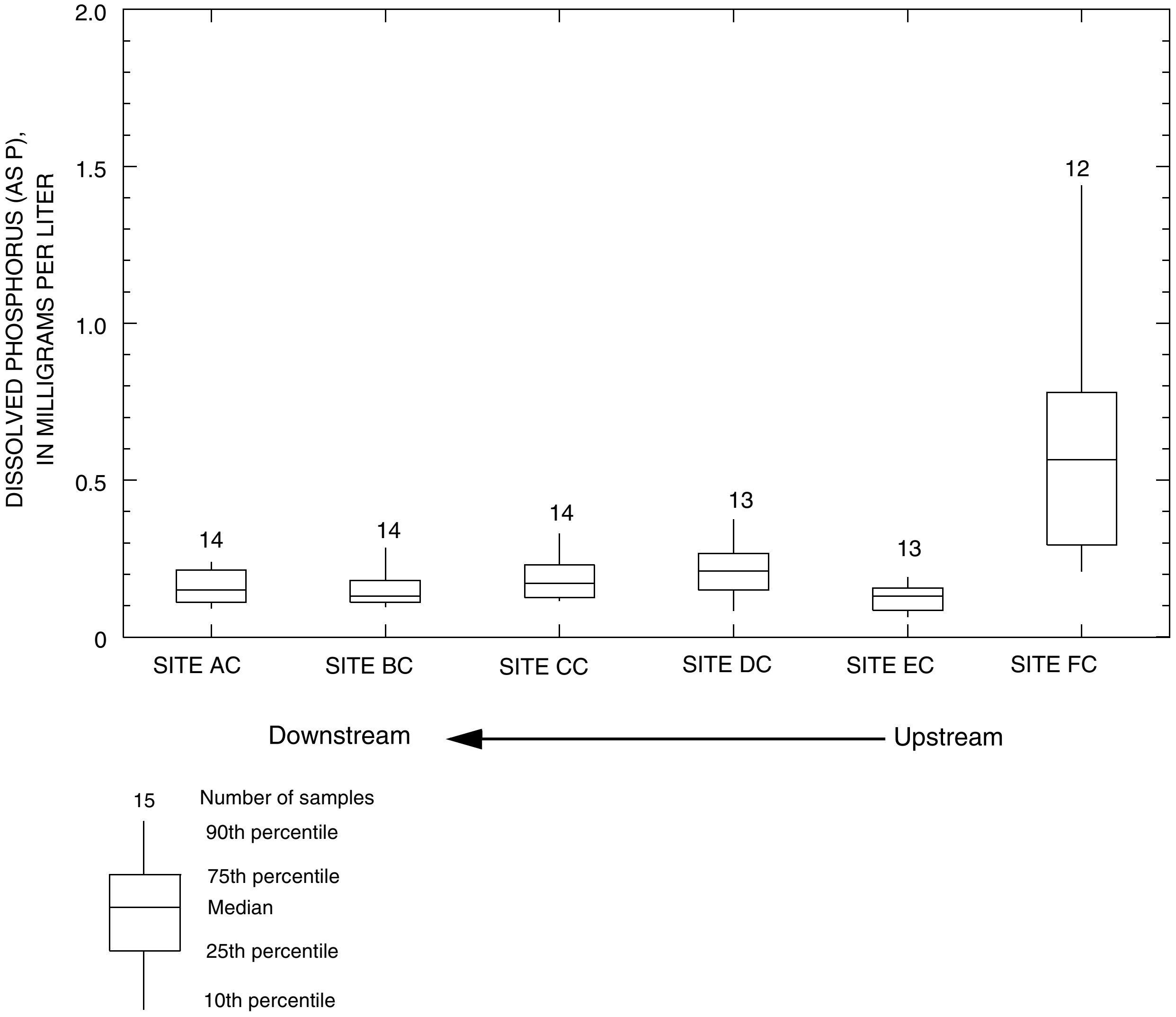


Figure 17. Distribution of dissolved phosphorus for water at six sites in Lake Houston, 1989–90.

and turbidity in Lake Houston with an error of ±13 percent. Transfer value of this model to other surface waterbodies depends on the uniqueness of conditions in Lake Houston, such as the nature of the dissolved organic matter that produces color in the water column. Application of this model to another waterbody might require new data to verify and refine the model.

An additional use of this model for Lake Houston could be to compute light-extinction coefficients and depth of the euphotic zone resulting from mixing with water of different color and turbidity values. If color and turbidity are considered as conservative properties during mixing, and coefficients for color and turbidity of the added water are assumed to be equivalent to Lake Houston water, then light-extinction coefficients can be computed from the relation:

$$\text{light-extinction coefficient} = 2.78 + 0.007\ ((X) \times (\text{color1} + (1-X)) + \text{color2}) + 0.036\ (X \times \text{turbidity1} + (1-X) \times \text{turbidity2}), \qquad (9)$$

where:

X = mixing fraction of lake water;
1–X = mixing fraction of added water;
color1 = color of lake water (platinum-cobalt units);
color2 = color of added water (platinum-cobalt units);

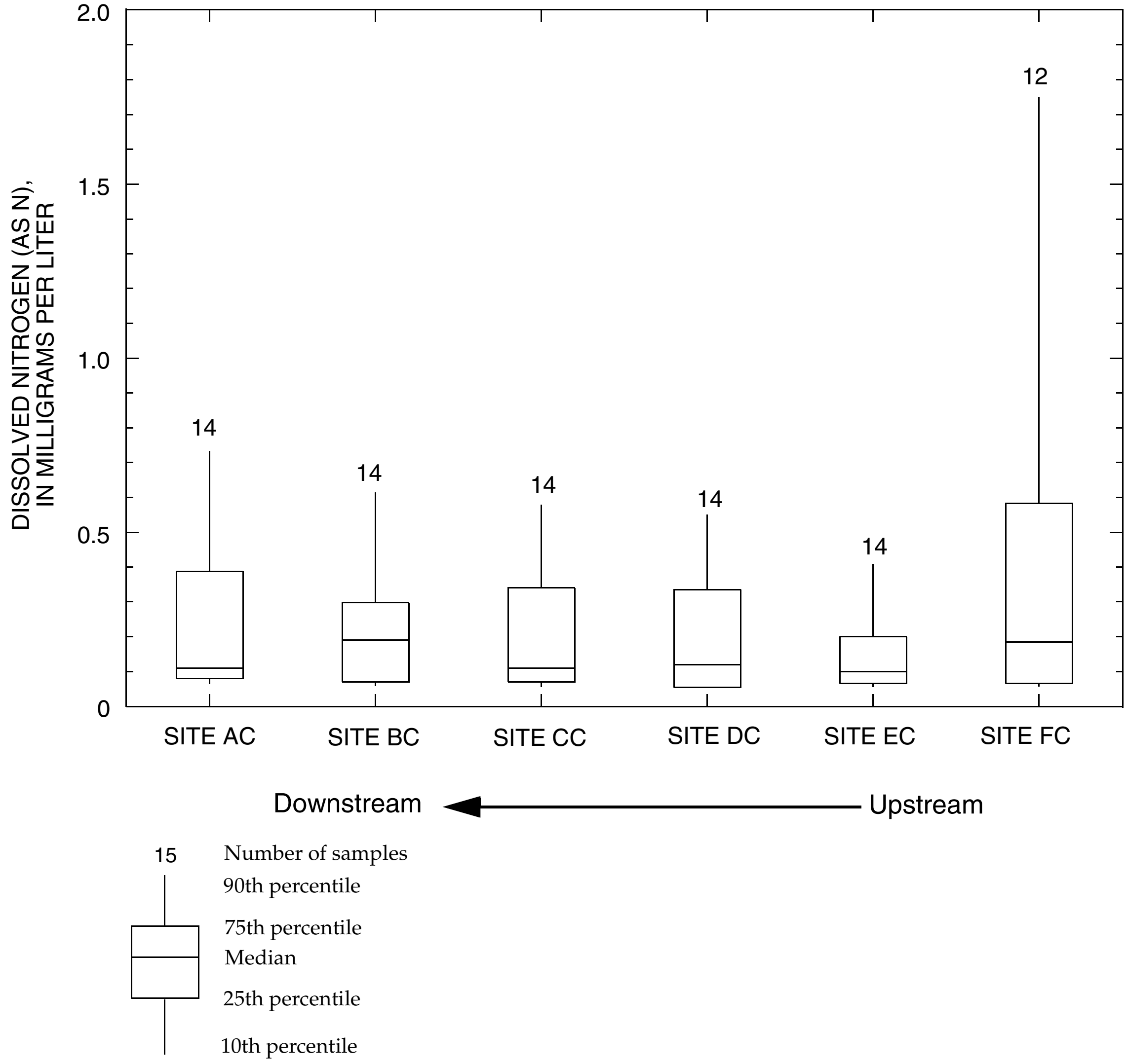


Figure 18. Distribution of dissolved nitrogen for water at six sites in Lake Houston, 1989–90.

turbidity1 = turbidity of lake water (nephelometric turbidity units); and

turbidity2 = turbidity of added water (nephelometric turbidity units).

From the computed light-extinction coefficient for the mixed water, the depth of the euphotic zone resulting from the blending of two waters can be computed from eq. 1 and primary productivity can be projected for Lake Houston (typical light-extinction coefficient of 4.25 with the depth of the euphotic zone 1.08 m). For example, a blend of 75-percent Lake Houston water with color and turbidity of 100 Pt-Co units and 25 ntu, respectively, and 25-percent other water with color and turbidity of 50 Pt-Co units and 10 ntu, respectively, would compute:

$$\text{light-extinction coefficient } (\eta) \text{ of blend} = 2.78 + 0.007\,(0.75 \times 100 + 0.25 \times 50) + 0.036\,(0.75 \times 25 + 0.25 \times 10); \tag{10}$$

$$\text{light-extinction coefficient } (\eta) \text{ of blend} = 4.16;$$

$$\text{depth of euphotic zone } (z) = \frac{4.6}{\eta}; \text{ and}$$

$$\text{computed depth of euphotic zone } (z) \text{ of blend} = 1.11 \text{ m}.$$

Because eq. 8 might have different coefficients for water from a source other than Lake Houston, results determined from eq. 10 should be used cautiously.

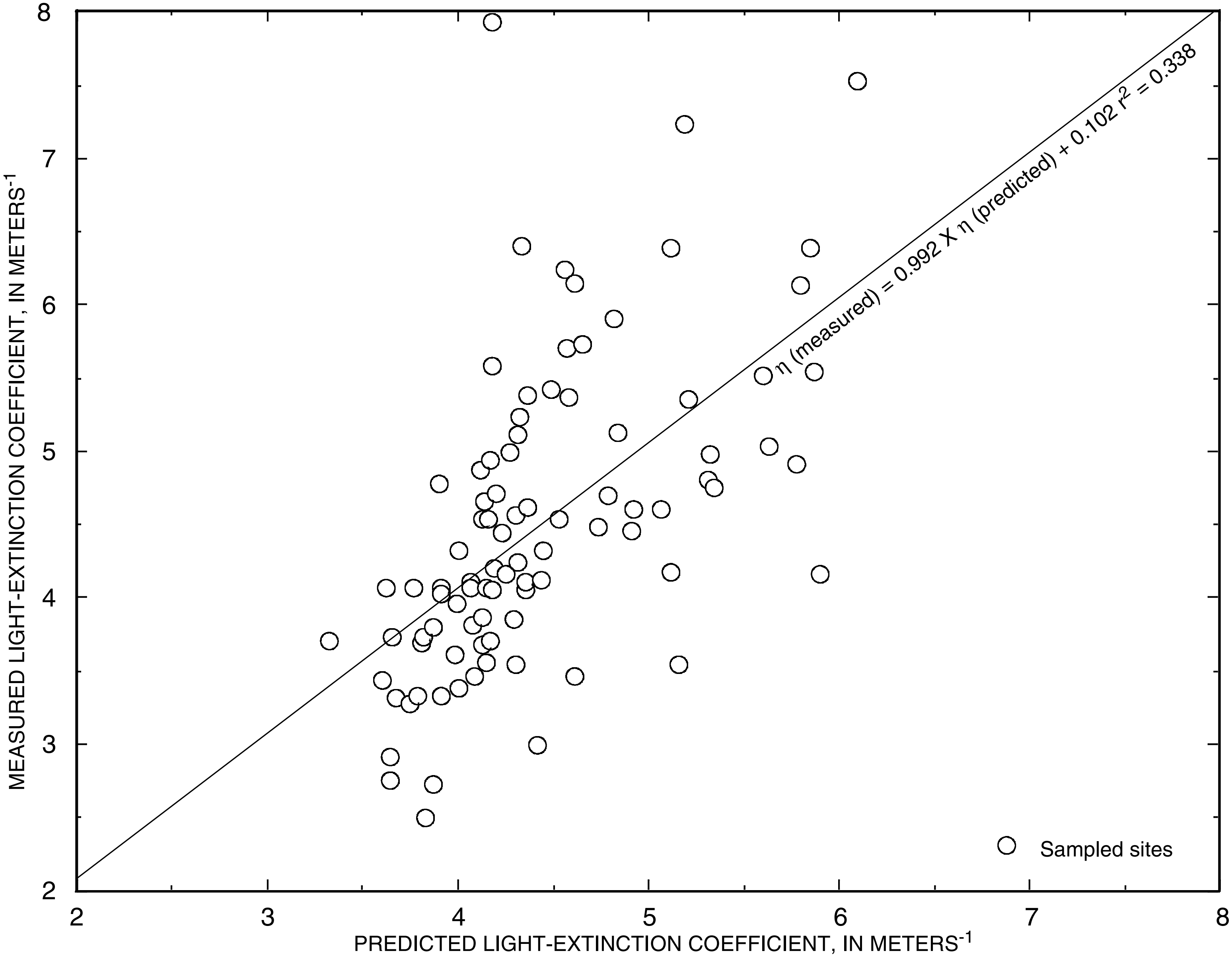


Figure 19. Relation of predicted light-extinction coefficients from water-quality data to measured light-extinction coefficients for water at six sites in Lake Houston, 1989–90.

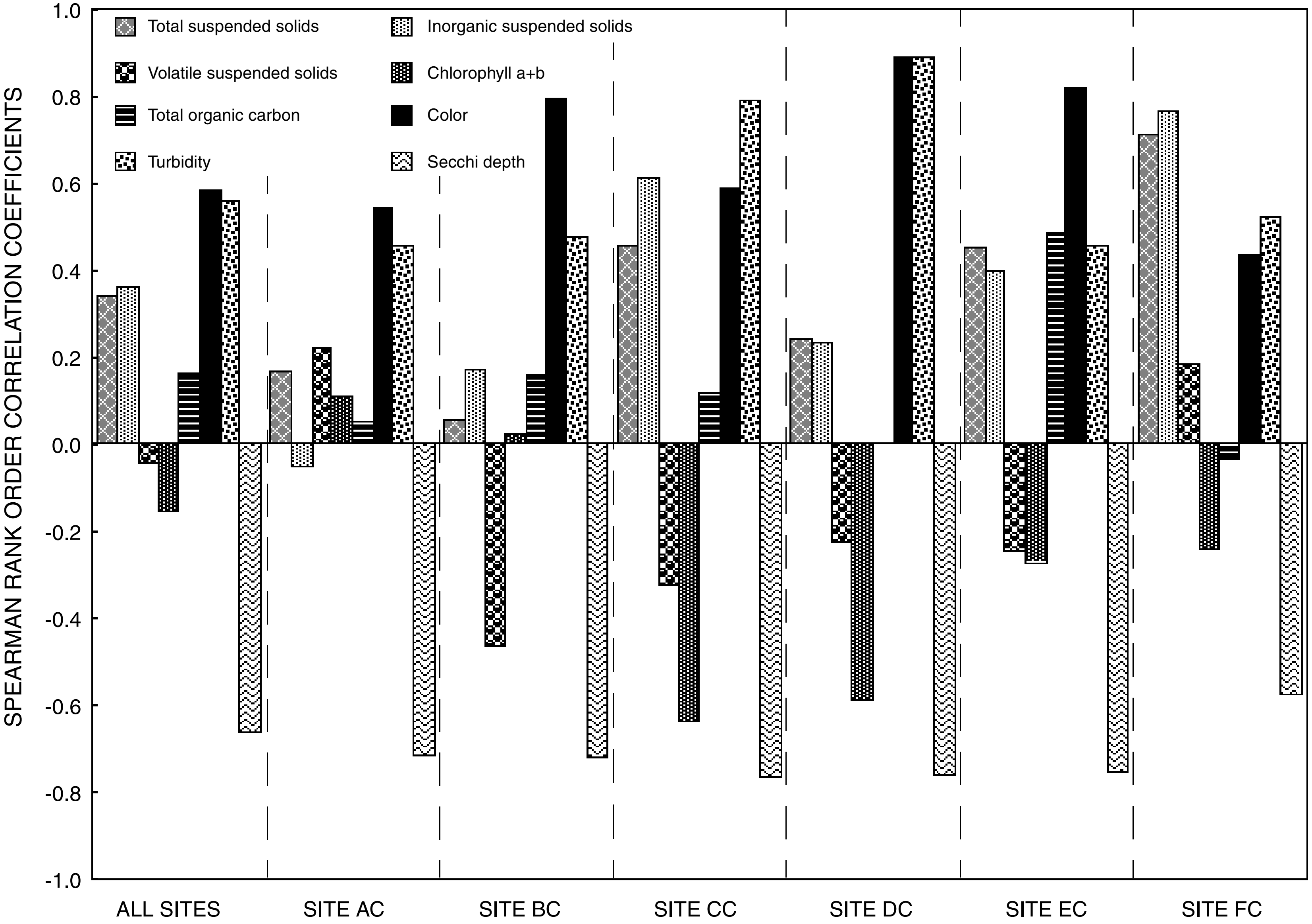


Figure 20. Spearman rank order correlation coefficients for the relation of light-extinction coefficients to total suspended solids, inorganic suspended solids, volatile suspended solids, chlorophyll a+b, total organic carbon, turbidity, color, and Secchi-depth transparency for water at six sites in Lake Houston, 1989–90.

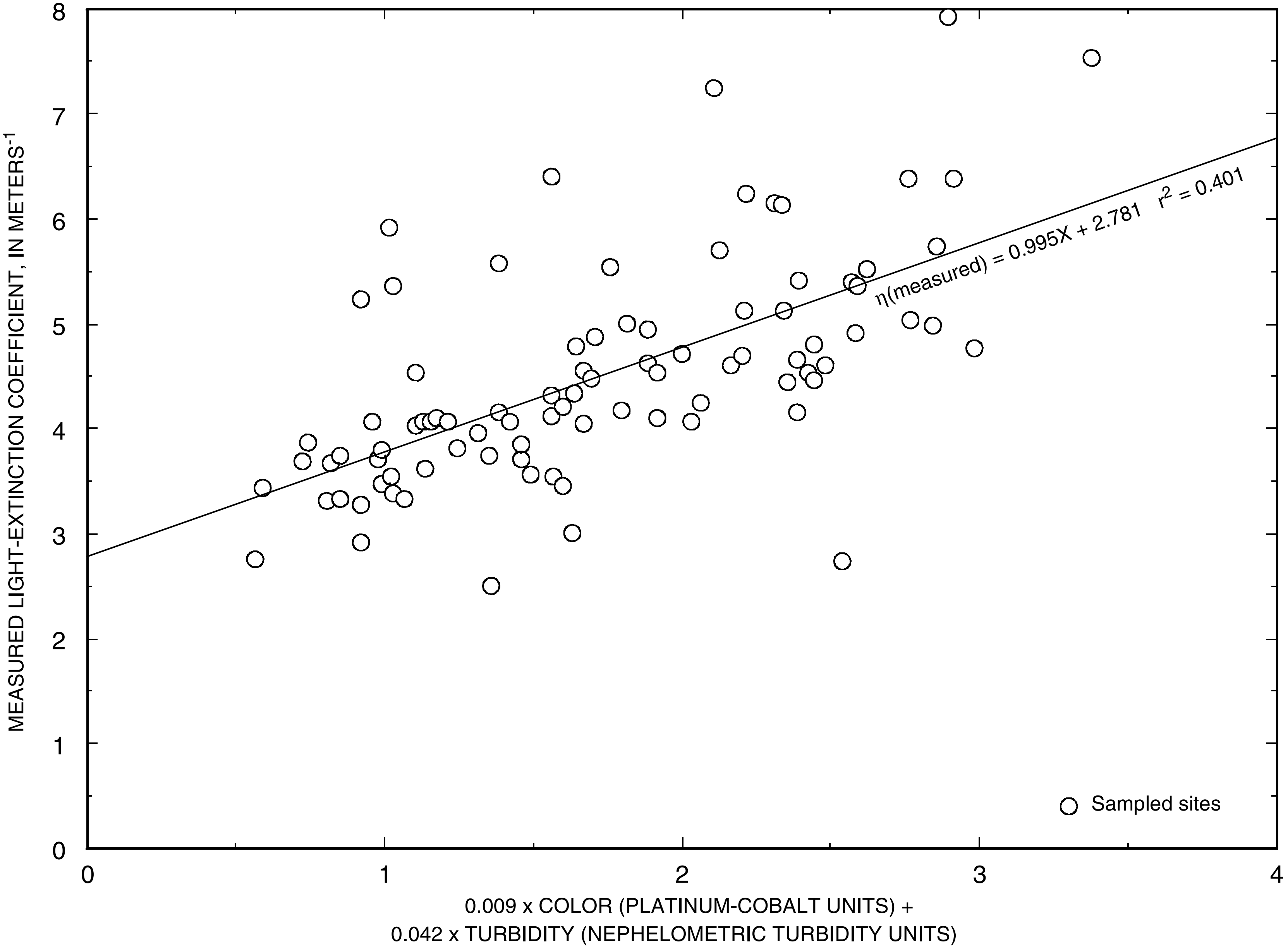


Figure 21. Relation of light-extinction coefficients to color and turbidity for water at six sites in Lake Houston, 1989–90.

CONCLUSIONS

During 1989–90, in-lake light measurements were made and surface-water samples were collected for water-quality analysis at six sites in Lake Houston, a shallow, turbid reservoir near Houston, Texas. The light-extinction coefficients and euphotic zone depths determined from the light-penetration measurements range from 2.49 to 7.93 m^{-1} and from 0.61 to 1.85 m, respectively, for all sites.

Primary production in Lake Houston is limited by light rather than by nutrients. The euphotic zone in Lake Houston is relatively thin owing to high levels of light attenuation in the water column. Principal sources of light attenuation include scattering of light caused by suspended organic and inorganic particles (TSS) and light absorption by dissolved organic matter (color) and chlorophyll a+b. Secchi-depth measurements in Lake Houston are a reasonable direct measure of light penetration but have been shown to represent the depth of penetration of about 3 percent of the original sunlight intensity in the water. This result indicates that use of light-extinction coefficients to determine the depth of the euphotic zone (1 percent of original sunlight intensity) might be preferred.

Measurements of water-quality constituents known to attenuate light show seasonal effects and changes from the upper part of Lake Houston toward the dam. Seasonal effects for light-extinction coefficients, TSS, color, turbidity, and the nutrients phosphorus and nitrogen typically show maximum values mostly during nongrowing-season months. Total organic carbon (TOC) and chlorophyll a+b typically show maximum values mostly during growing-season months. The principal source of TSS, TOC, phosphorus, and nitrogen concentrations in the reservoir is West Fork San Jacinto River. Light-extinction coefficients and TSS, TOC, and chlorophyll a+b concentrations decrease from water samples collected in the upper part of Lake Houston to water samples collected toward the dam, indicating physical sedimentation and decreasing primary productivity within Lake Houston. Decreases in phosphorus and nitrogen concentrations toward the dam indicate probable uptake of nutrients by biota such as phytoplankton in the reservoir. Dissolved phosphorus and nitrogen concentrations at all sites are greater than their growth-limiting concentrations and are not considered to be growth limiting during the study period. Overall increases in color and turbidity from the upper part of Lake Houston toward the dam contribute to light attenuation.

Because of high variability, the light-extinction coefficients measured in Lake Houston do not correlate well with the measured water-quality constituents that should contribute to light attenuation. Spearman rank order correlation indicates correlation of light-extinction coefficients to color and turbidity. Multiple regression-analysis, using the light-extinction coefficient as the dependent variable and using color and turbidity as the independent variables, produced the relation:

light-extinction
coefficient ( ) = 2.78 + 0.007 x color + 0.036 x turbidity (average error of computed coefficient to measured value, ±13 percent).

Using this statistical model and assuming similar coefficients for the added water and conservative mixing of color and turbidity, a light-extinction coefficient can be computed for a solution consisting of Lake Houston water mixed with water from another source and of different color and turbidity. Subsequently, the depth of the resulting euphotic zone in Lake Houston can be computed.

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Table 2. Water-quality constituents and physical properties in water from Lake Houston, 1989–90

[Concentrations in milligrams per liter unless otherwise specified. m^{-1}, $meters^{-1}$; m, meters; µg/L, micrograms per liter; Pt-Co, platinum-cobalt; ntu, nephelometric turbidity units; --, no data or not applicable]

Date	Light-extinction coefficient (m^{-1})	Computed depth of euphotic zone (m)	Total suspended solids (TSS)	Volatile suspended solids (VSS)	Inorganic suspended solids (ISS)	Total organic carbon (TOC)	Chlorophyll a+b (µg/L)	Color (Pt-Co units)	Turbidity (ntu)	Secchi depth (m)	Dissolved phosphorus (as P)	Dissolved nitrogen (as N)
Site AC												
07–27–89	4.17	1.10	9.00	0	9.00	14	2.20	180	15	0.52	0.150	0.11
08–22–89	4.31	1.07	12.0	0	12.0	14	5.50	110	22	.47	.220	.07
09–20–89	4.06	1.13	23.0	3.0	20.0	11	1.70	80	24	.46	.110	.06
11–03–89	4.24	1.09	19.0	3.0	16.0	9.0	1.60	100	38	.30	.090	.23
12–20–89	4.65	.99	16.0	16	0	8.0	.800	100	47	.23	--	--
01–29–90	4.97	.93	30.0	3.0	27.0	8.0	1.60	180	44	.29	.260	.65
03–26–90	4.87	.95	19.0	12	7.00	12	1.60	90	30	.40	.090	.41
05–01–90	4.93	.93	16.0	13	3.00	14	1.00	100	33	.38	.200	.37
06–15–90	4.59	1.00	19.0	5.0	14.0	12	1.60	170	36	.39	.130	.34
07–10–90	4.04	1.14	12.0	1.0	11.0	13	1.40	110	25	1.25	.220	.79
07–26–90	4.06	1.13	16.0	12	4.00	13	1.40	49	22	.43	.120	.08
08–06–90	6.39	.72	7.00	6.0	1.00	11	5.80	110	22	.40	.110	.09
08–24–90	2.90	1.59	7.00	7.0	0	10	1.80	55	15	.59	.150	--
09–14–90	3.70	1.24	11.0	5.0	6.00	9.0	.600	22	23	.48	.210	.10
09–28–90	3.54	1.30	23.0	5.0	18.0	9.0	1.60	96	25	.43	.190	.08
Site BC												
07–27–89	5.54	.83	38.0	5.0	33.0	16	25.2	180	14	.42	.120	.08
08–22–89	4.12	1.12	15.0	7.0	8.00	14	6.60	110	22	.40	.170	.07
09–20–89	4.20	1.10	17.0	11	6.00	12	6.10	90	27	.41	.120	.07
11–03–89	5.11	.90	18.0	2.0	16.0	9.0	1.80	100	42	.29	.130	.24
12–20–89	4.43	1.04	14.0	4.0	10.0	8.0	1.00	100	46	.25	--	--
01–29–90	4.75	.97	31.0	4.0	27.0	7.0	2.60	180	48	.29	.310	.75
03–26–90	4.69	.98	31.0	16	15.0	10	2.40	140	34	.40	.100	.41
05–01–90	5.70	.81	1.00	1.0	0	13	2.40	140	32	.36	.210	.36

Table 2. Water-quality constituents and physical properties in water from Lake Houston, 1989–90—Continued

Date	Light-extinction coefficient (m^{-1})	Computed depth of euphotic zone (m)	Total suspended solids (TSS)	Volatile suspended solids (VSS)	Inorganic suspended solids (ISS)	Total organic carbon (TOC)	Chlorophyll a+b (μg/L)	Color (Pt-Co units)	Turbidity (ntu)	Secchi depth (m)	Dissolved phosphorus (as P)	Dissolved nitrogen (as N)
Site BC—Continued												
06–15–90	4.45	1.03	2.00	0	2.00	14	2.00	170	35	0.40	0.110	0.22
07–10–90	4.10	1.12	8.00	2.0	6.00	12	4.10	110	32	1.12	.110	.19
07–26–90	4.06	1.13	23.0	9.0	14.0	12	3.70	47	23	.43	.090	.11
08–06–90	3.55	1.30	15.0	10	5.00	10	4.20	90	24	.49	.140	.22
08–24–90	3.27	1.41	17.0	8.0	9.00	11	1.70	55	15	.50	.260	--
09–14–90	3.73	1.23	20.0	10	10.0	9.0	1.20	60	26	.43	.160	.06
09–28–90	3.70	1.24	25.0	5.0	20.0	10	2.70	80	25	.42	.130	.06
Site CC												
07–27–89	4.91	.94	30.0	3.0	27.0	16	2.20	220	29	.36	.110	.11
08–22–89	2.99	1.54	14.0	12	2.00	14	8.40	110	24	.41	.120	.06
09–20–89	4.77	.97	26.0	3.0	23.0	11	1.60	55	35	.36	.220	.11
11–03–89	5.38	.86	24.0	4.0	20.0	9.0	1.80	100	52	.27	.240	.26
12–20–89	4.53	1.02	5.00	5.0	0	8.0	1.60	100	48	.24	--	--
01–29–90	4.80	.96	32.0	10	22.0	10	3.30	180	33	.33	.370	.66
03–26–90	4.53	1.02	36.0	17	19.0	12	3.80	110	32	.44	.150	.46
05–01–90	5.35	.86	38.0	14	24.0	14	2.20	170	39	.33	.270	.42
06–15–90	4.60	1.00	20.0	0	20.0	15	7.80	140	33	.36	.120	.23
07–10–90	4.15	1.11	186	26	160	12	5.80	75	24	1.35	.140	.08
07–26–90	3.79	1.22	17.0	12	5.00	12	4.60	65	15	.46	.130	.06
08–06–90	4.06	1.13	21.0	10	11.0	10	8.60	55	16	.42	.200	.08
08–24–90	4.02	1.15	29.0	9.0	20.0	10	3.40	55	20	.45	--	--
09–14–90	4.32	1.07	28.0	9.0	19.0	9.0	2.80	65	33	.38	.190	.12
09–28–90	3.32	1.39	19.0	5.0	14.0	9.0	3.50	50	20	.49	.170	.06

Table 2. Water-quality constituents and physical properties in water from Lake Houston, 1989–90—Continued

Date	Light-extinction coefficient (m^{-1})	Computed depth of euphotic zone (m)	Total suspended solids (TSS)	Volatile suspended solids (VSS)	Inorganic suspended solids (ISS)	Total organic carbon (TOC)	Chlorophyll a+b (µg/L)	Color (Pt-Co units)	Turbidity (ntu)	Secchi depth (m)	Dissolved phosphorus (as P)	Dissolved nitrogen (as N)
Site DC												
07–27–89	5.51	0.84	23.0	3.0	20.0	15	3.40	210	32	0.29	0.140	0.06
08–22–89	3.85	1.20	29.0	14	15.0	16	16.7	70	27	.35	.160	.07
09–20–89	4.70	.98	29.0	6.0	23.0	9.0	2.60	80	40	.32	.270	.28
11–03–89	5.73	.80	35.0	1.0	34.0	8.0	2.60	110	58	.26	.230	.25
12–20–89	4.15	1.11	25.0	17	8.00	8.0	1.80	100	47	.22	--	--
01–29–90	5.02	.92	35.0	5.0	30.0	9.0	3.90	200	38	.33	.340	.64
03–26–90	4.55	1.01	21.0	21	0	14	3.20	110	25	.42	.100	.42
05–01–90	6.38	.72	26.0	11	15.0	13	2.60	170	48	.25	.170	.39
06–15–90	4.61	1.00	7.00	2.0	5.00	14	5.30	110	31	.40	.070	.06
07–10–90	3.81	1.21	15.0	4.0	11.0	12	11.8	65	22	1.25	.260	.12
07–26–90	3.46	1.33	28.0	12	16.0	13	8.40	65	15	.46	.190	.06
08–06–90	3.61	1.28	22.0	6.0	16.0	10	4.00	65	19	.40	.260	.06
08–24–90	3.73	1.23	11.0	7.0	4.00	10	5.40	45	15	.44	--	--
09–14–90	4.10	1.12	26.0	8.0	18.0	10	6.40	65	20	.40	.400	.17
09–28–90	3.37	1.37	27.0	4.0	23.0	9.0	3.70	60	17	.43	.210	.06
Site EC												
07–27–89	6.38	.72	27.0	0	27.0	15	6.00	220	34	.33	.090	.11
08–22–89	3.95	1.17	12.0	1.0	11.0	11	5.30	70	23	.37	.080	.06
09–20–89	4.99	.92	38.0	14	24.0	9.0	4.70	80	35	.32	.190	.14
11–03–89	5.41	.85	39.0	4.0	35.0	8.0	4.30	90	49	.26	.120	.10
12–20–89	4.05	1.14	9.00	9.0	0	7.0	3.80	100	37	.30	--	--
01–29–90	5.12	.90	25.0	2.0	23.0	15	1.60	140	38	.33	.070	.18
03–26–90	4.48	1.03	25.0	24	1.00	16	7.10	140	20	.45	.060	.22
05–01–90	6.14	.75	27.0	17	10.0	15	2.00	130	39	.25	.190	.33

Table 2. Water-quality constituents and physical properties in water from Lake Houston, 1989–90—Continued

Date	Light-extinction coefficient (m^{-1})	Computed depth of euphotic zone (m)	Total suspended solids (TSS)	Volatile suspended solids (VSS)	Inorganic suspended solids (ISS)	Total organic carbon (TOC)	Chloro-phyll a+b (µg/L)	Color (Pt-Co units)	Turbidity (ntu)	Secchi depth (m)	Dissolved phos-phorus (as P)	Dissolved nitrogen (as N)
Site EC—Continued												
06–15–90	5.57	0.83	23.0	0	23.0	12	4.80	75	24	0.37	0.130	0.06
07–10–90	3.32	1.39	33.0	10	23.0	11	6.90	45	15	1.44	.110	.07
07–26–90	2.72	1.69	16.0	9.0	7.00	10	3.50	65	58	.48	.140	.08
08–06–90	3.68	1.25	16.0	4.0	12.0	9.0	7.60	47	11	.54	.160	.07
08–24–90	3.43	1.34	15.0	8.0	7.00	10	8.00	33	10	.53	--	--
09–14–90	3.31	1.39	24.0	8.0	16.0	8.0	5.90	33	16	.41	.150	.46
09–28–90	2.74	1.68	23.0	5.0	18.0	8.0	5.20	30	10	.62	.140	.06
Site FC												
07–27–89	3.54	1.30	28.0	1.0	27.0	18	42.7	90	11	.4	.360	.06
08–22–89	2.49	1.85	31.0	19	12.0	10	13.9	35	31	.25	.410	.47
09–20–89	7.93	.58	2.00	2.0	0	11	16.0	80	65	.24	.310	.21
11–03–89	6.23	.74	81.0	12	69.0	8.0	6.10	55	51	.23	1.50	2.1
12–20–89	3.45	1.33	26.0	12	14.0	6.0	17.0	100	25	.32	--	--
01–29–90	6.12	.75	67.0	13	54.0	11	2.10	190	28	.26	.510	.62
03–26–90	3.86	1.19	20.0	15	5.00	11	27.5	45	12	.46	.250	.12
05–01–90	7.52	.61	77.0	16	61.0	17	1.40	210	53	.24	.190	.06
06–15–90	4.06	1.13	34.0	0	34.0	12	3.30	55	23	.42	.270	.06
07–10–90	3.67	1.25	35.0	11	24.0	14	16.7	45	14	1.25	.620	.16
07–26–90	5.90	.78	54.0	17	37.0	13	40.9	48	19	.29	.780	.31
08–06–90	5.23	.88	30.0	5.0	25.0	9.0	21.0	55	15	.28	.780	.21
08–24–90	5.36	.86	23.0	11	12.0	12	38.8	60	17	.32	--	--
09–14–90	7.23	.64	65.0	12	53.0	6.0	36.1	75	44	.25	1.30	10
09–28–90	4.53	1.02	38.0	7.0	31.0	12	9.00	55	20	.42	.720	.08
Means	4.55	--	27.0	8.0	19.0	11	6.90	99	29	.44	.240	.25

Table 3. Spearman rank order correlation coefficients for light-extinction coefficients in relation to water-quality constituents and physical properties in water from Lake Houston, 1989–90

[Probability is probability of independence of light-extinction coefficient to variable; <, less than]

Lake Houston sites (fig. 2)	Total suspended solids	Probability	Volatile suspended solids	Probability	Inorganic suspended solids	Probability	Total organic carbon	Probability
All sites	0.34	0.00112	-0.0441	0.41100	0.363	0.00048	0.159	0.00001
Site AC	.165	.55635	.2173	.43655	-.052	.85432	.049	.863
Site BC	.052	.85419	-.4677	.07871	.17	.54483	.155	.581
Site CC	.454	.08916	-.3277	.23320	.608	.01625	.116	.681
Site DC	.238	.39272	-.2254	.41925	.229	.41128	.0000	1.000
Site EC	.45	.0925	-.2455	.37777	.398	.14541	.485	.0620
Site FC	.71	.00445	.181	.53525	.768	.00134	-.035	.9047

Lake Houston sites (fig. 2)	Chlorophyll a+b	Probability	Color	Probability	Turbidity	Probability	Secchi depth	Probability
All sites	-0.1584	0.3900	0.584	<0.00001	0.556	<0.00001	-0.667	<0.00001
Site AC	.1066	.7054	.539	.03825	.451	.09152	-.719	.00253
Site BC	.0215	.9395	.791	.00044	.474	.07452	-.724	.00227
Site CC	-.6419	.0099	.588	.02111	.789	.00047	-.765	.0009
Site DC	-.5914	.0202	.888	.00001	.889	.00001	-.763	.00093
Site EC	-.2750	.3212	.816	.00021	.452	.09059	-.755	.00114
Site FC	-.2440	.4006	.434	.12117	.521	.5615	-.58	.02971