Introduction

The U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency, conducted a time-of-travel study in the Buffalo Bayou watershed during low flow in August 1999. The study was done as part of the U.S. Environmental Protection Agency Environmental Monitoring for Public Access and Community Tracking (EMPACT) program. The EMPACT program was designed for the U.S. Environmental Protection Agency to work with communities to "make timely, accurate, and understandable environmental information available to millions of people in the largest metropolitan areas across the country." (U.S. Environmental Protection Agency, 2000).

Buffalo Bayou, located in Houston, Texas, was chosen as a pilot project because it is a frequently used recreational water source, it has many water-treatment facilities located along its stream segments, and it has a history of water-quality problems (Houston-Galveston Area Council, 2000). One component of the pilot project is to develop a water-quality simulation model that can be used to assess the effects of noncompliance events on Buffalo Bayou. Because accurate estimates of time of travel during low flow are required to develop the model, the time of travel of solutes in Buffalo Bayou and selected tributaries was determined using dye tracing methods.

The study was conducted during low flow in a 38.7-mile reach of Buffalo Bayou, a 9.6-mile reach of Whiteoak Bayou, a 5.9-mile reach of Mason Creek, and a 6.6-mile reach of Bear Creek. Efforts to determine the time of travel in a 7.5-mile reach of Horsepen Creek were unsuccessful. This report explains the approach used to conduct the study and presents the results of the study.

Study Area

The study area, about 45 miles north of the Gulf of Mexico, is located in the Houston metropolitan area of southeast Texas. The major stream draining the area is Buffalo Bayou. Buffalo Bayou is regulated by Barker and Addicks Reservoirs (Liscum, Brown, and Kasmarek, 1997, p. 2). These flood-detention reservoirs are located about 16 miles west of downtown Houston and provide flood protection for the Houston metropolitan area. "Both dams have controlled release structures, which allow the Corps of Engineers to drastically reduce flooding along Buffalo Bayou between the reservoirs and the Houston Ship Channel." (Liscum, Goss, and Paul, 1987, p. 3). The dam at Barker Reservoir is about 72,900 feet long and 37 feet high. Barker Reservoir has a capacity of 209,000 acre-feet and a surface area of 16,700 acres at a water-surface altitude of 106.0 feet above sea level (Liscum, Goss, and Paul, 1987, p. 3). The dam at Addicks Reservoir is about 61,200 feet long and 49 feet high. Addicks Reservoir has a capacity of 212,500 acre-feet and a surface area of about 17,000 acres at a water-surface altitude of 112.0 feet above sea level (Liscum, Goss, and Paul, 1987, p. 5)

Because both reservoirs are used exclusively for flood detention, the release gates remain open during periods of low flow. Water is not stored in the reservoirs except when the gates are closed during periods of high flow. Any water retained during high flows is gradually released following a storm.

Approach

Dye tracing is a technique frequently used to estimate the time of travel in streams. For this procedure, a known amount of dye is released into the stream at a site, and the dye cloud is measured downstream at sites of interest (Kilpatrick and Wilson, 1989). Fluorescent rhodamine-WT dye often is used because it has a low sorptive tendency and in solution has a specific gravity that is nearly equal to freshwater. Therefore, the time-of-travel characteristics of the dye are expected to be similar to those of most soluble contaminants in freshwater. A 20-percent concentration rhodamine-WT dye was used for this study.

The field procedure is as follows. A known amount of rhodamine-WT dye is released at an upstream site, and water samples are collected downstream at regularly spaced time intervals. The concentration of dye in each of these samples is measured with a fluorometer (Wilson and others, 1986). Once the dye cloud has passed a specified site, the field personnel move to the next downstream site and collect samples. Time-concentration curves developed from the sample data are used to estimate the time it takes for the leading edge, peak, centroid, and trailing edge of the dye cloud to reach a specific site. The leading edge is the initial concentration of dye detected. The peak is the maximum dye concentration. The centroid, which typically occurs after the peak, is the concentration when 50 percent of the dye has passed the sampling location. For this study, the trailing edge is defined as a dye concentration of 0.2 microgram per liter.

Daily mean streamflows for each stream segment were determined either from nearby USGS streamflow-gaging stations or from actual measurements made in sampling reaches where established streamflow-gaging stations did not exist. The mean velocity in each subreach was computed by dividing the downstream distance to the next site (using USGS 7.5-minute quadrangle topographic maps) by the time of travel from the previous site.

Acknowledgments

The USGS gratefully acknowledges the support of the U.S. Environmental Protection Agency—in particular, the participation of Trish McKenzie was instrumental in the success of the study. Jim Collins, of Tetra Tech, Inc., provided assistance in site selection during the planning stages of the study. The U.S. Army Corps of Engineers, Galveston District, provided access to property during the data-collection phase of the study.

Time of Travel of Solutes

Time of travel of solutes was measured during low flow in August 1999 using dye tracing in six segments in a 38.7-mile reach of Buffalo Bayou, in a 9.6-mile reach of Whiteoak Bayou, in a 5.9-mile reach of Mason Creek, and in a 6.6-mile reach of Bear Creek. The time-of-travel results are listed in the table. A map of the study area shows the locations of release and sampling sites in Buffalo Bayou and selected tributaries, as well as the locations of nearby USGS streamflow-gaging stations. Graphs show the time-concentration curves for each stream segment.

Buffalo Bayou was divided into two overlapping stream reaches to reduce the time required to complete the study. Reach 1 extended from site B1 downstream 19.0 miles to station 08073500 (site B5). Reach 2 extended from site B4 downstream 22.5 miles to station 08074000 (site B7). The two stream reaches overlap about 2.8 miles, from site B4 to station 08073500.

On August 3, dye was released at the upstream boundaries of both Buffalo Bayou reaches (sites B1 and B4, respectively). Dye concentrations were measured at three sites (B2, B3, and B5) in reach 1 and at three sites (B5, B6, and B7) in reach 2. Streamflow was determined in both stream reaches using daily mean streamflow from nearby stations (08072300, 08073500, 08073700, and 08074000). Base flow in Buffalo Bayou is sustained primarily by wastewater return flows. Scattered rainfall in the basin during the evening of August 3 had minimal effect on streamflow in the two reaches. In reach 1, the time of travel of the peak from the release site ranged from 3.7 hours at site B2 to 35.7 hours at site B5, while in reach 2 the time of travel of the peak from the release site ranged from 6.5 hours at site B5 to 47.5 hours at site B7.

Whiteoak Bayou, which drains a substantial area of northwest Houston, is a major tributary to Buffalo Bayou. Base flow in Whiteoak Bayou, as in Buffalo Bayou, is sustained primarily by wastewater return flows. Initially, two sample sites were selected for Whiteoak Bayou. On August 9, dye was released at site W1, and samples were collected at station 08074020 (site W2). However, after 2 days, the dye cloud had not reached the sampling site about 3.2 miles downstream of the release site. This was most likely caused by the flow characteristics of the upper end of Whiteoak Bayou resulting from low streamflow, deep pools of sluggish water, and flow obstructions. Because of these conditions, it was assumed that the dye did not disperse throughout the water column and (or) a substantial amount of the dye was lost to storage. Therefore, on August 11, dye was released at site W2, and samples were collected 9.6 miles downstream at site W3. Because site W3 is located at station 08074500, daily mean streamflow data were available for the duration of the sampling effort. The time of travel of the peak in this stream reach, from site W2 to site W3, was 54.5 hours.

Mason Creek is a small tributary to Buffalo Bayou. Base flow in Mason Creek also consists primarily of wastewater return flows. On August 10, dye was released at site M1, and samples were collected 5.9 miles downstream at site M3. Sampling site M3 is about 1.8 miles downstream of the confluence of Mason Creek with Buffalo Bayou. Because a streamflow-gaging station is not located on Mason Creek, streamflow was measured in Mason Creek at site M2, which is about 2.8 miles upstream of the confluence with Buffalo Bayou. The time of travel of the peak in the reach, from site M1 to site M3, was 17.8 hours.

Bear Creek, a tributary of Buffalo Bayou, drains the western part of the study area. On August 17, dye was released at site R1, and samples were collected 6.6 miles downstream at site R2. In this stream reach, Langham Creek and South Mayde Creek converge with Bear Creek, before discharging through the spillway of Addicks Reservoir. Sampling site R2 is about 0.75 mile downstream of Addicks Reservoir. Streamflow at the sampling site was estimated using flows from upstream stations 08072730, 08072700, and 08072800. During the study low-flow conditions were predominant, and the Addicks Reservoir release gates were open; therefore, no water was being stored in the reservoir, and the streamflow-gaging stations were not affected by backwater conditions. Stage-discharge ratings previously developed at each station were used to determine streamflow. The time of travel of the peak in this stream reach, from site R1 to site R2, was 18.8 hours.

Horsepen Creek is a small tributary to Langham Creek, which converges with Bear Creek. On August 11, dye was released in Horsepen Creek at site H1 (State Highway 6), and samples were collected 7.5 miles downstream at site H2. Site H2 is located on Langham Creek, just above its confluence with Bear Creek. The time-concentration curve developed from the dye concentrations was considered in error because of its multiple rises and recessions. On August 17, dye was released again at site H1, and samples were collected at site H2. Once again, the time-concentration curve had multiple rises and recessions. Because of these inconsistencies, time-of-travel estimates were not made for Horsepen Creek.

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VERTICAL DATUM

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

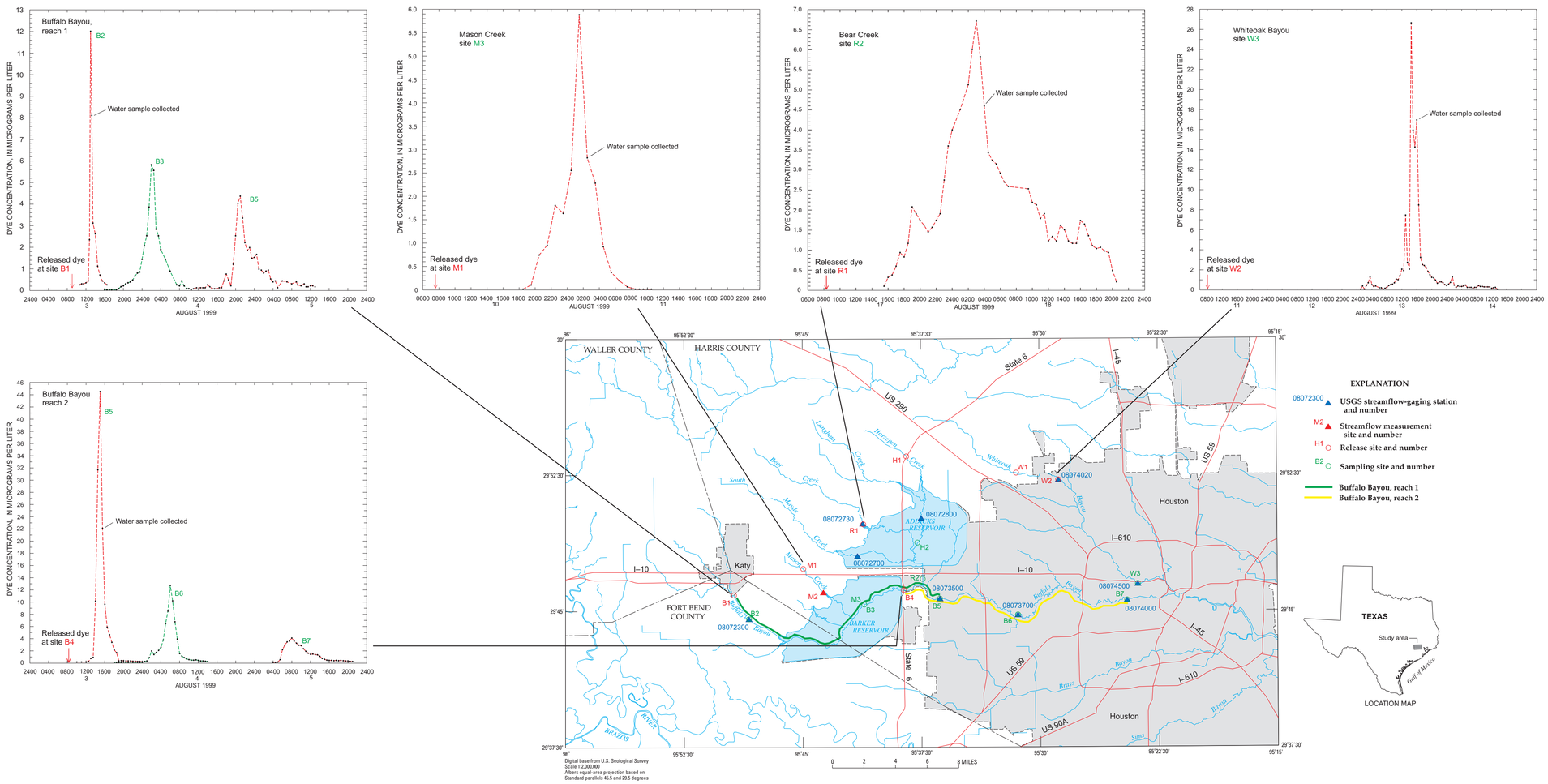
Table 1. Summary of time-of-travel results for Buffalo Bayou and selected tributaries, August 1999

[mi, miles; ft^3/s, cubic feet per second; hrs, hours; ft/s, feet per second; g, grams; --, not applicable]

Stream	Reach or subreach: Description	Length (mi)	From: Description	From: Site	To: Description	To: Site	Distance between sites (mi)	Mean streamflow (ft^3/s)[1]	Leading edge: Time of travel from release site (hrs)	Leading edge: Mean velocity in subreach (ft/s)[1]	Peak: Time of travel from release site (hrs)	Peak: Mean velocity in subreach (ft/s)[1]	Centroid: Time of travel from release site (hrs)	Centroid: Mean velocity in subreach (ft/s)[1]	Trailing edge: Time of travel from release site (hrs)	Trailing edge: Mean velocity in subreach (ft/s)[1]
Buffalo Bayou, reach 1	Katy Flewellen Road to USGS station 08073500, at Dairy Ashford Road	19.0	Katy Flewellen Road	B1	USGS station 08072300, at Greenbush Road	B2	2.3	24.0	1.3	2.63	3.7	0.92	4.2	0.81	7.2	0.47
Released 728 g of rhodamine-WT dye at 0920 on August 3, 1999			USGS station 08072300, at Greenbush Road	B2	Barker Clodine Road	B3	10.4	45.0	9.7	1.82	16.7	1.17	17.2	1.17	23.7	.92
			Barker Clodine Road	B3	USGS station 08073500, at Dairy Ashford Road	B5	6.3	75.0	28.7	.49	35.7	.49	36.7	.47	51.2	.34
Buffalo Bayou, reach 2	State Highway 6, just downstream of Barker Reservoir, to USGS station 08074000, at Shepherd Drive	22.5	State Highway 6	B4	USGS station 08073500, at Dairy Ashford Road	B5	2.8	76.0	4.0	1.03	6.5	.63	7.0	.59	14.0	.29
Released 1,553 g of rhodamine-WT dye at 0834 on August 3, 1999			USGS station 08073500, at Dairy Ashford Road	B5	USGS station 08073700, at Piney Point Road	B6	7.2	97.0	16.0	.88	21.5	.70	22.0	.70	29.0	.70
			USGS station 08073700, at Piney Point Road	B6	USGS station 08074000, at Shepherd Drive	B7	12.5	110	44.5	.64	47.5	.70	48.5	.69	60.0	.59
Whiteoak Bayou	USGS station 08074020, at Alabonson Road (site W2) to USGS station 08074500, at Heights Boulevard (site W3)	9.6	--	--	--	--	9.6	36.0	41.5	.34	54.5	.26	55.0	.26	76.0	.18
Released 971 g of rhodamine-WT dye at 0800 on August 11, 1999																
Mason Creek	Mason Road (site M1) to Barker Clodine Road, 1.8 mi downstream of the confluence with Buffalo Bayou (site M3)	5.9	--	--	--	--	5.9	[2]4.18	11.8	.74	17.8	.49	18.8	.46	22.8	.38
Released 97.1 g of rhodamine-WT dye at 0745 on August 10, 1999																
Bear Creek	Barker Cypress Road (site R1) to Memorial Drive, 0.75 mi downstream of Addicks Reservoir (site R2)	6.6	--	--	--	--	6.6	45.0	9.8	.99	18.8	.52	20.2	.48	36.2	.27
Released 1,942 g of rhodamine-WT dye at 0815 on August 17, 1999																

[1] When dye cloud was in the subreach.

[2] Discharge measured in subreach at Prince Creek Court, 2.8 mi upstream of confluence with Buffalo Bayou.



Map showing locations of release and sampling sites and graphs showing time-concentration curves for sampling sites, Houston, Texas, August 1999.

TIME OF TRAVEL OF SOLUTES IN BUFFALO BAYOU AND SELECTED TRIBUTARIES, HOUSTON, TEXAS, AUGUST 1999
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