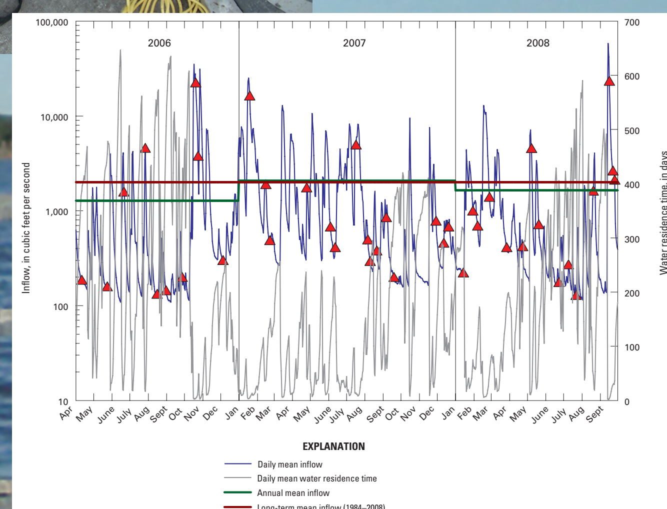
Prepared in cooperation with the City of Houston

Relations Between Hydrology, Water Quality, and Taste-and-Odor Causing Organisms and Compounds in Lake Houston, Texas, April 2006–September 2008



Scientific Investigations Report 2011–5121

U.S. Department of the Interior
U.S. Geological Survey

Front cover:

Background, Photograph showing a mobile, multi-depth continuous water-quality monitoring station, Lake Houston, January 2010.

Top, Photograph showing field personnel servicing a water-quality-monitoring sonde that is attached by a data cable to an automated reel, part of a mobile, multi-depth continuous water-quality monitoring station, Lake Houston, May 2008.

Back cover, Photograph showing field personnel collecting water from Lake Houston using a peristaltic pump (pump not shown) through Teflon-lined tubing into various water-quality-sample bottles, Lake Houston, April 2006.

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
milliliter (mL)	0.0338	ounces (oz)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic micrometer per milliliter (μm^3/mL)	1.805×10^{-12}	cubic inch per ounce (in^3/oz)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ounce (oz)	28.35	gram (g)
milligram (mg)	0.001	gram (g)
microgram (µg)	0.000001	gram (g)
nanogram (ng)	0.000000001	gram (g)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

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Abstract

Lake Houston is a surface-water-supply reservoir and an important recreational resource for the city of Houston, Texas. Growing concerns over water quality in Lake Houston prompted a detailed assessment of water quality in the reservoir. The assessment focused on water-quality constituents that affect the aesthetic quality of drinking water. The hydrologic and water-quality conditions influencing the occurrence of taste-and-odor causing organisms and compounds in Lake Houston were assessed using discrete and continuously monitored water-quality data collected during April 2006–September 2008.

The hydrology of Lake Houston is characterized by rapidly changing conditions. During inflow events, water residence time can change by orders of magnitude within a matter of hours. Likewise, the reservoir can stratify and destratify over a period of several hours, even during non-summer and at relatively short water residence times, given extended periods with warm temperatures and little wind. The rapidly changing hydrology likely influences all other aspects of water quality in Lake Houston, including the occurrence of taste-and-odor causing organisms and compounds.

Water quality in Lake Houston varied with respect to season and water residence time but typically was indicative of turbid, eutrophic to hypereutrophic conditions. In general, turbidity and nutrient concentrations were largest during non-summer (October–May) and when water residence times were relatively short (less than 100 days), which reflects the influence of inflow events on water-quality conditions. Large inflow events can cause substantial changes in water-quality conditions over relatively short periods of time (hours).

The taste-and-odor causing organisms cyanobacteria and actinomycetes bacteria were always present in Lake Houston. Cyanobacterial biovolume was largest during summer (June–September) and when water residence time was greater than 100 days. Annual maxima in cyanobacterial biovolume occurred during July-September of each year, when temperatures were larger than 27 degrees Celsius and water residence times were longer than 400 days. In contrast, actinomycetes bacteria were most abundant during non-summer and when water residence times were less than 100 days, reflecting the close association between these organisms and transport of suspended sediments.

Geosmin and 2-methylisoborneol are the taste-and-odor causing compounds most commonly produced by cyanobacteria and actinomycetes bacteria. Geosmin was detected more frequently (62 percent of samples) than 2-methylisoborneol (29 percent of samples) in Lake Houston. Geosmin exceeded the human detection threshold (10 nanograms per liter) only once during the study period and 2-methylisoborneol exceeded the human detection threshold twice. Manganese is a naturally occurring trace element that can occasionally cause taste-and-odor problems in drinking water. Manganese concentrations exceeded the human detection threshold (about 50 micrograms per liter) in about 50 percent of samples collected near the surface and 84 percent of samples collected near the bottom. The cyanotoxin microcystin was detected relatively infrequently (16 percent of samples) and at small concentrations (less than or equal to 0.2 micrograms per liter).

The abundance of the taste-and-odor causing organisms cyanobacteria and actinomycetes bacteria in Lake Houston was coupled with inflow events and subsequent changes in water-quality conditions. Cyanobacterial biovolume (biomass) in Lake Houston was largest during warm periods with little inflow and relatively small turbidity values. In contrast, actinomycetes bacteria were most abundant following inflow events when turbidity was relatively large. Severe taste-and-odor problems were not observed during the study period, precluding quantification of the hydrologic and water-quality conditions associated with large concentrations of taste-and-odor causing compounds and development of predictive models.

Reservoir inflow (water residence time) and turbidity, variables related to the abundance of potential taste-and-odor causing organisms, are currently (2011) continuously measured in Lake Houston, and predictive models could be developed in the future when the hydrologic and water-quality conditions associated with taste-and-odor problems have been better quantified. Seasonal and water residence time influences on water-quality conditions altered relations between hydrologic and water-quality conditions and taste-and-odor causing organisms and compounds. Future data collection and

development of predictive models need to account for the variability associated with season and water residence time.

Introduction

Houston, Tex., is the fourth most populous metropolitan area in the United States, with an estimated population of 5.9 million people in 2010 (Texas State Data Center, 2010a). Population in the Houston metropolitan area has increased by approximately 20 percent over the last decade (2000–10), a growth trajectory that is expected to continue for at least the next 20 years (Texas State Data Center, 2010b). The city of Houston is the regional water provider for the Houston metropolitan area and relies on a combination of surface-water and groundwater supplies for municipal and industrial water needs. Water-supply needs will continue to increase with ongoing population growth and urban development. Currently (2011), about 71 percent of the water supply comes from surface-water sources and 29 percent from groundwater sources (City of Houston, 2011). Subsidence, primarily because of groundwater withdrawal, has led to regulations to reduce groundwater withdrawals in the Houston metropolitan area to no more than 20 percent of the total water demand (Harris Galveston Subsidence District, 1999). Lake Houston is a surface-water-supply reservoir for the city of Houston and currently (2011) supplies between 10 to 20 percent of the total source-water supply (City of Houston, 2011). In addition to providing drinking water, Lake Houston is an important recreational resource. Because of future water needs and reliance on surface-water supplies, Lake Houston will become an increasingly important source-water supply for the Houston metropolitan area.

Taste-and-odor problems are a concern to drinking-water suppliers because of customer dissatisfaction with unpalatable drinking water and increased treatment costs to remove taste-and-odor causing compounds. There are many potential sources of taste and odor in finished drinking water, including biological activity in or chemical contamination of the source water, chemicals used during the treatment process, and biological activity or materials present in the distribution system. Biological activity associated with naturally occurring algae (phytoplankton) in surface source-water supplies is among the most common causes of taste-and-odor problems in finished drinking water (Taylor and others, 2005).

Geosmin and 2-methylisoborneol (MIB) cause earthy and musty tastes and odors and frequently are responsible for customer complaints about objectionable drinking water because the compounds are detectable by humans at extremely small concentrations (10 nanograms per liter). Most taste-and-odor problems associated with geosmin and MIB are caused by cyanobacteria (blue-green algae), but bacteria in the actinomycetes group also can produce geosmin and MIB (Taylor and others, 2005). Cyanobacteria are unique among the bacteria because they contain chlorophyll-*a*, a photopigment used for photosynthesis, and commonly are considered part of phytoplankton assemblages rather than bacterial assemblages in aquatic ecosystems (Wetzel, 2001). Many taste-and-odor producing cyanobacteria also have the potential to produce cyanotoxins that can cause illness after exposure through drinking water or recreational activities (Chorus and Bartram, 1999). The actinomycetes bacteria largely are terrestrial organisms associated with soils; inflow events with large suspended-sediment loads might result in taste-and-odor episodes caused by geosmin and MIB produced by actinomycetes bacteria (Zaitlin and others, 2003; Zaitlin and Watson, 2006). Lake Houston experienced multiple taste-and-odor episodes throughout 2005 that were described as earthy and musty and believed to be associated with geosmin and MIB produced by cyanobacteria (Belhateche and others, 2007).

Since 1983, the U.S. Geological Survey (USGS), in cooperation with the city of Houston, has collected water-quality and stage data for Lake Houston, as well as water-quality and streamflow data for the major tributaries to Lake Houston (Lee and Rast, 1997; Liscum and others, 1999; Sneck-Fahrer and others, 2005). Growing concerns over water quality in Lake Houston, including the taste-and-odor episodes during 2005, prompted a more detailed assessment of water quality in the reservoir (Oden and Graham, 2008). The assessment described in this report is focused on water-quality constituents that affect the aesthetic quality of drinking water such as geosmin, MIB, and manganese. Beginning in 2006, a real-time water-quality monitoring network was established in Lake Houston to supplement existing real-time water-quality monitors on the major tributaries. Discrete water-quality samples also were collected and analyzed for nutrients, potential taste-and-odor causing organisms and compounds, and other water-quality constituents (Beussink and Burnich, 2009). The current (2011) study improves the understanding of the hydrologic and water-quality conditions that favor the occurrence of taste-and-odor causing organisms and compounds in Lake Houston.

Purpose and Scope

The purpose of this report is to: (1) describe the hydrology of Lake Houston with respect to inflow, water residence time, and thermal stratification, (2) describe the water-quality conditions in Lake Houston, including taste-and-odor causing organisms and compounds, and (3) assess relations between hydrologic and water-quality conditions and taste-and-odor causing organisms and compounds in Lake Houston. Data collected by the USGS from Lake Houston and inflow from tributaries during April 2006–September 2008 were used to evaluate the hydrology and water quality of Lake Houston. The data analyzed in this report were collected as part of a larger water-quality monitoring network in Lake Houston. Data from the entire reservoir water-quality monitoring network were published for the period April 2006–September 2008 in Beussink and Burnich (2009). Lake Houston Site B is emphasized in this report because of its proximity to the Northeast Water Purification Plant (NEWPP) and the influence water-quality conditions near the plant have on drinking-water treatment processes. Site B also has the longest water-quality data record of all the reservoir-monitoring-network sites in Lake Houston.

Description of Study Area

Lake Houston, located about 25 miles northeast of downtown Houston (fig. 1), is a eutrophic to hypereutrophic reservoir and an important source-water-supply reservoir and recreational resource for the Houston metropolitan area. The dam impounding Lake Houston was constructed on the San Jacinto River in 1954 by the city of Houston to provide water for public supply and irrigation. The reservoir has a capacity of about 130,000 acre-feet and a surface area of 11,854 acres; mean depth is about 12 feet (ft) and maximum depth is about 50 ft (Liscum and East, 2000; Texas Water Development Board, 2004).

Lake Houston is located at the outlet of the 2,825-square mile (mi^2) San Jacinto River Basin. The basin at Lake Houston can be divided into an eastern subbasin and a western subbasin. The 987-mi^2 eastern subbasin represents about 35 percent of the basin and is rural, with predominantly forest and grassland land cover classes (Sneck-Fahrer and others, 2005) (fig. 1). Tributaries in the eastern subbasin include Caney Creek (drains approximately 8 percent of the basin), East Fork San Jacinto River (14 percent), Luce Bayou (7 percent), and Peach Creek (5 percent). The 1,756-mi^2 western subbasin represents about 62 percent of the basin and is more urban (fig. 1), with residential and commercial development, major transportation corridors, and fluvial gravel and sand mining operations. Tributaries in the western subbasin include Cypress Creek (drains approximately 11 percent of the basin), Spring Creek (16 percent), and the West Fork San Jacinto River (35 percent) (Sneck-Fahrer and others, 2005). Lake Houston and the area immediately surrounding the reservoir represent the remaining 3 percent of the basin (fig. 1). Land use on the Lake Houston shoreline includes forested land, residential homes, and a municipal park. Six wastewater-treatment facilities in the immediate vicinity contribute wastewater discharge to Lake Houston (Miertschin and Associates, 2007). Over 300 municipal wastewater discharges are permitted in the basin (Texas Commission on Environmental Quality, 2011a).

Previous Investigations

Numerous water-quality studies of Lake Houston have been conducted since the mid-1980s, including USGS studies in cooperation with the city of Houston and various State and university studies. Previous studies of Lake Houston have been limited to discrete data; the study described in this report includes continuously monitored (hourly) data, which allows description of changing water-quality conditions at a much finer temporal resolution.

Previous studies indicate that in general, larger loads of nutrients, suspended solids, and other water-quality constituents are contributed from the western tributaries to Lake Houston, largely because of urbanization in the western subbasin (Liscum and others, 1999; Van Metre and Sneck-Fahrer, 2002; Sneck-Fahrer and others, 2005). Lake Houston displays longitudinal gradients characteristic of reservoirs, with larger nutrient concentrations, turbidity, and algal biomass in the riverine zone (up-reservoir) of the reservoir and smaller concentrations in the lacustrine zone (down-reservoir) near the dam (Conrad, 1986; Sneck-Fahrer and others, 2005). Theoretical water residence time in Lake Houston ranges from about 12 hours to 400 days; annual mean water residence time during 2000–04 ranged from 24 to 176 days (Liscum and East, 2000; Sneck-Fahrer and others, 2005). Storm runoff generally passes through the reservoir within 24 hours. During storm events horizontal and vertical mixing is not complete for at least one-half the length of the reservoir (Matty and others, 1987; Kilson, 1992).

Lake Houston is generally a turbid reservoir. Sneck-Fahrer and others (2005) found that the amount of suspended sediment in Lake Houston is largely controlled by the amount and intensity of rainfall in the watershed and discharge from tributary inflows. However, several studies have demonstrated that turbidity and suspended sediment also are affected by turbulent mixing and resuspension of bottom sediments caused by wind (Baca and others, 1982; Matty and others, 1987; Sneck-Fahrer and others, 2005). Almost all (77 to 93 percent) of the sediment entering Lake Houston is retained in the reservoir (Baca and others, 1982; Matty and others, 1987).

Light attenuation in Lake Houston is caused primarily by total suspended solids, including suspended sediment, dissolved organic matter, and suspended organic matter, including phytoplankton (Lee and Rast, 1997). Many studies have found that although nutrients are sufficient to cause periodic algal blooms, algal growth in Lake Houston usually is limited by light because of the highly turbid conditions (Baca and others, 1982; Conrad, 1986; Matty and others, 1987; Lee and Rast, 1997; Sneck-Fahrer and others, 2005).Water residence time and inflow events also are important factors controlling algal growth in Lake Houston (Baca and others, 1982; Matty and others, 1987).

Methods

In 2006, the USGS, in cooperation with the city of Houston, established a water-quality monitoring network in Lake Houston to collect continuous (hourly) data for physicochemical properties (specific conductance, pH, water temperature, turbidity, and dissolved oxygen concentration). Mobile, multi-depth continuous-monitoring stations were installed at five sites in the southwestern quadrant of Lake Houston where reservoir conditions are lacustrine (lake-like). Monitoring locations attempted to represent water-quality upstream, near,

Figure 1. Location of monitoring stations in Lake Houston and inflowing tributaries and land cover in the San Jacinto River Basin.

and downstream from the NEWPP. Oden and Graham (2008) and Beussink and Burnich (2009) provide a detailed description of the strategy used during 2006–08 to monitor water quality in Lake Houston and inflowing tributaries.

The focus of this report is on data collected at reservoir monitoring station Site B (Lake Houston at mouth of Jack's Ditch near Houston, Tex., USGS station 295554095093401) (fig. 1) because it has the longest data record of all Lake Houston monitoring sites (Beussink and Burnich, 2009) and is in proximity to the NEWPP. Discrete and continuous data collected at Lake Houston Site B between April 1, 2006, and September 30, 2008 (discrete data collected from April 1, 2006, through September 30, 2008, and continuous data collected from October 1, 2006, through September 30, 2008) were used to assess relations between hydrologic and water-quality conditions and taste-and-odor causing organisms and compounds in Lake Houston.

Data Collection

Continuous Water-Quality Monitoring

Streamflow data from USGS continuous water-quality monitoring stations on seven tributaries to the reservoir (fig. 1) and reservoir storage (volume) data were used to describe reservoir inflows and water residence time during April 2006–September 2008. Streamflow and reservoir storage data are available on the USGS National Water Information System website (*http://waterdata.usgs.gov/nwis*). Streamflow and reservoir storage were measured using standard USGS methods (Kenney, 2010; Sauer and Turnipseed, 2010; Turnipseed and Sauer, 2010).

Continuous water-quality monitoring at Lake Houston Site B began in October 2006 and includes hourly measurements at 1, 6, 12, and 16 ft below the water surface. Continuous measurements of specific conductance, pH, water temperature, turbidity (YSI 6136 optical turbidity sensor), and dissolved oxygen concentration (YSI 6150 optical dissolved oxygen sensor) were made by using a YSI 6600EDS water-quality monitor. Monitors were maintained and data were processed in accordance with standard USGS procedures (Wagner and others, 2006). Additional detail on continuous water-quality monitoring at Lake Houston is described in Beussink and Burnich (2009).

Discrete Water-Quality Samples

Discrete water-quality samples were collected at Lake Houston Site B during a range of inflow conditions and water residence times from April 2006–September 2008 (fig. 2). Water-quality samples were collected at about 1-ft below the water surface, at the midpoint depth of the water column, and at about 1-ft above the bottom sediments (typically around 16 ft below the water surface). Physicochemical properties (the five continuously monitored properties) were measured at each depth where discrete water-quality samples were collected. Water-quality samples were analyzed for various properties and constituents including nutrients, chlorophyll, taste-and-odor causing organisms and compounds, and the cyanotoxin microcystin. Geosmin, MIB, and microcystin analyses were performed on whole water samples; therefore, the concentrations presented in this report represent the total concentrations of these compounds (Graham and others, 2008). Additional detail on discrete water-quality sample collection and analysis is described in Beussink and Burnich (2009).

Chlorophyll (uncorrected for degradation products) was analyzed at the USGS Texas Water Science Center laboratory in Shenandoah, Texas. Chlorophyll was extracted in heated ethanol (Sartory and Grobbelaar, 1986) and analyzed fluorometrically using U.S. Environmental Protection Agency (USEPA) Method 445.0 (Arar and Collins, 1997). All discrete water-quality data are available on the USGS National Water Information System website (*http://waterdata.usgs.gov/nwis*).

Quality-Assurance and Quality-Control

Quality-assurance and quality-control samples were collected to evaluate sample-collection procedures and laboratory analyses; quality-assurance and quality-control results are summarized in Beussink and Burnich (2009). Chlorophyll data are not included in the Beussink and Burnich (2009) summary. Laboratory-split replicate samples for chlorophyll analysis were collected from all samples. Relative percent difference (RPD) was used to evaluate differences between replicates. The RPD was calculated using the following equation:

$$RPD = \left[\left| A - B \right| / \left(\frac{A + B}{2} \right) \right] \times 100 \qquad (1)$$

where A and B are concentrations in each replicate pair. Most laboratory-split replicate chlorophyll samples (91 percent, number of replicate pairs was 23) from Lake Houston Site B at 1-ft depth had RPDs less than 10 percent (median 3 percent); however, one replicate pair had a RPD of 11 percent (collected on January 30, 2008) and one had a RPD of 93 percent (collected on May 20, 2008). Laboratory-split replicate samples with large RPDs likely were caused by clumps of algae or other chlorophyll-containing plant material that could not be homogenized by vigorous shaking. The sample collected on January 30, 2008, was retained in data analyses. The replicate with the largest chlorophyll concentration (15.3 micrograms per liter, μg/L) on May 20, 2008, was retained for data analysis because it was most similar to chlorophyll concentrations measured in samples collected from 1-ft depths at two other Lake Houston sites sampled on that date (23.1 and 26.8 μg/L).

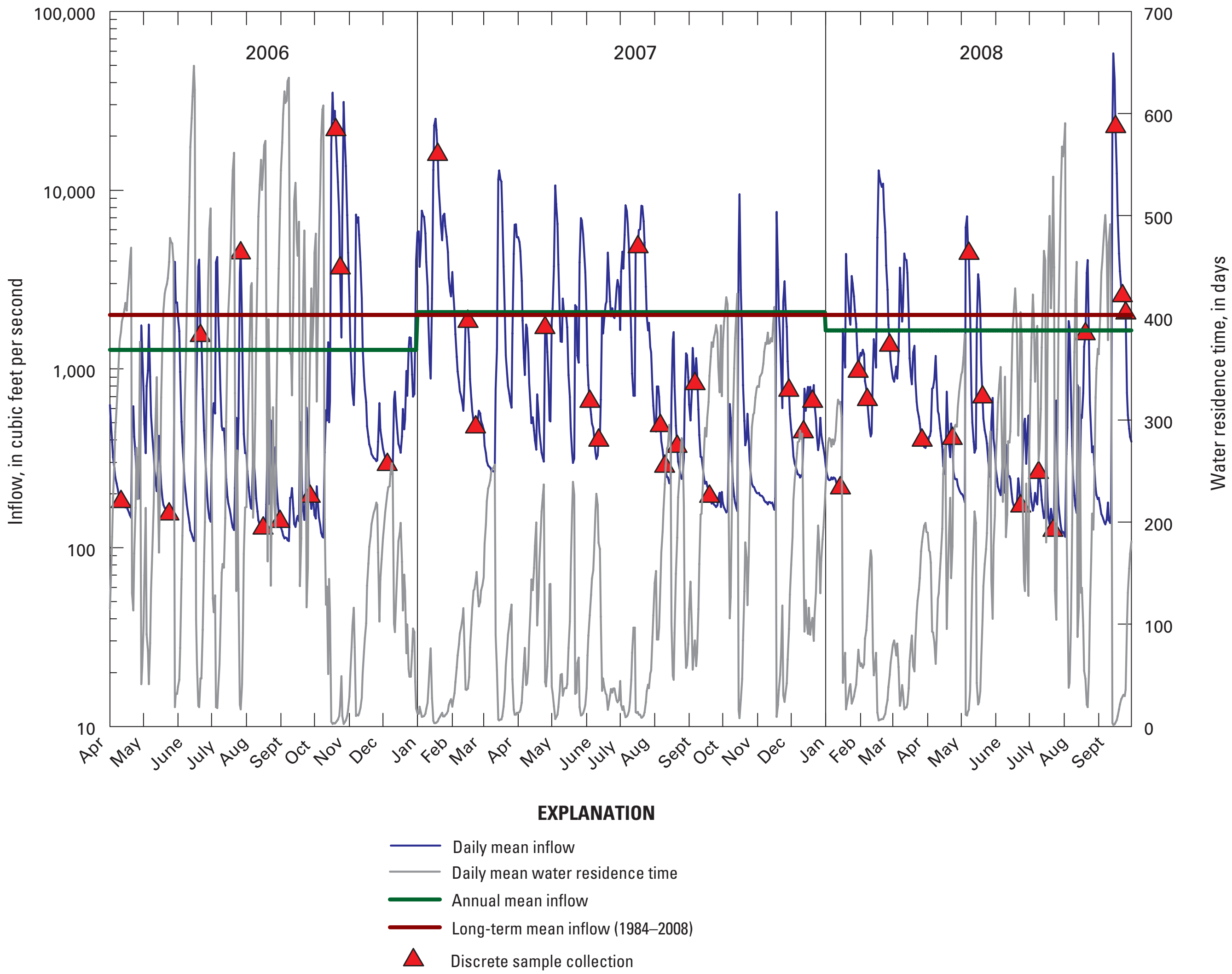

Figure 2. Daily mean inflow, daily water residence time, and timing of discrete-sample collection at Lake Houston Site B during April 2006–September 2008.

Data Analysis

Hydrologic Data

The seven gaged tributaries to Lake Houston (fig. 1) represent all of the major contributing inflows to the reservoir. Total daily inflow to the reservoir was calculated as the sum of the daily mean streamflow of each of the seven major tributaries. Streamflow has been measured on the seven major tributaries to Lake Houston since 1984; these data were used to compare reservoir inflows during April 2006–September 2008 to historical inflow conditions. Water residence time (WRT) is a measure of the average amount of time a water molecule will spend in a lake or reservoir; generally, WRT is inversely proportional to inflow. WRT was calculated as the ratio of daily mean reservoir volume to daily mean inflow (Kalff, 2002) using reservoir storage data and the summed inflow data.

Relative thermal resistance to mixing (RTRM), a unitless measure of the stability of thermal stratification in a water column, represents the relative amount of energy required to mix a column of water and is based on temperature-related density differences between adjacent depths (Kalff, 2002). Large RTRM values occur when temperature-related density at a given depth is substantially greater than overlying water, indicating a tendency toward thermal stratification. Daily RTRM values were calculated for October 2006–September 2008 using the continuous water-temperature profile data in Beussink and Burnich (2009). Data from the 1500 hour (3:00 p.m. local time) were selected to calculate daily RTRM because the largest vertical gradients in temperature typically occurred around that time. Vertical gradients likely were largest in mid-afternoon because the largest water temperatures generally lag behind the largest ambient air temperatures and incoming solar radiation, which occur at midday. Thermal resistance to mixing for the entire water column was calculated by summing the RTRM values from each depth.

Duration curves were used to describe data for reservoir inflow, WRT, and RTRM during the study period. Duration curves are cumulative distribution functions and were constructed using hourly values to evaluate frequency and magnitude characteristics. The curves show the percentage of time that specified conditions were equaled or exceeded (frequency of exceedance; Maidment, 1993). Although several similar formulas exist for calculating plotting position, the Weibull formula (Helsel and Hirsch, 2002) was used in this study.

Water-Quality Data

Water quality was evaluated using data collected from only the 1-ft depth because the water column at Lake Houston Site B typically did not thermally stratify, and gradients in water-quality conditions generally were small (Beussink and Burnich, 2009). Duration curves were used to describe continuously measured water-quality data collected during the study period using the approach described for hydrologic data. Continuous and discrete water-quality data were summarized using descriptive statistics for the entire data set, as well as by season and water residence time. Seasons were defined as non-summer (October–May) and summer (June–September), after Liscum and others (1999). WRT groups were defined as WRT less than 100 days and WRT greater than or equal to 100 days. In general, WRTs less than 100 days indicate substantial riverine influence on water-quality conditions, and WRTs greater than 100 days indicate substantial influence of in-reservoir processes on water-quality conditions (Søballe and Kimmel, 1987; Kalff, 2002).

Correlation Analysis

Relations between hydrologic and water-quality conditions and taste-and-odor causing organisms and compounds at Lake Houston Site B were described using the nonparametric Spearman Rank correlation analysis (Sokal and Rohlf, 1995; Helsel and Hirsch, 2002). The Spearman Rank correlation analysis tests the strength of the monotonic (consistent increase or decrease) association between two variables (X and Y) by ranking the variates and calculating a coefficient of rank correlation (r_s) scaled to range from minus one to one. A positive correlation indicates the tendency of Y to increase with increases in X; a negative correlation indicates the tendency of Y to decrease with increases in X. When there is no correlation between two variables, r_s is near zero. Spearman Rank correlation coefficients were considered statistically significant when probability values (*p*-value) were less than 0.05. Spearman Rank correlation analysis assumes that all variables are at least ordinal, and the data represent a random sample from the population of interest (Hampton, 1994). All analyses were conducted using SAS 9.2 software (SAS Institute Inc., 2009).

Hydrology of Lake Houston

Inflows, WRT, and RTRM are important hydrologic characteristics of reservoirs because they affect physical, chemical, and biological processes, which affect water quality. Streamflow and reservoir storage data were used to describe inflows and WRT for Lake Houston during April 2006–September 2008. Water temperature profile data were used to describe RTRM for Lake Houston Site B during October 2006–September 2008.

Inflows and Water Residence Time

Overall, inflow conditions to Lake Houston were generally representative of years with below-normal to normal inflow; annual mean inflows to Lake Houston were 36 percent and 18 percent less than the long-term mean (2,000 cubic feet per second, ft^3/s) during 2006 and 2008, respectively, and near-typical (2,080 ft^3/s) during 2007 (fig. 2). However, three notable inflow events, all more than 25,000 ft^3/s, occurred during the study period. The largest inflow to Lake Houston during the study period (58,200 ft^3/s) occurred 2 to 3 days after Hurricane Ike made landfall (September 13, 2008).

Daily mean inflow to Lake Houston during April 2006–September 2008 ranged from 109 to 58,200 ft^3/s and typically (80 percent of the time) exceeded 202 ft^3/s (fig. 3A, table 1). The median of all daily mean inflows during summer (316 ft^3/s) was about 2 times less than the median of all daily mean inflows during non-summer (626 ft^3/s), though runoff from storm events punctuated the hydrograph records during both seasons (fig. 2). Increased inflow caused decreased WRT; the median of all daily mean inflow was about 8 times larger when WRT was less than 100 days (2,070 ft^3/s) than when water residence time was greater than 100 days (268 ft^3/s) (table 1).

Water residence time in Lake Houston during April 2006–September 2008 ranged from 2 to 647 days and typically (80 percent of the time) exceeded 37 days (fig. 3B, table 1). WRT was greater than 100 days (indicating dominance of in-reservoir processes) on 554 days and less than 100 days (indicating dominance by riverine processes) on 360 days. Therefore, during the study period, in-reservoir processes likely influenced water-quality conditions more often (about 61 percent of the time) than riverine processes. Median WRT was about 2 times longer in summer (219 days), when inflows were smaller, than in non-summer (114 days) (table 1), indicating in-reservoir processes likely influenced water quality more during summer than non-summer.

Relative Thermal Resistance to Mixing

Relative thermal resistance to mixing at Lake Houston Site B ranged from zero (no thermal resistance to mixing, indicative of well-mixed conditions) to 296 (indicative of thermally stratified conditions). RTRM was less than 56 about 80 percent of the time (fig. 3C), and the overall median RTRM

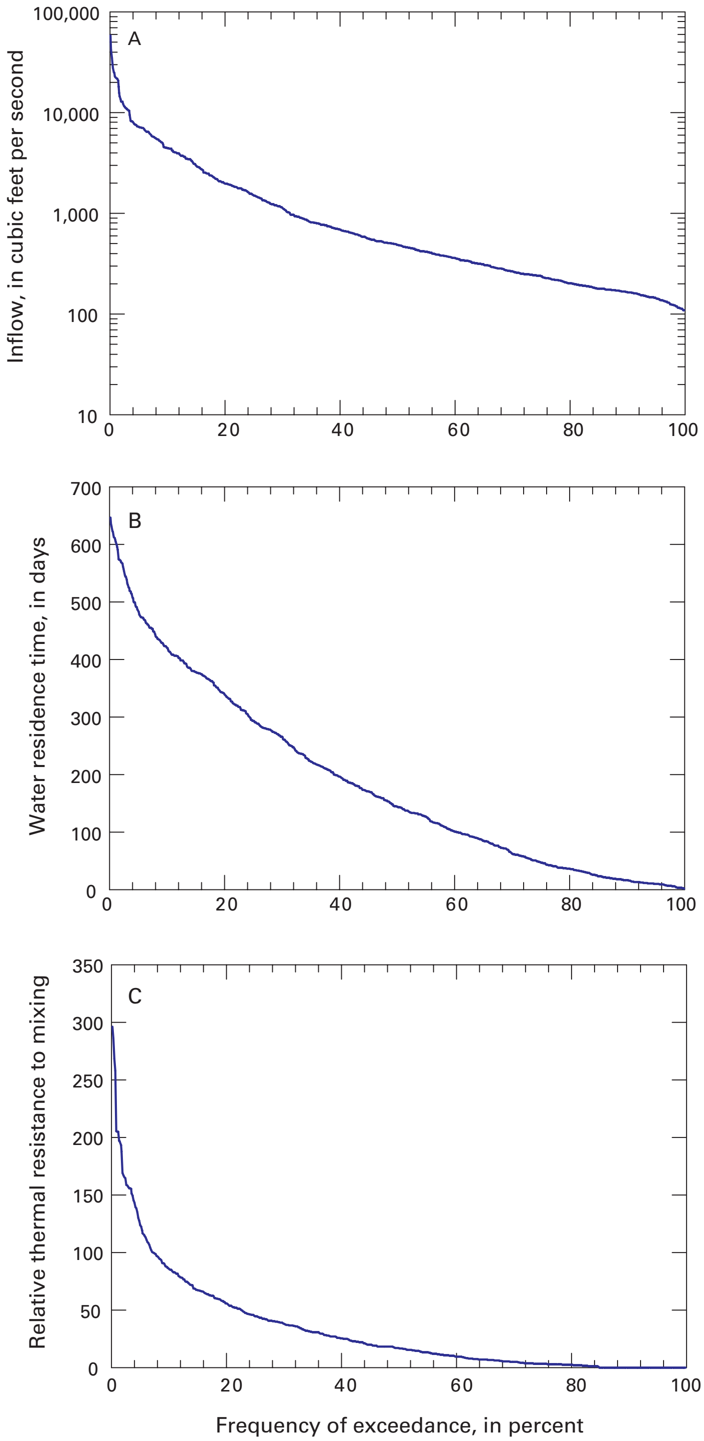

Figure 3. Duration curves for daily mean inflow (A) and water residence time (B) at Lake Houston during April 2006–September 2008 and relative thermal resistance to mixing (C) at Lake Houston Site B during October 2006–September 2008.

during the study period was relatively small (17) (table 1), indicating that Lake Houston at Site B typically is well mixed. RTRM varied by up to an order of magnitude between two consecutive days, and extended periods (greater than one week) of stable stratification did not occur at Lake Houston Site B during October 2006–September 2008. In general, the largest RTRM values occurred during summer, when heating of surface water is largest and WRTs are longest. Median RTRM in summer (44) was about 4 times larger than in nonsummer (10) (table 1), and median RTRM when WRT was greater than 100 days (20) was about 1.5 times larger than when WRT was less than 100 days (13). However, RTRM ranged from zero to greater than 200 in all seasonal and WRT classes, indicating thermal stratification at Lake Houston Site B is ephemeral and changes rapidly in response to changing hydrological and meteorological conditions. Lake Houston Site B is relatively shallow (about 16 ft) compared to the deepest locations in the reservoir (about 50 ft), and RTRM at Site B might not be representative of the entire reservoir. However, previous studies at deeper locations in Lake Houston also have found that stratification rarely occurs (Baca and others, 1982; Conrad, 1986; Sneck-Fahrer and others, 2005).

Water Quality in Lake Houston

Water-quality was evaluated using continuous (October 2006–September 2008) and discrete (April 2006–September 2008) water-quality data collected at 1-ft depth from Lake Houston Site B during April 2006–September 2008. Continuous water-quality data included specific conductance, pH, water temperature, dissolved oxygen, and turbidity. Discrete samples were analyzed for nutrients, chlorophyll, taste-and-odor causing organisms and compounds, and the cyanotoxin microcystin.

Specific Conductance

Specific conductance is an indirect measure of dissolved solids in water. The concentration of dissolved solids in water and, therefore, specific conductance is affected by watershed characteristics such as soils, geology, and watershed size, as well as point-source discharges and urban runoff (Hem, 1992). In general, dissolved solids concentrations in rainwater are small and inflow events will decrease the specific conductance of a lake or reservoir. Conversely, evaporation of water from lakes and reservoirs during periods of little inflow will concentrate dissolved solids, increasing specific conductance (Kalff, 2002).

Overall, daily mean specific conductance ranged from 66.1 to 303 microsiemens per centimeter at 25 degrees Celsius (µS/cm) and typically (80 percent of the time) exceeded 143 µS/cm (fig. 4A). Seasonal differences in specific conductance were not evident. Median specific conductance was about 1.2 times larger when WRT was greater than 100

Table 1. Summary statistics in the overall data set and during non-summer (October–May), summer (June–September), short water residence time (less than 100 days), and long water residence time (greater than or equal to 100 days) for hydrologic characteristics and water-quality constituents measured continuously (hourly) and in discrete water-quality samples at 1-foot depth at Lake Houston Site B, April 2006–September 2008.

[WRT, water residence time; <, less than; ≥, greater than or equal to; *n*, number of samples; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; FNU, formazin nephelometric units; mg/L, milligrams per liter; µg/L, micrograms per liter; ng/L, nanograms per liter; col/100 mL, colonies per 100 milliliters of sample; $\mu m^3/L$, cubic micrometers per liter; MIB, 2-methylisoborneol]

Hydrologic characteristic or water-quality constituent (unit of measure)	Season									Water Residence Time					
	All			Non-summer			Summer			WRT < 100 days			WRT ≥ 100 days		
	n	Range	Median	*n*	Range	Median	*n*	Range	Median	*n*	Range	Median	*n*	Range	Median
Hydrologic characteristics															
Reservoir inflow[1] (ft^3/s)	914	109–58,200	487	548	114–35,100	626	366	109–58,200	316	360	678–58,200	2,070	554	109–733	268
Water residence time[2] (days)	914	2–647	144	548	2–608	114	366	2–647	219	360	2–99.2	36.0	554	100–647	261
Relative thermal resistance to mixing[3]	624	0–296	17.0	442	0–205	10.0	182	0–296	44.0	313	0–205	13.0	311	0–296	20.0
Physicochemical properties															
Specific conductance, field[4] (µS/cm)	690	66.1–303	186	474	66.1–259	187	216	71.3–303	186	324	66.1–291	166	366	70.7–303	208
pH, field[4] (standard units)	661	6.5–9.7	7.7	462	6.7–9.7	7.6	199	6.5–9.6	8.2	316	6.5–9.1	7.5	345	6.8–9.7	8.1
Water temperature, field[4] (degrees Celsius)	699	7.71–32.6	22.3	481	7.71–29.4	18.6	218	24.4–32.6	29.8	325	7.71–31.3	20.3	374	10.3–32.6	24.7
Dissolved oxygen, field[4] (mg/L)	655	4.0–12	8.1	447	4.0–12	8.5	208	4.2–12	7.4	312	4.2–12	7.9	343	4.0–12	8.3
Turbidity, field[4] (FNU)	619	3.70–180	28.4	440	4.54–180	38.0	179	3.70–83.0	10.3	302	5.10–180	39.1	317	3.70–55.7	20.1
Nutrients															
Total nitrogen (mg/L)	29	.67–1.67	.95	13	.81–1.67	1.15	16	.67–1.21	.88	10	.80–1.67	.96	19	.67–1.39	.90
Total phosphorus (mg/L)	32	.07–.56	.20	14	.11–.56	.24	18	.07–.31	.19	12	.07–.56	.21	20	.11–.31	.19
Total nitrogen to total phosphorus ratio	29	2.3–7.3	5.1	13	2.3–7.3	5.5	16	2.6–7.2	4.8	10	2.3–7.2	4.5	19	2.6–7.3	5.1
Chlorophyll (µg/L)	23	5.4–61	34	10	5.4–54	16	13	10–61	34	8	8.4–61	37	15	5.4–54	33
Taste-and-Odor Causing Organisms and Compounds															
Cyanobacteria (million μm^3/mL)	33	.04–2.6	.60	15	.04–.90	.20	18	.09–2.6	1.2	14	.04–2.6	.40	19	.07–2.4	.60
Percent cyanobacteria[5]	33	3.3–54	15	15	3.3–28	9.1	18	4.1–54	23	14	3.3–41	14	19	3.5–54	15
Potential taste-and-odor producing cyanobacteria (million μm^3/mL)	33	.01–1.9	.30	15	.02–.50	.10	18	.01–1.9	.60	14	.01–1.9	.20	19	.02–1.4	.30
Percent potential taste-and-odor producing cyanobacteria[6]	33	8.9–88	49	15	23–88	45	18	8.9–78	55	14	16–88	46	19	8.9–74	49
Actinomycetes bacteria (col/mL)	26	2–1,900	65	12	43–1,900	140	14	2–160	21	11	6–1,900	160	15	2–540	43
Geosmin (ng/L)	24	<1.0–14	1.5	13	<1.0–14	1.0	11	<1.0–5.0	2.0	7	<1.0–14	2.0	17	<1.0–9.0	1.0
MIB (ng/L)	24	<1.0–22	<1.0	13	<1.0–5.0	<1.0	11	<1.0–22	<1.0	7	<1.0–22	<1.0	17	<1.0–13	<1.0
Manganese, 1-foot depth (µg/L)	28	22.0–388	51.5	14	29.0–110	56.0	14	22.0–388	50.0	10	30.0–110	55.5	18	22.0–388	50.0
Manganese, near bottom (µg/L)	31	34.0–650	90.0	14	35.0–200	81.0	17	34.0–650	100	11	50.0–170	90.0	20	34.0–650	90.0
Microcystin (µg/L)	32	<.10–.20	<.10	15	<.10–.10	<.10	17	<.10–.20	<.10	12	<.10–.10	<.10	20	<.10–.20	<.10

[1] Reservoir inflow was calculated as the sum of the daily mean streamflow from the seven major tributaries to Lake Houston for the period April 2006–September 2008.

[2] Water residence time was calculated for the period April 2006–September 2008 based on daily mean streamflow from the seven major tributaries to Lake Houston and daily mean storage for Lake Houston.

[3] Relative thermal resistance to mixing calculations are for the period October 2006–September 2008.

[4] Continuously monitored properties; summary statistics are based on daily mean values at 1-foot depth, except for pH, which is based on daily median values, for the period October 2006–September 2008.

[5] Percentage contribution of cyanobacterial biovolume to the total phytoplankton biovolume.

[6] Percentage contribution of potential taste-and-odor producing cyanobacteria biovolume to the total cyanobacterial biovolume.

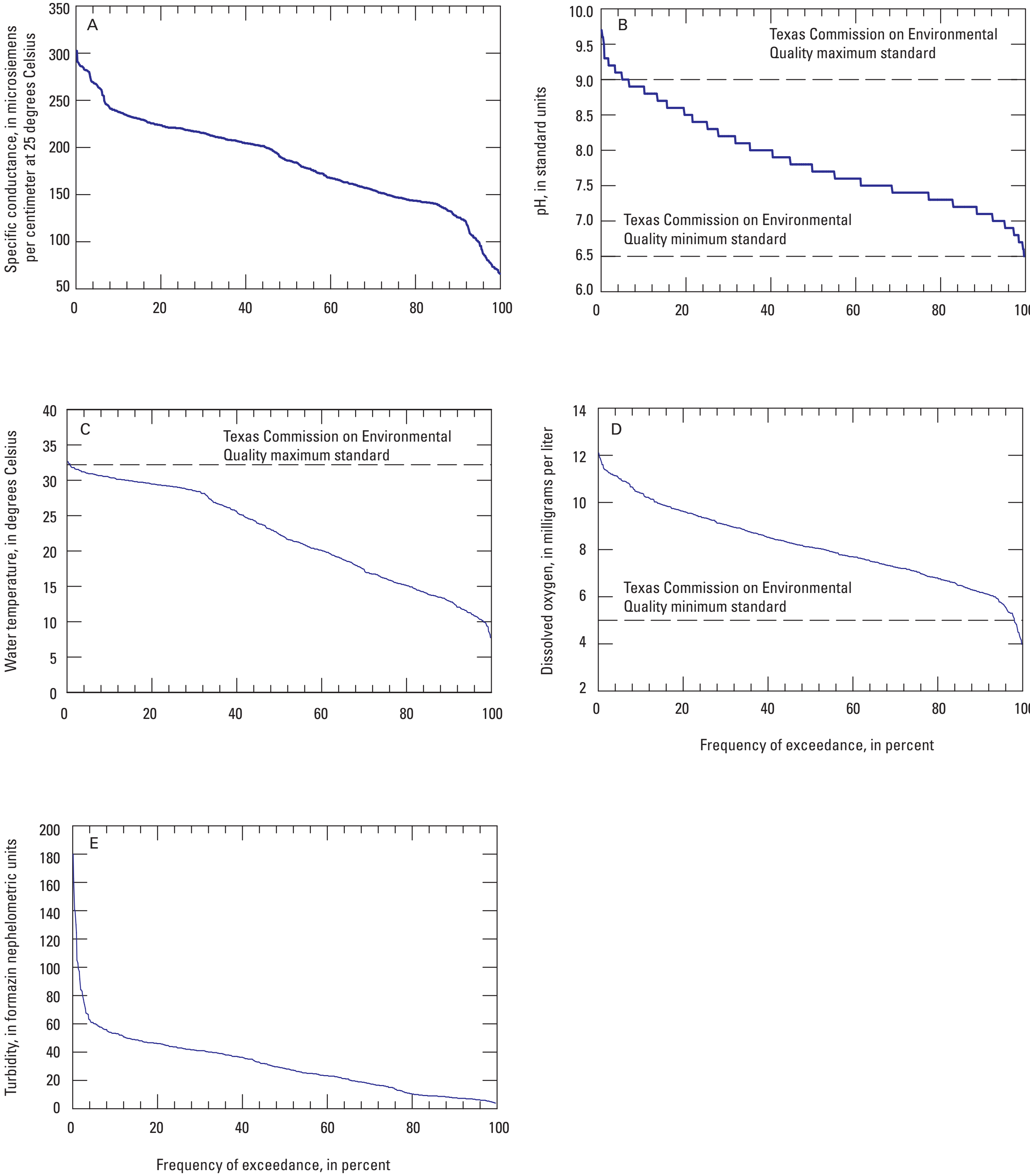

Figure 4. Duration curves for daily mean specific conductance (A), daily median pH (B), daily mean water temperature (C), daily mean dissolved oxygen concentration (D), and daily mean turbidity (E) at Lake Houston Site B during October 2006–September 2008.

days (208 µS/cm) than when WRT was less than 100 days (166 µS/cm) (table 1). In general, extended periods of high specific conductance in Lake Houston were associated with periods of low inflow and long WRTs, when evaporation leads to concentration of dissolved ions.

In-reservoir responses to inflow events vary depending on storm and rainfall characteristics such as magnitude, duration, time since last event, and antecedent watershed and tributary conditions. Many inflow events to Lake Houston initially caused a 1.1- to 1.5-fold increase in specific conductance (fig. 5), likely because the first flush washed accumulated water-quality constituents into the reservoir (Kilson, 1992). Following the first flush, specific conductance in Lake Houston typically declined. Large inflow events caused 2- to 3-fold decreases in the specific conductance of Lake Houston over relatively short periods of time (hours) (fig. 5), which presents challenges to optimizing drinking-water treatment processes. When the water quality of raw water changes rapidly, adjustments to drinking-water treatment processes must also be made quickly. For example, city of Houston water-treatment plant operators have found that rapid decreases in the specific conductance of Lake Houston water are indicative of changes in other water-quality properties, which require changing to a different type of coagulant or other adjustments (Y. Wang and T.L. Lo, City of Houston, written commun., 2011). During the study period, daily mean specific conductance was less than 75 µS/cm (near the minimum values recorded during the study period) less than 2 percent of the time (fig. 4A); specific conductance dropped below 75 µS/cm in October 2006 and September 2008 when inflows exceeded 30,000 ft^3/s (fig. 5).

Inflows to Lake Houston can be used as an indicator of changing water-quality conditions in the reservoir. Increased inflows and associated changes in specific conductance for select runoff events indicate approximately a 48- to 96-hour lead time before large inflows from the tributaries to Lake Houston result in changes in specific conductance at Lake Houston Site B near the NEWPP drinking-water plant (fig. 5). The continuous water-quality monitoring network in Lake Houston and the major tributaries to the reservoir might provide an advanced warning and allow adjustment to drinking-water treatment processes prior to substantial changes in water-quality conditions.

pH, Water Temperature, and Dissolved Oxygen

pH is a measure of the effective hydrogen ion concentration and is used as an index of the status of chemical and biological equilibrium reactions in water. The pH of natural water generally ranges from 6.5 to 8.5 standard units (Hem, 1992). Texas water-quality standards for lakes and reservoirs require that pH measure not less than 6.5 and not more than 9.0 standard units (Texas Commission on Environmental Quality, 2011b). Daily median pH ranged from 6.5 to 9.7, with an overall median of 7.7 (table 1). During the study period, daily median pH never dropped below 6.5 and exceeded 9.0 less than 5 percent of the time (fig. 4B). Exceedances likely were associated with periods of high photosynthetic activity. Median daily pH values generally were similar between seasons and WRT classes (table 1).

Water temperature affects water density, the solubility of constituents in water, specific conductance, pH, the rate

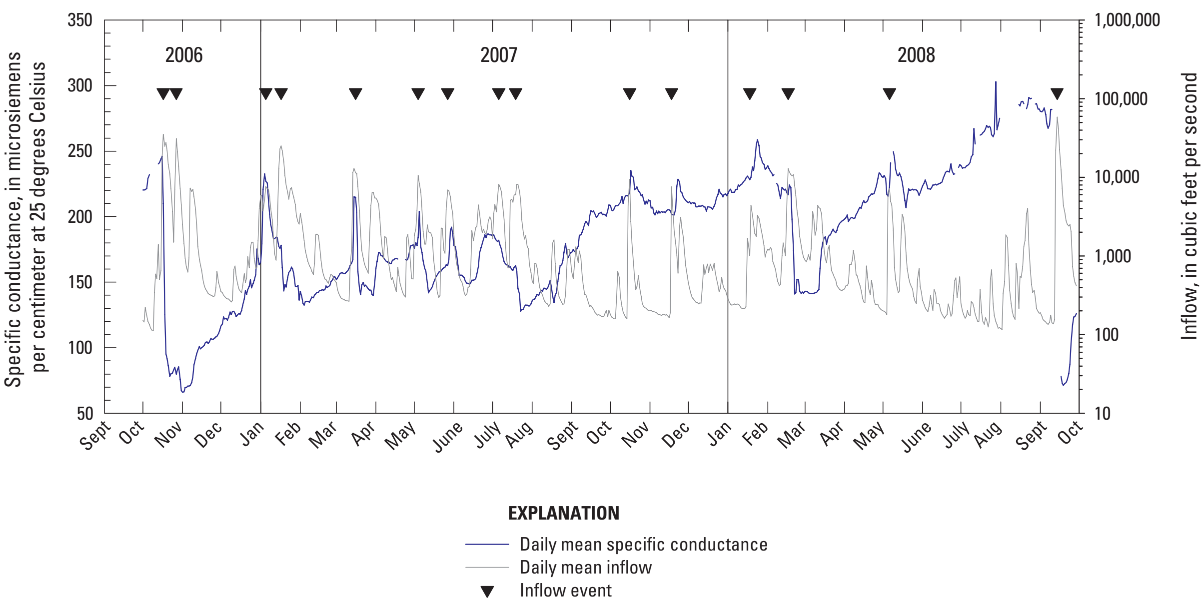

Figure 5. Daily mean specific conductance, daily mean inflow, and occurrence of inflow events resulting in substantial declines in specific conductance at Lake Houston Site B during October 2006–September 2008.

of chemical reactions, and biological activity in water (Hem, 1992). Texas water-quality standards for lakes and reservoirs require that water temperature not exceed 32.2 degrees Celsius (ºC) (Texas Commission on Environmental Quality, 2011b). Daily mean water temperature ranged from 7.71 to 32.6ºC with an overall median of 22.3ºC (table 1). During the study period, daily mean water temperature exceeded the Texas Commission on Environmental Quality (TCEQ) standard (32.2ºC) less than one percent of the time (fig. 4C). Median water temperature in summer (29.8ºC) was 11.2 degrees warmer than in non-summer (18.6ºC). When WRT was greater than 100 days, median water temperature was 4.4 degrees warmer (24.7ºC) than when WRT was less than 100 days (20.3ºC), likely because WRTs typically are longer during summer (table 1).

Dissolved oxygen concentration in surface water is controlled primarily by photosynthetic activity of phytoplankton and aquatic plants, atmospheric reaeration, and water temperature (Lewis, 2006). Dissolved oxygen concentration affects chemical reactions and the survival of aquatic organisms. Texas water-quality standards for lakes and reservoirs require that dissolved oxygen concentrations are not less than 5.0 milligrams per liter (mg/L) (Texas Commission on Environmental Quality, 2011b). Daily mean dissolved oxygen ranged from 4.0 to 12 mg/L with an overall median of 8.1 mg/L (table 1). During the study period, daily mean dissolved oxygen concentration exceeded 5.0 mg/L 98 percent of the time (fig. 4D). Small dissolved oxygen concentrations generally coincided with larger water temperatures, which cause decreased oxygen solubility in water. The medians of daily mean dissolved oxygen concentrations were generally similar between seasons and WRT classes (table 1).

Turbidity

Turbidity, caused by suspended and dissolved matter such as clay, silt, fine organic matter, microscopic organisms, organic acids, and dyes (ASTM International, 2003), is often used as a surrogate for suspended solids and sediment. Suspended solids include sediment, phytoplankton, and other organic and inorganic matter. Increased turbidity reduces light penetration and photosynthesis, smothers benthic habitats, and interferes with feeding activities. Relatively large turbidity values persisting for short periods might be less harmful to benthic invertebrates compared to relatively smaller turbidity values persisting for long periods (Wetzel, 2001). In addition, suspended particulates provide attachment sites for nutrients, organic compounds, and other potential contaminants. Suspended sediment in surface water contributes to overall turbidity and typically comes from erosion and subsequent transport of surface and channel bank soils from the watershed and in-lake resuspension of deposited sediments (Wetzel, 2001). There are no State water-quality standards for turbidity or suspended sediment in Texas lakes and reservoirs.

Daily mean turbidity ranged from 3.70 to 180 formazin nephelometric units (FNU) with an overall median of 28.4 FNU (table 1). Turbidity exceeded 10.2 FNU about 80 percent of the time during the study period (fig. 4E). Median turbidity during the non-summer (38.0 FNU) was almost 4 times larger than during summer (10.3 FNU), likely because of the larger inflows and associated transport of sediment and other suspended solids during non-summer compared to summer. Similarly, median turbidity was about 2 times larger when WRT was less than 100 days (39.1 FNU) than when WRT was longer (20.1 FNU) (table 1).

Nutrients

Nutrients, particularly nitrogen and phosphorus, are considered one of the leading causes of water-quality impairment in the Nation (U.S. Environmental Protection Agency, 2009). Nutrients are essential for the growth of all organisms; however, excessive concentrations in lakes and reservoirs can cause nuisance algal growth. Overly abundant algal growth causes aesthetic concerns, degrades habitats, and decreases dissolved oxygen concentrations (Wetzel, 2001; Kalff, 2002).

In 2000, the USEPA recommended ecoregion-based nutrient criteria for lakes and reservoirs. Lake Houston is located in level III, ecoregion 35. The USEPA defined the characteristics of water bodies least impacted by human activities (reference conditions) for each ecoregion to describe the nutrient concentrations that would protect designated uses and mitigate the effects of nutrient enrichment. Reference conditions for total nitrogen (TN) and total phosphorus (TP) for level III, ecoregion 35 lakes and reservoirs are defined as 0.492 and 0.0325 mg/L, respectively; these criteria are preliminary and not used for regulatory purposes (U.S. Environmental Protection Agency, 2000). TCEQ nutrient standards currently (2011) are being developed. Measured total nutrient concentrations at Lake Houston Site B during April 2006–September 2008 always exceeded reference conditions. TN concentrations (range 0.67 mg/L to 1.67 mg/L; median 0.95 mg/L) were about 1.4 to 3.5 times larger than the reference conditions and TP concentrations (range 0.07 mg/L to 0.56 mg/L; median 0.20 mg/L) were about 2.2 to 17 times larger than the reference conditions (table 1). Total nutrient data collected from Lake Houston during 1983–90 (Liscum and others, 1999) and 2000–04 (Sneck-Fahrer and others, 2005) show a similar pattern, with TN and TP concentrations typically exceeding reference conditions for total nutrients. Nutrient concentrations in Lake Houston are typical of those found in eutrophic to hypereutrophic lakes and reservoirs (Nürnberg, 1996).

Median total nutrient concentrations during non-summer (TN median 1.15 mg/L; TP median 0.24 mg/L) (table 1) were about 1.3 times larger than during summer (TN median 0.88 mg/L; TP median 0.19 mg/L), likely because of larger inflows and associated transport of nutrients during non-summer. Differences in total nutrient concentrations among WRT classes also might reflect the influence of larger inflows, with slightly larger median values when WRT was less than 100 days; however, seasonal differences were more pronounced than differences between WRT classes.

Nutrient supply ratios, such as TN to TP (TN:TP), reflect the relative amount of each nutrient available for algal growth. In general, TN:TP ratios larger than 17 are indicative of potential phosphorus limitation, and TN:TP ratios less than 10 are indicative of potential nitrogen limitation (Forsberg and Ryding, 1980). Many cyanobacteria have the ability to fix atmospheric nitrogen and can form nuisance blooms when nitrogen is limited (small TN:TP ratios) (Wetzel, 2001). At Lake Houston Site B, TN:TP ratios were always less than 8 (median 5.1) during the study period (table 1), indicating potential nitrogen limitation and nutrient concentrations favorable for cyanobacterial growth. However, previous studies indicate that Lake Houston is likely light-limited, rather than nutrient-limited, most of the time (Matty and others, 1987; Lee and Rast, 1997; Sneck-Fahrer and others, 2005).

Chlorophyll

Chlorophyll, a light-gathering pigment present in all photosynthetic organisms, often is used as an estimate of algal biomass because it is simpler and less time consuming than identifying, counting, and measuring algal cells. In 2000, the USEPA recommended ecoregion-based chlorophyll criteria for lakes and reservoirs. The reference condition for chlorophyll-*a* in level III, ecoregion 35 lakes and reservoirs is defined as 2.84 micrograms per liter (µg/L) (U.S. Environmental Protection Agency, 2000). This criterion was intended as a preliminary attempt to describe the chlorophyll-*a* concentrations that would protect designated uses and is not used for regulatory purposes. Chlorophyll criteria have been developed for some lakes and reservoirs in Texas but not Lake Houston (Texas Commission on Environmental Quality, 2011b).

Chlorophyll concentrations in Lake Houston during April 2006–September 2008 ranged from 5.4 to 61 µg/L (table 1), and always exceeded the reference condition; however, this result must be interpreted with caution because the reference condition is based only on chlorophyll-*a*, whereas these data represent total chlorophyll concentrations and therefore are expected to be larger compared to chlorophyll-*a* concentrations. The median total chlorophyll concentration (34 µg/L) in Lake Houston is indicative of hypereutrophic conditions (Nürnberg, 1996).

Median total chlorophyll concentration during summer (34 µg/L) was about 2 times larger than during non-summer (16 µg/L), likely because of warmer temperatures and longer day length and WRT. Total chlorophyll concentrations were similar between the WRT classes; however, they were expected to be larger during periods of longer residence time because there is more time for growth before algal cells are flushed from the system (Søballe and Kimmel, 1987; Jørgensen, 2003; Xu and others, 2009). Because water residence time can change so rapidly in Lake Houston during any time of the year (fig. 2), seasonal influences (such as temperature and longer day length) might mask the influence of WRT on chlorophyll concentration. Sample numbers are too small (range 4 to 9) to evaluate chlorophyll by both season and WRT.

Taste-and-Odor Causing Organisms and Compounds in Lake Houston

There are many potential sources of taste-and-odor in finished drinking water, including biological activity or chemical contamination of the source water, chemicals used in the treatment process, and biological activity or materials present in the distribution system. Biological activity associated with naturally occurring algae in source water is among the most common causes of tastes and odors in finished drinking water. Geosmin and MIB cause earthy and musty tastes and odors and frequently are responsible for customer complaints about objectionable drinking water because they are detectable by humans at extremely small concentrations (10 nanograms per liter, ng/L). Taste-and-odor problems are a concern to drinking-water suppliers because of customer dissatisfaction with unpalatable drinking water and increased treatment costs to remove taste-and-odor causing compounds (Taylor and others, 2005). The taste-and-odor causing organisms cyanobacteria and actinomycetes bacteria, the taste-and-odor compounds geosmin, MIB, and manganese, and the cyanotoxin microcystin were measured in discrete water-quality samples collected at Lake Houston Site B during April 2006–September 2008 (Beussink and Burnich, 2009).

Cyanobacteria

Biovolume is used to describe the cyanobacterial community in Lake Houston because it is an indicator of biomass (Hillebrand and others, 1999). Peak cyanobacterial biovolume occurred during summer, with the summer median biovolume about 6 times larger than the non-summer median biovolume (fig. 6; table 1). Likewise, cyanobacteria contributed about 2.5 times more to total phytoplankton biovolume during summer than non-summer. Larger cyanobacterial biovolume during summer likely is because of warmer temperatures and longer WRTs; during April 2006–September 2008, annual maxima in cyanobacterial biovolume occurred during July-September, when temperatures were greater than 27°C and WRTs were longer than 400 days (fig. 6). Although reservoir temperatures and WRTs during summer generally were favorable for their growth, cyanobacteria never dominated the phytoplankton community (3.3 to 54 percent of total biovolume; median 15 percent) (table 1), and cyanobacterial blooms were not observed.

Cyanobacterial taxa that form nuisance blooms, such as *Anabaena*, *Aphanizomenon*, and *Microcystis*, are relatively large and typically grow more slowly than other

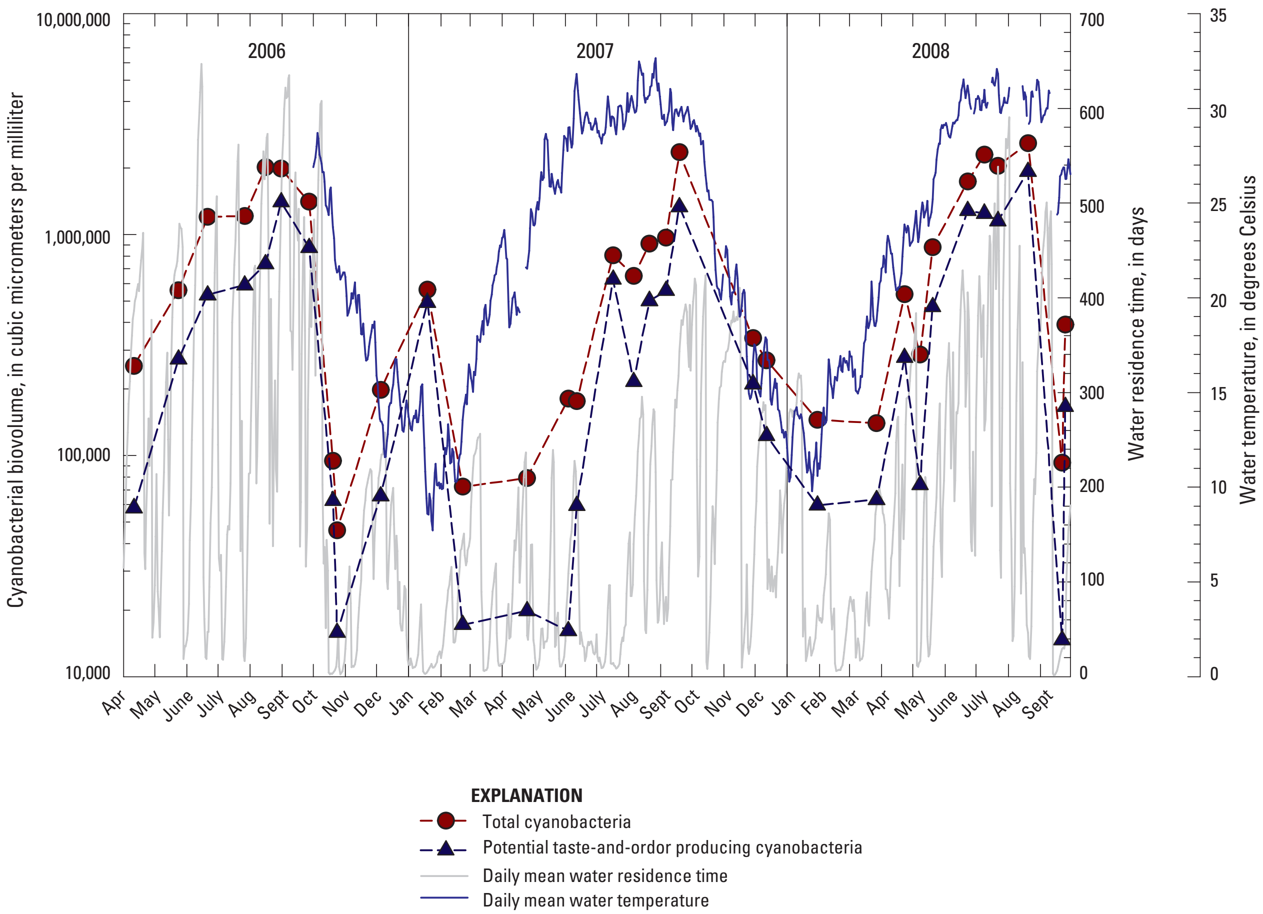

Figure 6. Total cyanobacterial biovolume, biovolume of potential taste-and-odor producing cyanobacteria, daily mean water residence time, and daily mean water temperature at Lake Houston Site B during April 2006–September 2008.

phytoplankton groups (Wetzel, 2001). Therefore, nuisance cyanobacteria require longer WRTs to become dominant and form blooms and it was expected that cyanobacterial biovolume would be larger during periods of long WRT. Large declines (7 to 30 fold) in cyanobacterial biovolume occurred in response to inflow events of more than 25,000 ft^3/s (October 2006, January 2007, September 2008) and in general, cyanobacterial biovolume was about 1.5 times larger when WRTs were greater than 100 days than when WRTs were less than 100 days (fig. 6, table 1). As discussed for chlorophyll, seasonal influences might mask the influence of WRT on cyanobacterial biovolume. For example, though sample numbers are too small for a substantive analysis, cyanobacterial biovolume was about 1.7 times larger during summer when WRT was greater than 100 days (median 1.7 million $\mu m^3/mL$; number of samples [n]=11) than during summer when WRT was less than 100 days (median 1.0 million $\mu m^3/mL$; n=7).

Of the 26 cyanobacterial genera identified in Lake Houston (Beussink and Burnich, 2009), eight are known potential taste-and-odor producers: *Anabaena* and *Aphanizomenon* (geosmin producers); *Lyngbya*, *Oscillatoria, Planktolyngbya, Pseudanabaena, Synechocococcus* (geosmin and MIB producers); and *Jaaginema* (MIB producer). Many of these genera also are potential producers of cyanotoxins including anatoxin, cylindrospermopsin, microcystin, and saxitoxin (Graham and others, 2008). Although potential taste-and-odor and toxin producing taxa can be identified, strain isolation and culture are required to conclusively determine the organisms that produce these compounds in a given lake or reservoir (Taylor and others, 2005). Potential taste-and-odor producing cyanobacteria composed 8.9 to 88 percent of the total cyanobacterial biovolume (median 49 percent) in Lake Houston. Patterns with respect to season and WRT reflected the dynamics of the overall cyanobacterial community (fig. 6; table 1).

Actinomycetes Bacteria

Actinomycetes bacteria typically are associated with terrestrial soils and sediment. Abundance of actinomycetes bacteria ranged from 2 to 1,900 colonies per milliliter (col/mL), with a median of 65 col/mL (table 1). Median abundance of actinomycetes bacteria during non-summer (140 col/mL) was about 7 times larger than during summer (21 col/mL), likely because of the larger inflows and associated transport of sediments during non-summer. Differences in actinomycetes abundance among WRT classes also reflected the influence of larger inflows; the median concentration was about 4 times larger when WRT was less than 100 days (160 col/mL) than when WRT was greater than 100 days (43 col/mL).

Geosmin and MIB

Geosmin and MIB are the taste-and-odor causing compounds most commonly produced by cyanobacteria and actinomycetes bacteria. Geosmin was detected more frequently (62 percent of samples) than MIB (29 percent of samples) at Lake Houston Site B during April 2006–September 2008. Concentrations of both compounds were relatively small (typically less than 5 ng/L) throughout the study period (table 1). Geosmin exceeded the human detection threshold of 10 ng/L once, in January 2007, during the study period, and MIB concentrations exceeded the human detection threshold on two dates in September 2007. Median geosmin concentration was 2 times larger during summer (2 ng/L) than non-summer (1 ng/L) (table 1); however, the maximum geosmin concentration occurred during non-summer. Median and maximum geosmin concentrations were largest when WRT was less than 100 days (table 1). Patterns in MIB were difficult to discern because so few samples had detectable concentrations of MIB; however, maximum concentrations occurred during summer when WRT was less than 100 days. Seasonal processes and inflow events might influence the occurrence of geosmin and MIB in Lake Houston.

Manganese

Manganese is a naturally occurring trace element that occasionally can cause taste-and-odor problems in drinking water. During periods of thermal stratification, when bottom sediments become anoxic, manganese in the bottom sediments of lakes and reservoirs can be reduced and dissolved into the water column (Hem, 1992); therefore, concentrations in near bottom samples also were evaluated as part of this study. Larger concentrations of manganese generally occurred in water samples collected near the bottom, with the median concentration (90.0 μg/L) about 1.7 times larger than the median concentration in samples collected near the surface (51.5 μg/L) (table 1). Although seasonal patterns in manganese concentration in surface samples were not evident, in bottom samples the median concentration was about 1.2 times larger during summer (100 μg/L) compared to the median concentration during non-summer (81.0 μg/L), likely because of the periodic thermal stratification and subsequent loss of oxygen near the sediment-water interface.

The USEPA secondary drinking-water regulation for manganese is 50 μg/L (U.S. Environmental Protection Agency, 2006), the concentration above which humans can typically detect manganese in water. Manganese concentrations measured at Lake Houston Site B exceeded 50 μg/L in 50 percent of water samples collected near the surface and 84 percent of water samples collected near the bottom. Thus, manganese concentrations in untreated water from Lake Houston occasionally might be large enough to cause potential taste-and-odor problems in finished drinking water.

Microcystin

Microcystins are a class of cyanobacterial hepatotoxins common in lakes and reservoirs worldwide. Exposure to microcystins can occur through drinking water; however, the largest risk of exposure to cyanotoxins is through accidental ingestion and inhalation during recreational activities (Chorus and Bartram, 1999). Microcystins currently (2011) are on the USEPA drinking-water contaminant candidate list and several States include microcystins in their freshwater beach monitoring programs (Graham and others, 2009). There currently are no regulatory standards for microcystin in the United States, but the World Health Organization (WHO) has proposed provisional guidelines for exposure to microcystin through finished drinking water (1 μg/L) and recreation (20 μg/L) (Chorus and Bartram, 1999). During the study period, microcystin was detected in 16 percent of samples. All detections were at concentrations less than or equal to 0.2 μg/L, well below the WHO guidelines (table 1).

Relations Between Hydrology, Water Quality, and Taste-and-Odor Causing Organisms and Compounds in Lake Houston

Relations between hydrology, water quality, and taste-and-odor causing organisms and compounds were developed using correlation analysis to determine the environmental conditions that favor occurrence in Lake Houston. Relations were developed using the overall data set (all samples at Site B, 1-ft depth), as well as the overall data set grouped by season (non-summer and summer), and by WRT (WRT less than 100 days and WRT greater than or equal to 100 days). Because most MIB and microcystin results were non-detections, these compounds were not included in the correlation analyses. All correlations between environmental variables and taste-and-odor causing organisms and compounds are presented in appendixes 1–3.

Chlorophyll is an indicator of algal biomass, and the relations between chlorophyll and environmental variables often are used to evaluate the potential factors influencing algal growth. Algae need nutrients and light to grow; total phosphorus, total nitrogen, and measures of the light environment (such as turbidity) frequently explain a large percentage of the variance in chlorophyll concentrations (Jones and Bachmann, 1976; Jones and others, 2008). Seasonal differences, such as warmer temperatures and longer day lengths during summer, and WRT also can have a substantial influence on algal biomass. During April 2006–September 2008, chlorophyll at Lake Houston Site B was not significantly correlated with total nutrient concentrations (all $r_s \leq 0.48$; all $p > 0.07$) regardless of season or WRT. Likewise, chlorophyll generally was not significantly correlated with turbidity during the study period. However, when WRT was less than 100 days, chlorophyll was significantly and negatively correlated with turbidity (r_s=-0.85, p<0.01, n=8), indicating both WRT and light might have a substantial influence on algal biomass in Lake Houston. Other Lake Houston studies have found similar results indicating that algal biomass is controlled primarily by washout during periods of short WRT and light during periods of longer WRT (Baca and others, 1982; Matty and others, 1987).

Cyanobacteria are a natural part of phytoplankton assemblages in lakes and reservoirs and commonly are present in at least small abundances. Cyanobacterial biomass and community composition vary seasonally as a result of changes in water temperature, solar irradiance, meteorological conditions, hydrology, and nutrient supply. In temperate climates, cyanobacteria typically dominate the phytoplankton community during mid-summer to early fall. Conditions favoring cyanobacterial blooms include warmer temperatures, elevated nutrient concentrations, small TN:TP ratios, reduced light penetration, long WRTs, and a stable water column (Reynolds, 1984; Jones and Korth, 1995; Chorus and Bartram, 1999; Wetzel, 2001).

In general, water-quality conditions at Lake Houston Site B (elevated nutrient concentrations, small TN:TP ratios, and reduced light penetration) were typical of conditions that favor cyanobacteria. However, cyanobacteria did not dominate the phytoplankton community, even during summer (table 1), which indicates other factors such as severe light limitation, might limit cyanobacterial growth. Cyanobacterial biovolume was always negatively correlated with turbidity, regardless of season or WRT (fig. 7A; table 2). However, the two largest turbidity values sampled during the study period corresponded with relatively large cyanobacterial biovolumes (fig. 7A). These samples with large turbidity values were collected during inflow events of more than 25,000 ft^3/s (October 2006 and January 2007) and might not represent the typical relation between cyanobacteria and turbidity; for example, cyanobacteria might not have been completely flushed from the system at the time of sample collection or might have been flushed to Site B from upstream locations.

Correlations between cyanobacteria and turbidity were strongest in the overall data set and when WRT was greater than 100 days (both r_s=-0.79, p<0.001, n=33). Negative correlations with turbidity indicate that cyanobacterial biovolume was larger when turbidity values were relatively small at Lake Houston Site B. Cyanobacterial biovolume also was always negatively correlated with total phosphorus and total nitrogen, though correlations were not always significant

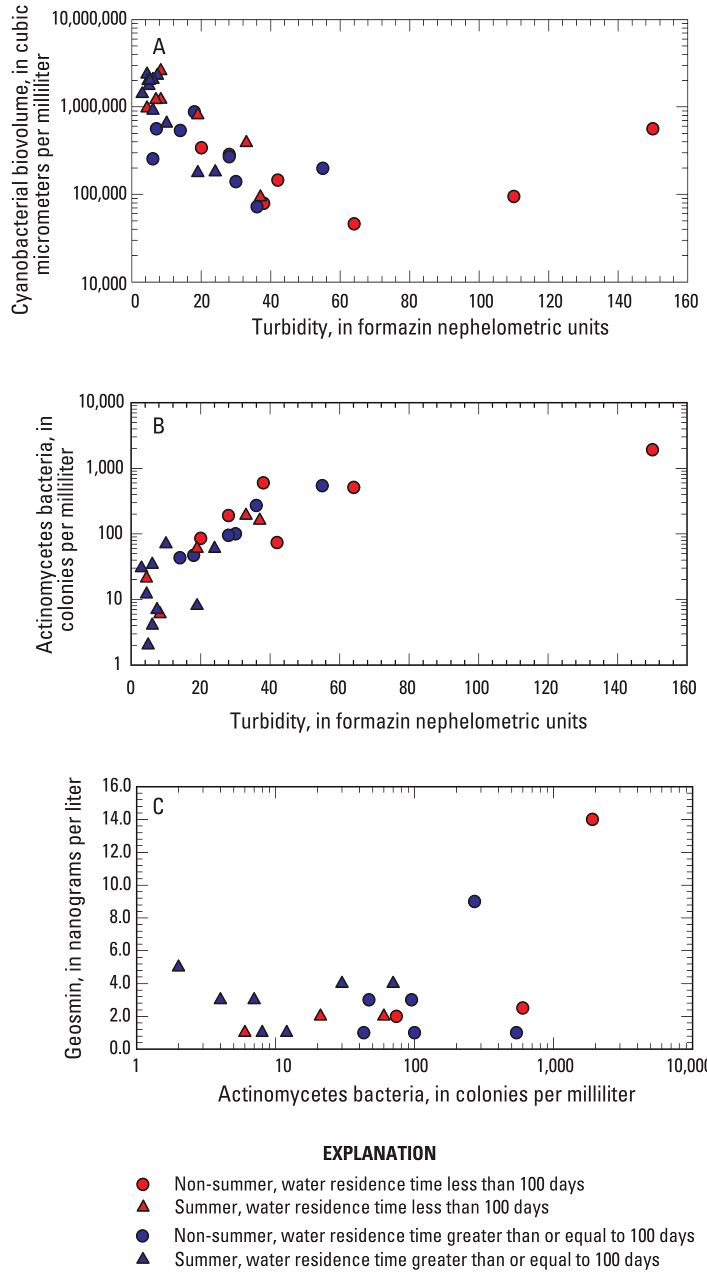

Figure 7. Relations between turbidity and cyanobacterial biovolume (A), turbidity and actinomycetes bacteria (B), and actinomycetes bacteria and geosmin (C) at Lake Houston Site B during April 2006–September 2008.

(table 2). Correlations between cyanobacterial biovolume and total nutrient concentrations typically are positive (Downing and others, 2001); the negative correlation in Lake Houston likely is indicative of light limitation. A large portion of external nutrient loads to reservoirs typically is associated with suspended particulates during inflow events (Thornton and others, 1990), a pattern reflected in the significant, positive correlations between nutrients and turbidity in Lake Houston (TP: r_s=0.66, p<0.001, n=32; TN: r_s=0.81, p< 0.001, n=29). Thus, when nutrient concentrations are large in Lake

Table 2. Spearman-rank correlations (r_s) between select environmental variables and taste-and-odor causing organisms and compounds at 1-foot depth at Lake Houston Site B in the overall dataset and during non-summer (October–May), summer (June–September), short water residence time (less than 100 days), and long water residence time (greater than or equal to 100 days), April 2006–September 2008.

[Spearman-rank correlation coefficients (r_s) shown in bold are significant at *p*-value less than 0.05; yellow highlight indicates values significant at *p*-value less than 0.001; gray shading indicates the location in the matrix where the variable is correlated with itself (r_s=1.0); <, less than; ≥, greater than or equal to]

Environmental variables	Taste-and-odor causing organisms and compounds		
	Cyanobacteria	Actinomycetes bacteria	Geosmin
All data			
Water residence time	**0.40**	**-0.59**	-0.17
Relative thermal resistance to mixing	-.09	-.21	-.06
Turbidity	**-.79**	**.88**	.08
Total nitrogen	-.63	**.71**	.03
Total phosphorus	**-.51**	**.68**	.19
Geosmin	.09	.13	
Non-summer			
Water residence time	.19	-.36	**-.59**
Relative thermal resistance to mixing	.07	-.17	.07
Turbidity	-.48	**.80**	.38
Total nitrogen	-.37	.32	.36
Total phosphorus	-.19	.63	.38
Geosmin	.10	.36	
Summer			
Water residence time	**.51**	**-.66**	.25
Relative thermal resistance to mixing	-.52	.00	-.17
Turbidity	**-.64**	**.58**	-.14
Total nitrogen	-.33	.23	-.38
Total phosphorus	-.22	.12	-.11
Geosmin	-.23	-.01	
Water residence time < 100 days			
Water residence time	.16	-.51	-.04
Relative thermal resistance to mixing	-.21	-.10	-.34
Turbidity	**-.74**	**.81**	.34
Total nitrogen	-.61	.50	.43
Total phosphorus	**-.64**	**.78**	.41
Geosmin	-.32	**.94**	
Water residence time ≥ 100 days			
Water residence time	**.58**	**-.62**	-.26
Relative thermal resistance to mixing	-.30	-.11	.21
Turbidity	**-.79**	**.80**	-.01
Total nitrogen	-.63	**.74**	-.07
Total phosphorus	-.32	.46	.09
Geosmin	.14	-.11	

Houston, turbidity also is large and likely limits algal growth. Cyanobacterial biovolume was always positively correlated with WRT; the strongest correlations were during summer (r_s=0.51, p=0.03, n=18 and when WRTs were already greater than 100 days (r_s=0.58, p<0.01, n=19), indicating periodic inflow events might be important in controlling cyanobacterial biovolume during times when it would likely dominate otherwise.

Another factor potentially limiting cyanobacterial growth and bloom formation in Lake Houston is the well-mixed water column (small RTRM). Dense cyanobacterial blooms occur most often during extended periods of long WRT and stable stratification (large RTRM) (Reynolds, 1984; Jones and Korth, 1995; Chorus and Bartram, 1999; Wetzel, 2001). Cyanobacterial biovolume was not significantly correlated with RTRM in Lake Houston (table 2), likely because RTRM varied on a daily basis and Lake Houston Site B did not stably stratify for extended periods of time during the study period.

The abundance of actinomycetes bacteria was always significantly and positively correlated with turbidity and negatively related to WRTs in Lake Houston (fig. 7B, table 2), reflecting the tendency of these organisms to be associated with large suspended-sediment loads during inflow events (Zaitlin and others, 2003; Zaitlin and Watson, 2006). The correlation between actinomycetes bacteria and turbidity was strongest in the overall data set (r_s=0.88, p<0.001, n=26) and weakest (r_s=0.58, p=0.03, n=14) during summer, when WRTs typically are longer. However, the abundance of actinomycetes bacteria was most strongly correlated with WRT during summer (r_s=-0.66, p, p=0.01, n=14), indicating inflows likely are still influencing actinomycetes abundance. These correlations indicate that actinomycetes-related taste-and-odor events in Lake Houston are most likely to occur during runoff events or wind events that resuspended reservoir bottom sediments.

Most taste-and-odor problems associated with geosmin and MIB are caused by cyanobacteria (Taylor and others, 2005), but relations between water-quality conditions, such as nutrients and light, and cyanobacterial biovolume (biomass), community composition, and production of nuisance compounds are complex (Graham and others, 2004; Christensen and others, 2006; Dzialowski and others, 2009), and further complicated by extreme hydrologic variability (Vanni and others, 2006). In the overall data set, geosmin was not significantly correlated with any measured variables, including cyanobacterial biovolume (table 2; appendix 1). Correlations with the biovolume of only those cyanobacteria that can produce taste-and-odor causing compounds and individual cyanobacterial taxa also were not significant (all p>0.05).

Geosmin and MIB also can be produced by actinomycetes bacteria, though they are less frequently linked to taste-and-odor problems and are not as well studied as the cyanobacteria (Zaitlin and others, 2003; Taylor and others, 2005; Zaitlin and others, 2006). Noteworthy was the strong, positive correlation between actinomycetes bacteria and geosmin when water residence time was less than 100 days (r_s=0.94, p=0.005, n=6) (fig. 7C, table 2). This result indicates that actinomycetes bacteria might occasionally be linked to taste-and-odor problems in Lake Houston. However, this result must be interpreted with caution because the number of samples in this analysis (n=6) was small. Water residence time was the only other variable significantly correlated with geosmin. The negative correlation between geosmin and WRT during non-summer (r_s=-0.59, p=0.03, n=13) indicates geosmin concentrations are larger during periods of shorter WRT. The correlation between geosmin and WRT might reflect the greater abundance of actinomycetes bacteria during periods of shorter WRT, though the correlation between actinomycetes bacteria and geosmin was not significant in non-summer (table 2).

Manganese concentrations can occasionally be large enough to cause taste-and-odor problems in Lake Houston, especially during periods when stratification and subsequent loss of oxygen near the sediment-water interface results in release of manganese from the sediments. However, manganese was weakly, and negatively, correlated with RTRM (stratification) (r_s=-0.49, p=0.03, n=19), indicating manganese concentrations decreased as the strength of stratification increased. The negative correlation might reflect a decrease in manganese concentration near the surface because of algal uptake or sedimentation losses. Because manganese concentrations typically were larger near the bottom, the correlation with RTRM also was evaluated using bottom data; the correlation was similar to 1-ft depth, though not statistically significant (r_s=-0.49, p=0.08, n=20).

The hydrology of Lake Houston is characterized by rapidly changing conditions. During inflow events WRT can change by orders of magnitude within a matter of hours. Likewise, the reservoir can stratify and destratify over a period of several hours, even during non-summer and at relatively short WRTs, given extended periods with warm temperatures and little wind. The rapidly changing hydrology likely influences all other aspects of water quality, including the occurrence of taste-and-odor causing organisms and compounds, in Lake Houston.

The abundance of the taste-and-odor causing organisms cyanobacteria and actinomycetes bacteria in Lake Houston were coupled with inflow events and subsequent changes in water-quality conditions. Cyanobacterial biovolume was largest during warm periods with little inflow and relatively small turbidity values. In contrast, actinomycetes bacteria were most abundant following inflow events when turbidity values were relatively large. Because severe taste-and-odor problems were not observed during the study period, quantification of the hydrologic and water-quality conditions associated with large concentrations of taste-and-odor causing compounds and development of predictive models were not possible. Reservoir inflow (WRT) and turbidity, variables related to the abundance of potential taste-and-odor causing organisms, are currently (2011) continuously measured in Lake Houston, and predictive models could be developed in the future when the hydrologic and water-quality conditions associated with taste-and-odor problems have been better quantified. Seasonal and WRT influences on water-quality conditions altered the relations between hydrologic and water-quality conditions and taste-and-odor causing organisms and compounds. Future data collection and development of predictive models need to account for the variability associated with season and WRT.

Summary

Lake Houston is a surface-water-supply reservoir and an important recreational resource for the city of Houston, Texas. Growing concerns over water quality in Lake Houston prompted a detailed assessment of water quality in the reservoir. The assessment focused on water-quality constituents that affect the aesthetic quality of drinking water. Beginning in 2006, a real-time water-quality-monitoring network was established on Lake Houston to supplement existing real-time water-quality monitors on the major tributaries. Discrete water-quality samples also were collected and analyzed for nutrients, potential taste-and-odor causing organisms and compounds, and other water-quality constituents. The purpose of this report is to describe the hydrologic and water-quality conditions influencing the occurrence of taste-and-odor causing organisms and compounds from April 1, 2006, through September 30, 2008, at Lake Houston Site B, located in proximity to the Northeast Water Purification Plant. This report includes: (1) description of the hydrology of Lake Houston with respect to inflow, water residence time, and thermal stratification; (2) description of the water-quality conditions in Lake Houston, including taste-and-odor causing organisms and compounds; and (3) assessment of the relations between hydrologic and water-quality conditions and taste-and-odor causing organisms and compounds in Lake Houston. This information improves the understanding of the hydrologic and water-quality conditions that favor the occurrence of taste-and-odor causing organisms and compounds in Lake Houston.

Streamflow data from gages on seven tributaries to Lake Houston and reservoir storage data were used to describe reservoir inflows and water residence time during April 2006–September 2008. A continuous water-quality monitor was operated at Lake Houston Site B during October 2006–September 2008 and measured physicochemical water-quality properties, including specific conductance, pH, water temperature, turbidity, and dissolved oxygen at 1, 6, 12, and 16 feet below the water surface. Relative thermal resistance to mixing, a measure of the stability of thermal stratification in the water column, was calculated for the period October 2006–September 2008 using the continuous water-temperature profile data from the 1500 hour (3:00 p.m. local time). Discrete water-quality samples were collected at about 1 foot below the water surface, at the midpoint depth of the water column, and at about 1 foot above the bottom during April 2006–September 2008 and analyzed for physicochemical properties, nutrients, chlorophyll, the taste-and-odor causing organisms cyanobacteria and actinomycetes bacteria, the taste-and-odor causing compounds geosmin, 2-methylisoborneol (MIB), and manganese, and the cyanotoxin microcystin. Water quality was evaluated using data collected from only the 1-foot depth because Lake Houston Site B typically did not thermally stratify, and gradients in water-quality conditions generally were small.

Inflows to Lake Houston were about 2 times less during summer (June–September) than non-summer (October–May), though storm events punctuated the hydrograph during both seasons. Water residence time was about 2 times longer during summer, when inflows were smaller, than in non-summer, indicating in-reservoir processes likely influenced water quality more during summer than non-summer. Thermal stratification at Lake Houston Site B occurred more frequently during summer than non-summer, but stratification was ephemeral and changed rapidly in response to changing hydrological and meteorological conditions.

Large inflow events can cause substantial changes in water-quality conditions, such as specific conductance, over relatively short periods of time (hours). There was approximately a 48- to 96-hour lead time before large inflow events detected in the tributaries resulted in changes in water-quality conditions at Lake Houston Site B. The continuous water-quality monitoring network in Lake Houston and the major tributaries to the reservoir might provide an advanced warning and allow adjustment to drinking-water treatment processes prior to substantial changes in water-quality conditions.

Water quality at Lake Houston Site B varied with respect to season and water residence time but typically was indicative of turbid, eutrophic to hypertrophic conditions. Total nitrogen to total phosphorus ratios were always less than 8 during the study period, indicating potential nitrogen limitation and nutrient conditions favorable for cyanobacterial growth. In general, turbidity and nutrient concentrations were largest during non-summer, and when water residence times were relatively short (less than 100 days), reflecting the influence of inflow events on water-quality conditions. Chlorophyll concentrations, an indicator of algal biomass, were about 2 times larger during summer than non-summer, likely because of warmer temperatures and longer day lengths and water residence times.

Cyanobacteria and actinomycetes bacteria were always present at Lake Houston Site B. Cyanobacterial biovolume (biomass) was about 6 times larger during summer than non-summer and 1.5 times larger when water residence time was greater than 100 days than when water residence time was less than 100 days. Annual maxima in cyanobacterial biovolume occurred during July-September each year, when temperatures were larger than 27 degrees Celsius and water residence times were longer than 400 days. In contrast, actinomycetes bacteria were about 7 times more abundant during non-summer than summer, and 4 times more abundant when water residence times were relatively short (less than 100 days), reflecting the close association between these organisms and transport of suspended sediments by large inflows.

Geosmin and MIB are the taste-and-odor causing compounds most commonly produced by cyanobacteria and actinomycetes bacteria. Geosmin was detected more frequently (62 percent of samples) than MIB (29 percent of samples) at

Lake Houston Site B. Geosmin exceeded the human detection threshold (10 nanograms per liter) only once during the study period and MIB exceeded the human detection threshold twice. Manganese is a naturally occurring trace element that can occasionally cause taste-and-odor problems in drinking water. Because manganese in bottom sediments of lakes and reservoirs can be reduced and dissolved into the water column during periods of thermal stratification when bottom sediments become anoxic, manganese concentrations in bottom samples also were evaluated as part of this study. Manganese concentrations exceeded the human detection threshold (about 50 micrograms per liter) in about 50 percent of samples collected near the surface and 84 percent of samples collected near the bottom. The cyanotoxin microcystin was detected relatively infrequently (16 percent of samples) and at small concentrations (less than or equal to 0.2 micrograms per liter).

Cyanobacterial biovolume in Lake Houston was always negatively correlated with turbidity and total nutrient concentrations, relations likely indicative of light limitation of cyanobacterial growth. Cyanobacterial biovolume was always positively correlated with water residence time, but correlations were strongest during summer and when water residence times were already greater than 100 days, indicating periodic inflow events might be important in controlling cyanobacterial biomass during times when it would likely dominate otherwise. The abundance of actinomycetes bacteria was always significantly and positively correlated with turbidity and negatively related to water residence times, reflecting the tendency of these organisms to be associated with large suspended-sediment loads during inflow events. In the overall data set, geosmin was not significantly correlated with any measured variables at Lake Houston Site B. There was a strong, positive correlation between actinomycetes bacteria and geosmin when water residence time was less than 100 days; however, this result must be interpreted with caution because the number of samples in this analysis was small.

The abundance of the taste-and-odor causing organisms cyanobacteria and actinomycetes bacteria in Lake Houston was coupled with inflow events and subsequent changes in water-quality conditions. Cyanobacterial biovolume (biomass) was largest during warm periods with little inflow and relatively small turbidity. In contrast, actinomycetes bacteria were most abundant following inflow events when turbidity was relatively large. However, severe taste-and-odor problems were not observed during the study period, precluding quantification of the hydrologic and water-quality conditions associated with large concentrations of taste-and-odor causing compounds and development of predictive models. Reservoir inflow (water residence time) and turbidity, variables related to the abundance of potential taste-and-odor causing organisms, are currently (2011) continuously measured in Lake Houston. Predictive models could be developed in the future when the hydrologic and water-quality conditions associated with taste-and-odor problems have been better quantified. Seasonal and water residence time influences on water-quality conditions altered relations between hydrologic and water-quality conditions and taste-and-odor causing organisms and compounds. Future data collection and development of predictive models need to account for the variability associated with season and water residence time.

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Appendixes

Appendix 1. Spearman-rank correlations (r_s) between environmental variables and taste-and-odor causing organisms and compounds at 1-foot depth at Lake Houston Site B in the overall dataset, April 2006–September 2008.

[Spearman-rank correlation coefficients (r_s) shown in bold are significant at *p*-value less than 0.05; *n*, number of samples; yellow highlight indicates values significant at *p*-value less than 0.001; gray shading indicates the location in the matrix where the variable is correlated with itself (r_s=1.0); --, value presented in upper part of the matrix]

Hydrologic characteristic or water-quality constituent	Taste-and-odor causing organisms and compounds							
	Cyanobacteria		Actinomycetes bacteria		Geosmin		Manganese	
	r_s	*n*	r_s	*n*	r_s	*n*	r_s	*n*
Water residence time	**0.40**	33	**-0.59**	26	-0.17	24	0.18	28
Relative thermal resistance to mixing	-.09	23	-.21	22	-.06	16	**-.49**	19
Specific conductance	**.51**	33	**-.63**	26	-.15	24	**.52**	28
pH	**.58**	33	**-.82**	26	-.16	24	.09	28
Water temperature	**.61**	33	**-.76**	26	-.04	24	.05	28
Dissolved oxygen	-.05	32	-.13	25	-.01	23	-.16	27
Turbidity	**-.79**	33	**.88**	26	.08	24	-.21	28
Total nitrogen	**-.63**	27	**.71**	22	.03	24	-.26	27
Total phosphorus	**-.51**	30	**.68**	23	.19	24	-.36	28
Chlorophyll	.23	22	-.28	22	**-.55**	18	-.12	21
Cyanobacteria			**-.75**	26	.09	23	**.43**	27
Actinomycetes bacteria	--	--			.13	19	-.35	22
Geosmin	--	--	--	--			-.12	24
Manganese	--	--	--	--	--	--		

Appendix 2. Spearman-rank correlations (r_s) between environmental variables and taste-and-odor causing organisms and compounds at 1-foot depth at Lake Houston Site B during non-summer (October–May) and summer (June–September), April 2006–September 2008.

[Spearman-rank correlation coefficients (r_s) shown in bold are significant at *p*-value less than 0.05; *n*, number of samples; yellow highlight indicates values significant at *p*-value less than 0.001; gray shading indicates the location in the matrix where the variable is correlated with itself (r_s=1.0); --, value presented in upper part of the matrix]

Hydrologic characteristic or water-quality constituent	Taste-and-odor causing organisms and compounds							
	Cyanobacteria		Actinomycetes bacteria		Geosmin		Manganese	
	r_s	n	r_s	n	r_s	n	r_s	n
Non-summer								
Water residence time	0.19	15	-0.36	12	**-0.59**	13	0.27	14
Relative thermal resistance to mixing	.07	12	-.17	11	.07	9	-.55	10
Specific conductance	**.55**	15	**-.74**	12	-.27	13	.31	14
pH	**.64**	15	**-.86**	12	-.19	13	.19	14
Water temperature	.24	15	-.35	12	-.42	13	.34	14
Dissolved oxygen	.28	14	**-.67**	11	.28	12	-.17	13
Turbidity	-.48	15	**.80**	12	.38	13	-.18	14
Total nitrogen	-.37	12	.32	9	.36	13	**-.56**	13
Total phosphorus	-.19	13	.63	10	.38	13	-.34	14
Chlorophyll	.07	10	-.36	10	-.49	9	.01	10
Cyanobacteria			-.40	12	.10	12	.46	13
Actinomycetes bacteria	--	--			.36	9	-.09	10
Geosmin	--	--	--	--			-.45	13
Manganese	--	--	--	--	--	--		
Summer								
Water residence time	**.51**	18	**-.66**	14	.25	11	.16	14
Relative thermal resistance to mixing	-.52	11	.00	11	-.17	7	-.47	9
Specific conductance	**.86**	18	**-.86**	14	.08	11	**.71**	14
pH	.43	18	**-.69**	14	-.28	11	.05	14
Water temperature	.17	18	-.53	14	-.06	11	.14	14
Dissolved oxygen	.09	18	-.45	14	-.07	11	-.16	14
Turbidity	**-.64**	18	**.58**	14	-.14	11	-.31	14
Total nitrogen	-.33	15	.23	13	-.38	11	-.34	14
Total phosphorus	-.22	17	.12	13	-.11	11	-.37	14
Chlorophyll	.08	12	.12	12	**-.69**	9	-.15	11
Cyanobacteria			**-.72**	14	-.23	11	**.66**	14
Actinomycetes bacteria	--	--			-.01	10	**-.73**	12
Geosmin	--	--	--	--			.29	11
Manganese	--	--	--	--	--	--		

Appendix 3. Spearman-rank correlations (r_s) between select environmental variables and taste-and-odor causing organisms and compounds at 1-foot depth at Lake Houston Site B during short water residence times (less than 100 days), and long water residence times (greater than or equal to 100 days), April 2006–September 2008.

[Spearman-rank correlation coefficients (r_s) shown in bold are significant at *p*-value less than 0.05; *n*, number of samples; yellow highlight indicates values significant at *p*-value less than 0.001; gray shading indicates the location in the matrix where the variable is correlated with itself (r_s=1.0); --, value presented in upper part of the matrix]

Hydrologic characteristic or water-quality constituent	Taste-and-odor causing organisms and compounds							
	Cyanobacteria		Actinomycetes bacteria		Geosmin		Manganese	
	r_s	*n*	r_s	*n*	r_s	*n*	r_s	*n*
Water residence time < 100 days								
Water residence time	0.16	14	-0.51	11	-0.04	7	-0.50	9
Relative thermal resistance to mixing	-.21	12	-.10	11	-.34	7	-.53	10
Specific conductance	**.56**	14	-.50	11	-.22	7	.18	10
pH	**.57**	14	-.60	11	-.11	7	-.07	10
Water temperature	**.60**	14	**-.62**	11	-.51	7	.07	10
Dissolved oxygen	.14	13	-.21	10	.68	6	-.35	9
Turbidity	**-.74**	14	**.81**	11	.34	7	.08	10
Total nitrogen	-.61	9	.50	7	.43	7	-.20	9
Total phosphorus	**-.64**	11	**.78**	8	.41	7	-.14	10
Chlorophyll	.67	8	**-.88**	8	-.70	6	.19	8
Cyanobacteria			-.61	11	-.32	7	.58	10
Actinomycetes bacteria	--	--			**.94**	6	-.36	8
Geosmin	--	--	--	--			-.37	7
Manganese	--	--	--	--	--	--		
Water residence time ≥ 100 days								
Water residence time	**.58**	19	**-.62**	15	-.26	17	**.57**	18
Relative thermal resistance to mixing	-.30	11	-.11	11	.21	9	-.43	10
Specific conductance	.43	19	**-.70**	15	-.08	17	**.69**	18
pH	**.54**	19	**-.83**	15	-.16	17	.11	18
Water temperature	**.53**	19	**-.83**	15	.09	17	.06	18
Dissolved oxygen	-.38	19	.06	15	-.17	17	-.20	18
Turbidity	**-.79**	19	**.80**	15	-.01	17	-.30	18
Total nitrogen	**-.63**	18	**.74**	15	-.07	17	-.36	18
Total phosphorus	-.32	19	.46	15	.09	17	-.45	18
Chlorophyll	.02	14	.00	15	-.51	12	-.35	13
Cyanobacteria			**-.73**	15	.14	16	.36	17
Actinomycetes bacteria	--	--			-.11	13	-.38	14
Geosmin	--	--	--	--			-.17	17
Manganese	--	--	--	--	--	--		

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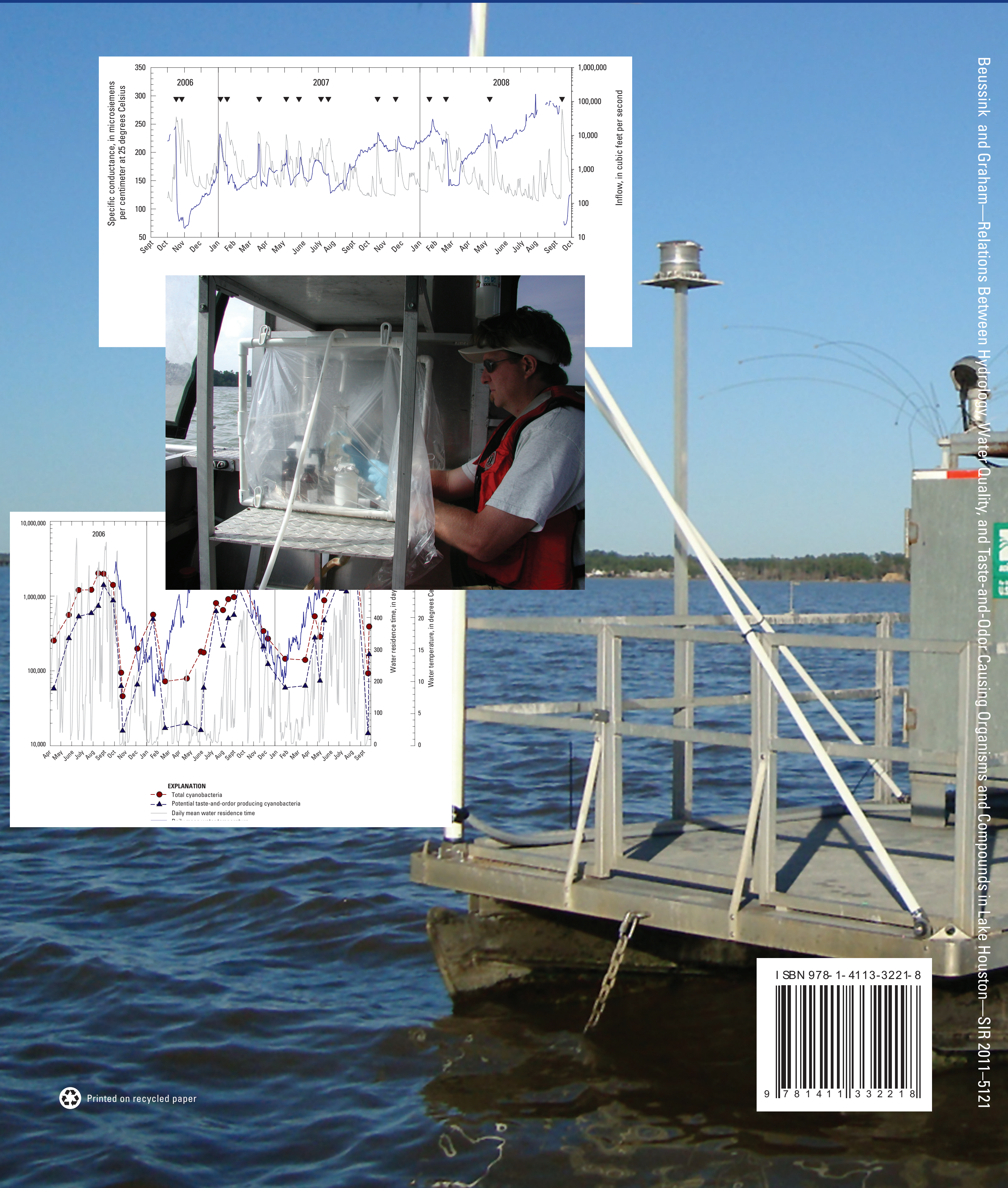

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