

1 **Physical, Chemical, and Microbial Quality of Floodwaters in Houston**

2 **Following Hurricane Harvey**

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8 **Abstract**

9 Hurricane Harvey brought more than 50 inches of rainfall to some areas of the Greater Houston
10 Metro area (GHMA) starting on August 25, 2017; the Hurricane was also associated with
11 damage to environmental infrastructure such as wastewater facilities, Superfund sites, and leaks
12 and spills from industrial and municipal facilities. This study collected post-Harvey water quality
13 data in multiple streams for several weeks after the Hurricane. In addition to measuring impact,
14 the study compared the observed concentrations of several physical, chemical, and microbial
15 constituents and water properties to their historical counterparts in an effort to understand the
16 water quality impacts of Harvey on the natural water systems within the GHMA. Unusual water
17 quality findings such as low pH were observed that likely had acute and chronic effects on
18 ecosystems including the loss of oyster populations in Galveston Bay. In-stream microbial
19 concentrations, using *E. coli* as the indicator, were within historical norms typically reported for
20 the GHMA. The observed levels of measured dissolved metals post Harvey, while relatively low,
21 when multiplied by the significant volume of water discharged from bayous to Galveston Bay,
22 meant the delivery of a substantial load of trace metals to the estuary. Specifically, the load in the
23 particulate phase would be expected to accumulate and gradually repartition to the dissolved
24 phase for a long period of time. Total metal concentrations, when elevated relative to their

historical counterparts, could be associated with the presence of industrial activities. Overall, anthropogenic activities including the presence of hydraulic flood control structures, local runoff from industrialized areas, and active superfund sites were recognized as key factors affecting short-term acute water quality impacts. Watersheds with very little human alterations experienced minimal water quality changes and had relatively rapid recoveries post-Harvey.

Introduction

Hurricane Harvey landed on the coast of Texas as a Category 4 storm on August 25, 2017, and brought an unprecedented > 50 inches of rainfall in some parts of the Greater Houston Metropolitan area (GHMA) ¹ and more than 15 trillion gallons of water into Houston's waterways. In addition to physical damage to infrastructure and buildings, Harvey had significant environmental impacts including the generation of polluted runoff, mobilization of very large amounts of sediment, and reduction of salinities in Galveston Bay. The damages included, but were not limited to, inundation of wastewater treatment plants ¹; loss of integrity in active superfund sites ², and spills and leaks from various industrial and domestic facilities ³. The environmental impacts of severe events such as Harvey are typically manifested in the form of acute and chronic changes in physical, chemical and microbiological water quality ⁴⁻⁸. Such changes, however, are highly dependent on the nature of the event, the anthropogenic activities within watersheds, and the characteristics of the affected natural water systems ⁴. For example and in the case of Houston, the presence of superfund sites ⁹ and hydraulic structures such as the Addicks and Barker flood control reservoirs ¹⁰⁻¹¹ may amplify environmental impacts because of the potential for the release of pollutants and contaminated stored floodwaters from such systems.

For a region as large as the GHMA in Texas encompassing 9,444 sq. mi ¹², environmental impacts and subsequent recoveries are expected to vary within its geographic extent and the receiving Galveston Bay estuary due to the differing characteristics of its 22 watersheds and the anthropogenic activities within them. While post-hurricane studies that focus on a relatively limited area with a single sampling event are necessary to quantify local and immediate impacts; spatially and temporally broader monitoring of several waterbodies over a longer period of time is needed to develop an in-depth understanding of overall system response and recovery. Such monitoring would also enable an understanding of the contribution of anthropogenic activities towards the degradation of sediment and water quality resulting from hurricanes and severe events.

Several variables are often monitored after a severe event: water temperature and conductivity (total dissolved solid, TDS, and specific conductance) are typically used for rapid screening of overall water conditions. Dissolved oxygen (DO), organic constituents, metals, nitrogen, phosphorus, and fecal coliform (E. coli and Enterococci are the current standard indicators for pathogens in fresh and saline water, respectively) have been measured to elucidate specific impacts ^{6, 13-14}. Among the chemical constituents and water properties, metals and pH are of particular concern to environmental and ecological systems ¹⁵⁻¹⁶; elevated levels of metals such as zinc, copper, lead, arsenic, cadmium, chromium, and nickel have been reported in previous studies ^{4, 15, 20}. Metals have both acute and chronic effects while dissolved metals pose an immediate threat to aquatic life; the particulate phase can be accumulated in the sediment and gradually repartition to the dissolved phase over time causing chronic long-term impacts ¹⁷⁻¹⁹. The pH could affect aquatic life and change the adsorption-desorption processes for many

chemicals including metals; levels of pH between 4 and 6 increase the rate of heavy metal release from sediment and soils into the water¹⁶.

This paper describes a comprehensive longitudinal sampling campaign that was launched immediately following Hurricane Harvey with the goal of characterizing the physical, chemical, and microbial changes in Houston's natural water systems; the research begins to develop a conceptual framework for the recovery of such systems from extreme events. To the best knowledge of the authors, such a study has not been undertaken before. Physical, chemical, and microbial water characteristics including water temperature, conductivity, pH, dissolved oxygen, *E. coli*, and metal concentrations were measured in 41 locations in four bayous, two creeks and two reservoirs for several weeks following Hurricane Harvey. The sampled systems were carefully chosen to reflect different land use and land cover characteristics, varying soil types, and degrees of urbanization in an effort to understand how the characteristics of the affected water system have reflected on system recovery following an extreme event such as Hurricane Harvey. The measured data are presented in this paper to demonstrate impact but they are also compared to their historical counterparts to provide context to the level of acute and chronic change observed after Hurricane Harvey. In addition, the potential contribution of anthropogenic activities towards the observed changes in water quality is described; a relatively undeveloped watershed that was part of the study served as a control for this purpose.

Materials and Methods

Sampled Watersheds. Field sampling was initiated immediately following Harvey beginning on September 1, 2017, one week after landfall, and continued for three months. Based on past experience and knowledge of the bayou system in Houston, a total of 41 water quality-monitoring (WQM) stations located in four bayous, two creeks and one reservoir were identified

for the longitudinal sampling effort (see Figure 1). The sampled systems included Buffalo Bayou, Brays Bayou, Greens Bayou, Hunting Bayou, Clear Creek, Peach Creek, and Barker and Addicks Reservoirs.

Buffalo Bayou, the main waterway in Houston encompassing the Addicks and Barker flood-control reservoir system, is heavily industrialized in its downstream reaches, and drains most of Houston into Galveston Bay. Brays Bayou is the most urban of the studied watersheds exhibiting relatively high population densities; Greens Bayou is a mixed use watershed with forested space in its headwaters and industries near its outfall; Hunting Bayou is also a mixed land use of residential, green space and industries; Clear Creek is a coastal system that was severely inundated during Harvey; and Peach Creek is almost entirely undeveloped and drains to Lake Houston, the main water supply for Houston. Due to minimal anthropogenic activities within it, the Peach Creek watershed served as a control relative to the more developed watersheds in the study. The frequency of measurements was the highest in Buffalo Bayou because of its significance as the main drainage waterway in Houston and also due to the stored floodwater releases from the Barker and Addicks Reservoirs that occurred during Harvey. Flooding events from hurricanes are typically short-lived events, however, the presence of the reservoirs in Buffalo Bayou and their post-event releases provided an opportunity to conduct a relatively long sampling campaign of floodwaters and their impacts on receiving streams.

Sampled Constituents and Properties. Physical and chemical characteristics including pH, DO, water temperature and specific conductance; were measured on a weekly basis after Harvey using a field multi parameter water quality sonde (600 XLM, YSI Inc.). The YSI with all its probes was calibrated and post calibrated daily before and after use, respectively. Post calibration confirmed the absence of drift in probe readings throughout the day. For in-stream measurements

115 at each location, the YSI Multi-probe was immersed in water from bridges to measure the total
116 depth. Vertical depth profiles were developed starting at a depth of 0.3 meter (one foot) followed
117 by one meter (3 ft) and then using 1 m intervals and ending 0.3 meters above the bottom of the
118 bayou or stream. Vertical depth profiles were necessary to determine if there was any measurable
119 stratification across the water column. During the sampling campaign, some of the sites had high
120 flows and/or high water velocity and it was not possible to measure total flow and develop
121 vertical depth profiles in such cases. A total of three DO measurements in two stations located in
122 Brays Bayou (15851 and 15855) with values greater than the saturation level (14.6 mg/l at
123 freezing point) were excluded from the dataset. Such high values for DO are likely due to an
124 error in the YSI reading. Although historical DO values above saturation levels, as high as 27.7
125 mg/l were reported for Brays Bayou in the Texas Commission on Environmental Quality
126 (TCEQ) Surface Water Quality Monitoring Information System (SWQMIS) tool ²¹, these data
127 were excluded since they were erroneous.

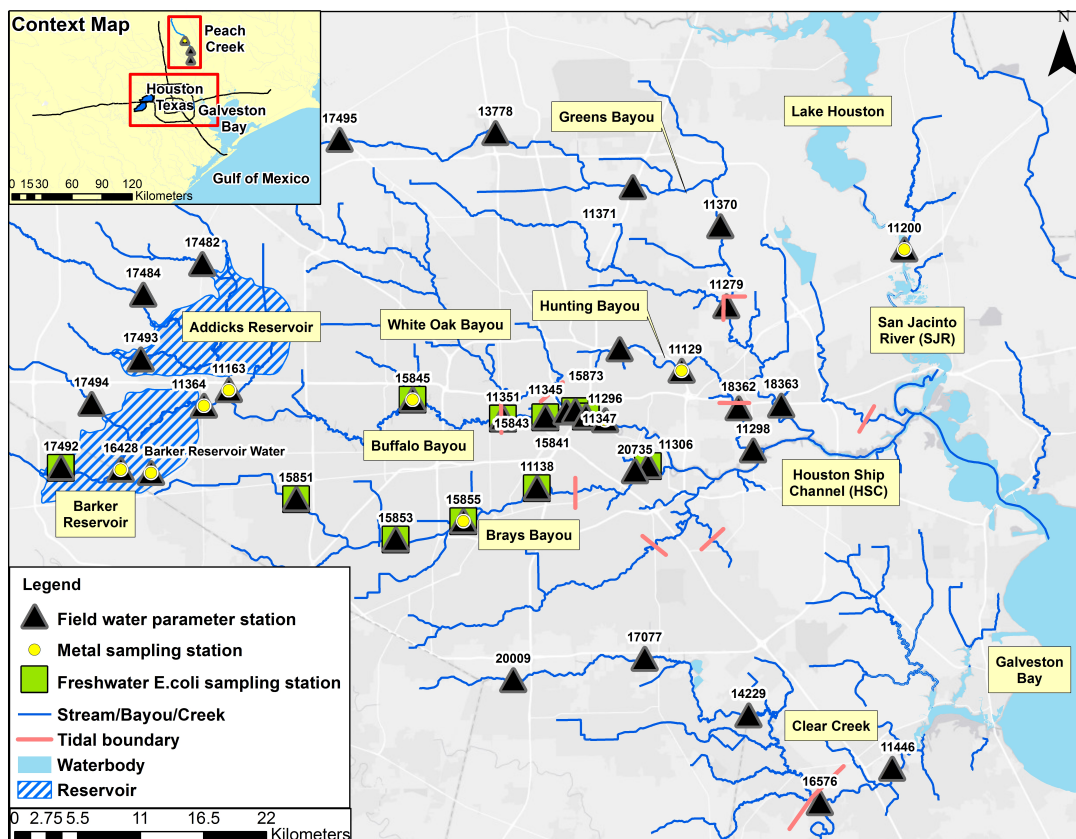


Figure 1. Schematic of the locations of field measurements: pH, DO, conductivity, *E. coli*, and metals. Locations within Peach Creek are shown in the Inset Map. Stations located downstream of the shown tidal boundaries are considered tidal stations (total of 14 stations).

Trace Metals. A total of 22 samples were collected from 10 locations (see Figure 1) to quantify trace metal concentrations in bayous and floodwater. Water sampling for total and dissolved metals was undertaken following EPA and TCEQ methodologies²²⁻²³. Pre-cleaned HPDE bottles (16 OZ, Environmental Sampling Supply - ESS) were used to collect water samples and all sample containers were maintained at a temperature below 4°C prior to analysis. To measure metals in the dissolved phase at each site, provided the water was not too turbid, 250 ml of water were filtered using a 60 mL syringe and multiple 0.45 micrometer Nylon syringe filters (Corning® syringe filters, Sigma Aldrich). Texas guidelines²⁴ provide dissolved metal criteria in fresh water as a function of hardness. Thus, hardness was also analyzed using the same sample used for total metals. Arsenic, chromium, lead, and nickel were selected for analysis due to the

abundance of industries in the areas with discharge permits for the four metals and also the presence of superfund sites contaminated with the four metals near the studied waterways. The detection limits used for metals analysis were 0.5, 3, 0.5, 2 $\mu\text{g/l}$ for arsenic, chromium, lead, and nickel, respectively. The detection limit for hardness was 5 mg CaCO_3/l . All samples were analyzed using a commercial laboratory.

Microbial Parameters. Freshwater samples from Buffalo Bayou (six samples) and Brays Bayou (five samples) were collected (see Figure 1) two weeks after Harvey and analyzed for *E. coli*. Samples were analyzed within the required 6-hour hold time²³.

Data Acquisition and Analysis. Historical water quality data for the period 1983 to 2017 were acquired from TCEQ's SWQMIS Tool²¹. It should be noted that historical data for trace metals is very limited and is not available for all sites sampled in the study, thus for sites with no data; upstream and downstream monitored stations were used to provide a comparative context. Additionally, historical trace metal data were analyzed with extreme caution and care because of data quality concerns with metals data prior to 1997²⁵ that had not been analyzed using EPA 1669²². Metals data prior to 1997 were eliminated from the analysis. Soil data were retrieved from the Natural Resources Conservation Service (NRCS) web soil survey²⁶ and soil properties including acidity were obtained from the U.S. Department of Agriculture (USDA) Official Soil Series Description (OSD) database²⁷.

Flow, water surface elevation, and storage time series for the reservoirs were compiled from the United States Geological Survey (USGS). Rainfall data were compiled from the Harris County Flood Control District (HCFCD) Flood Warning System (FWS) database²⁸. To calculate the wet area of reservoirs, the water surface elevation within the reservoirs was subtracted from the bottom elevation data, acquired from Digital Elevation Map (DEM) blocks downloaded from

the Texas Natural Resources Information System (TNRIS) database²⁹. The total rainfall volume was calculated as the amount of rainfall multiplied by the wet surface area of the reservoirs.

Visual analysis, comparison tests, regression, and statistical box plots were performed using Microsoft Excel to determine the difference, if any, between the concentrations or values of different water quality variables before and after Hurricane Harvey and trends that might be observable in the data. Pearson correlation analyses were performed using IBM® SPSS®³⁰. Trace metal sampling results after Harvey were compared to historical data and observed trends after severe storms to determine patterns, if any, following Harvey. Dissolved metal concentrations in water samples, additionally, were compared to criteria used by TCEQ for aquatic life (Table S1 in the Supporting Information (SI)) and human health protection²⁴ (Table S2 in the SI).

Results and Discussion

None of the studied waterbodies showed stratification for salinity, DO, or temperature; thus, results only from measurements at 0.3 m depth are reported in this paper. Table 1 provides a statistical summary of the measurements for all bayous.

Specific Conductance. The ranges of measured specific conductance in all bayous and locations are shown in Table 1. Low specific conductance, mostly below 1.0 mS/cm, was observed in all stations during the entire sampling period; likely due to the relatively large amount of freshwater from the >50 inches of rainfall. The highest specific conductance was measured in Buffalo Bayou behind the Barker Dam (Station 16428 in Figure 1) two weeks after Harvey with a value of 1.073 mS/cm that is equivalent to a salinity of 0.53 ppt. The measured specific conductance in all stations except a few stations located in Buffalo Bayou was within the range observed in the historical data from 1983-2017 (Figure S1 in the SI). Observed low specific conductance for

tidal stations (see Figure 1 for the tidal line) up to six weeks after Hurricane Harvey indicated the dominance of fresh water emanating from upstream watersheds and the two reservoirs on these normally saline tidally influenced systems. Such “freshening” in Galveston Bay likely had a significant impact on aquatic life that is sensitive to the changes in salinity³¹.

Table 1. Summary of post-Harvey measurements in different bayous

Location	Station ID(s)	#	pH		DO (mg/l)		Sp. Cond (mS/CM)	
			Min [*]	Max [*]	Min	Max	Min	Max
Addicks Discharge	11163	7	5.3	8.11	5.92	10.68	0.10	0.76
Barker Discharge	11364	7	5.61	8.21	6.09	9.91	0.09	0.98
Barker Reservoir water	NA	1	6.80	6.80	9.49	9.49	0.11	0.11
Behind Addicks Reservoir	17482, 17484, 17493	3	6.57	7.17	6.74	6.86	0.06	0.06
Behind Barker Reservoir	17494	3	6.64	7.13	5.95	7.78	0.08	0.22
Brays Bayou	15851, 15853, 15855, 11138, 20735, 11306	22	7.16	8.53	2.00	12.58	0.19	0.87
Buffalo Bayou	17492, 16428, 15845, 11351, 15843, 11345, 15841, 11347, 11296	51	5.67	8.88	2.56	14.68	0.07	1.07
Clear Creek	20009, 17077, 14229, 16576, 11446	10	7.02	7.39	2.65	11.92	0.28	0.46
Greens Bayou	17495, 13778, 11371, 11370, 11279, 18363	13	6.51	7.66	2.62	9.18	0.27	0.81
Hunting Bayou	15873, 11129, 18362, 11298	10	6.82	7.50	3.13	7.71	0.33	0.96
Peach Creek	11336, 11337, 11338	6	6.18	7.08	8.30	10.24	0.08	0.17
San Jacinto River (SJR)	11200	3	6.04	7.70	7.62	10.08	0.10	0.62

^{*} Min and Max refer to the minimum and maximum value for the specific variable and waterbody that was measured following Harvey; NA: Not applicable - measurement location was not a WQM station; # : Number of samples.

Dissolved Oxygen. Higher DO levels were observed closer to the headwaters in all bayous.

Peach Creek, the most rural waterbody had minimal DO temporal fluctuations (Figure S2 in the SI). DO levels were significantly higher in Peach Creek compared to all the studied bayous (see Table 1 and Figure S2 in the SI) supporting the hypothesis of less impacts post-hurricanes on bayous within watersheds with little or no anthropogenic activities. The observed relatively low DO levels post-Harvey were comparable to the low levels of dissolved oxygen observed in coastal streams and bayous due to urbanization³²⁻³³. Low DO concentration (hypoxia) below 3.0

204 mg/l can cause severe damage or even death to fish populations^{34, 35-36, 37} such as ones that are
205 commonly found in GHMA's bayous. DO concentrations below 3 mg/l were measured for two
206 weeks after Harvey in Brays, Buffalo, and Greens Bayous and in Clear Creek; the lowest DO
207 measurements, in some cases, were below the minimum DO observed in the historical data.
208 Importantly, DO levels had a decreasing trend for more than two weeks after Harvey at some
209 locations before returning to their historical norms. A DO level of 6.76 mg/L, for example, was
210 recorded at Station 15845 in Buffalo Bayou (Figure 1) one week after Harvey and dropped to
211 4.46 and 2.56 mg/l, seven and 16 days after Harvey, respectively. At the same station, 24 and 35
212 days after Harvey, the DO concentration rebounded to 5.19 and 6.20 mg/l, respectively.

213 **pH.** The data in Figure 2 demonstrate that a pH below historical levels was observed at almost
214 all sampled stations along Buffalo Bayou, one station in Greens Bayou and one in Hunting
215 Bayou. The range of measured pH and deviation from the historical median were the highest in
216 Buffalo Bayou; the bayou with the most industrial activities and with flood control hydraulic
217 structures. The minimum variation from historical measurements was observed in Peach Creek
218 with the lowest system alterations. The lowest measured pH, 5.3, was recorded four weeks after
219 the start of discharge from the reservoirs at Station 11163 (Figure 1). This is significant because
220 a pH below 6.0 had not been observed in the past after any prior severe hydrologic events in the
221 studied watersheds as was observed here following Harvey.

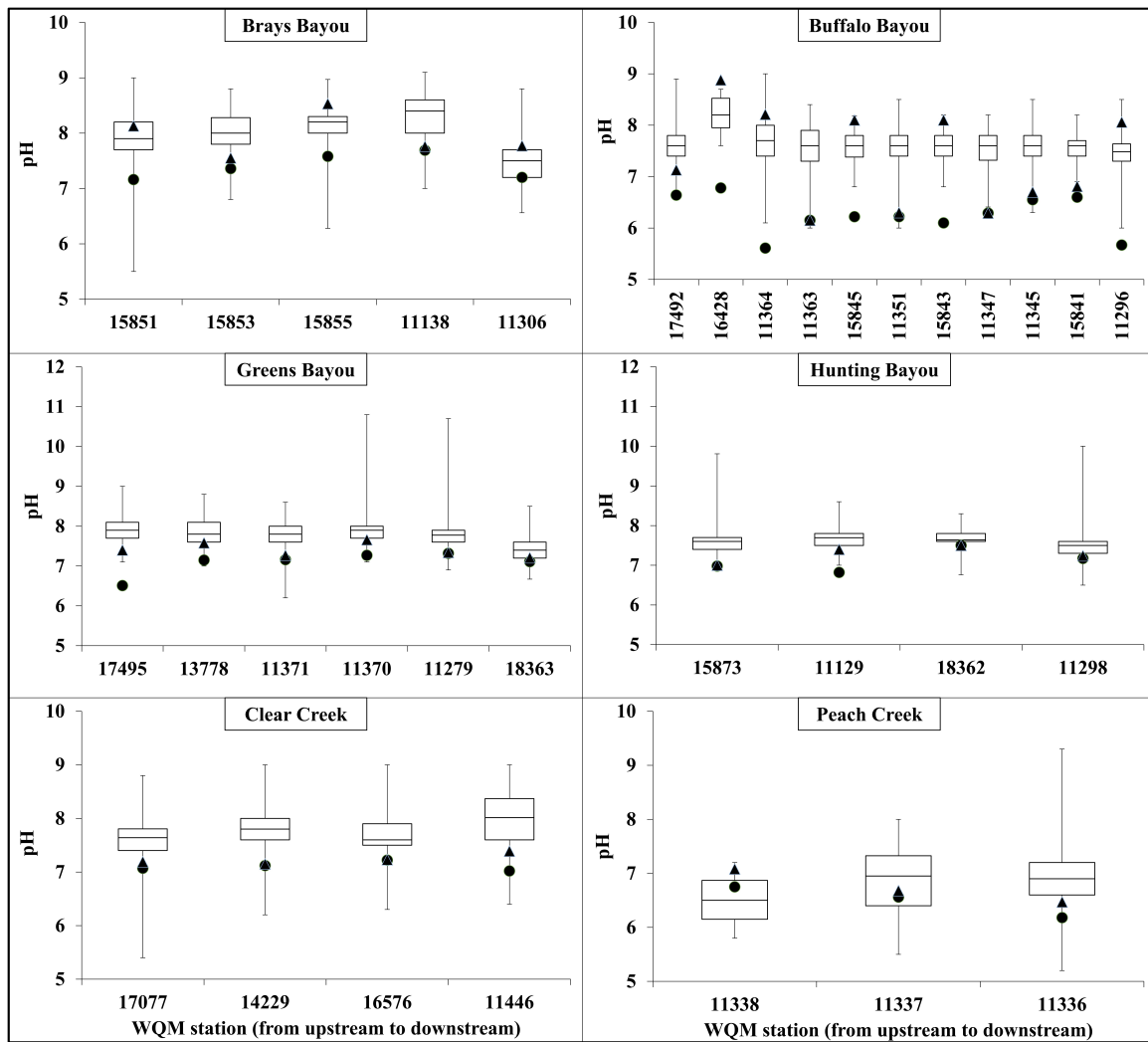


Figure 2. Measured pH extremes (circles: minimum and triangles: maximum) following Hurricane Harvey compared to historical pH data from 1983-2017 for sampled locations in six water bodies compiled from TCEQ²¹. The boxes span the interquartile range with the horizontal in the middle showing the median. The whiskers outside the boxes extend to minimum and maximum to represent the total range.

Acidic water with pH levels as low as 5.61 was observed in Buffalo Bayou within one week after Harvey and the low pH persisted for almost six weeks till the releases from the Addicks and Barker Reservoirs ended. The observed relatively low pH levels suggested that water became acidic while residing for a relatively extended period of time in the flood control reservoirs. Significant, positive, strong correlations with high corresponding R-values were observed among the pH values released from Addicks (P-values of 6E-06, and 2E-03) and

Barker (P-values of 5E-03, and 1E-03) with the stations located just downstream of the release points (11296 and 15845, respectively in Figure 1). Slopes close to one with high R-squared values (Figure S3 in the SI) indicated a high correlation between observed pH values in Buffalo Bayou and those observed in the water released from the reservoirs suggesting that the released water was the main source for the low-pH. Low pH combined with low salinity, both observed in this study, could cause severe damage to aquatic life especially oysters³⁸⁻³⁹. Destruction of the oyster population was repeatedly reported in Galveston Bay in the aftermath of Hurricane Harvey⁴⁰⁻⁴². The presence of flood control reservoirs and their continuous discharge of acidic water for more than six weeks after Hurricane Harvey likely amplified the impacts and damages.

Two possible lines of reasoning were evaluated to explain the relatively low pH levels and their decreasing temporal trends in Buffalo Bayou. The first was related to the ratio between the total volume of rainwater that has a pH of around 5.6⁴³ relative to the total volume of water stored in the reservoirs. The net “pH” in the reservoirs would be a result of the mixing between the acidic rainfall that fell strictly on the reservoirs and the runoff water entering the reservoirs that has a relatively higher pH. During Harvey, 15% and 23% of the total water could be attributed to rainfall that fell onto the Addicks and Barker reservoirs’ wet surface, respectively (these are significantly higher percentages than in prior extreme events because of the extreme amount of rainfall in Harvey). It should also be noted that while it took approximately 4 days to reach the peak storage during Hurricane Harvey, this number was around 7 days for other historical floods. Faster accumulation of stored water in the reservoirs means higher chances that the stored water would be more acidic.

The second line of reasoning was related to the surface soil types (Figure 3) covering the bottom of the reservoirs; some of which are acidic. Extremely acidic soils with pH levels as low

as 4.5 (Waller, Katy, and Bibb series) are notable on the western side of both reservoirs while the middle and eastern most parts of both reservoirs are covered with less acidic soils. Harvey was the first storm where all areas of the reservoirs were inundated and the structures filled to capacity thereby allowing interaction between the rainwater and runoff with the acidic soils present in the western parts of the reservoirs. In comparison, the most dominant soil series in Harris County, with the exception of impervious surfaces, are the Lake Charles and Bernard series²⁶ which are characterized as neutral and slightly acidic²⁷.

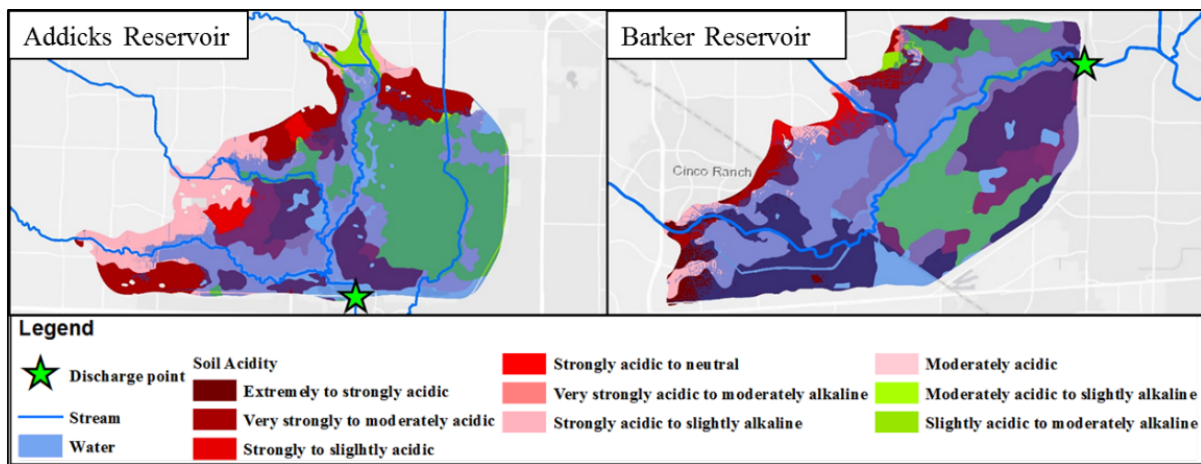


Figure 3. Inundated land in the reservoirs during Harvey superimposed on mapped soil acidity. Water surface elevation data was compiled from USGS. To calculate wet area, the water surface elevation within the reservoirs was subtracted from the bottom elevation data, acquired from DEM blocks downloaded from TNRIS database²⁹. Soil data were retrieved from the NRCS web soil survey²⁶ and soil acidity were obtained from the USDA's OSD database²⁷.

E. coli. In samples collected from Brays Bayou and Buffalo Bayou, *E. coli* levels were 17 and four times higher compared to TCEQ primary contact water standards, respectively. However, as shown in Figure 4, none of the measurements exceeded historical values in corresponding stations. The literature is replete with reported elevated *E. coli* in freshwater systems after storms mostly because of urbanization and human activities^{4, 44-46}. For Houston in particular, elevated bacteria levels are the norm⁴⁷⁻⁵⁰ and total maximum daily loads (TMDL) for bacteria have been developed to address this chronic problem. It should also be noted that in-stream indicator

bacteria concentrations are only one measure of biological impacts; similar measurements made by others in standing water within and outside flooded homes and flooded wastewater facilities, for instance, exhibited much higher *E. coli* levels. It is also noteworthy that Brays Bayou exhibited higher levels than Buffalo that can be attributed to the abundance of wastewater treatment plants along the bayou that were inundated during Hurricane Harvey. Also noteworthy is the near non-detect *E. coli* levels in stormwater entering the Barker Reservoir at station 17492 (see Figure 1 for location).

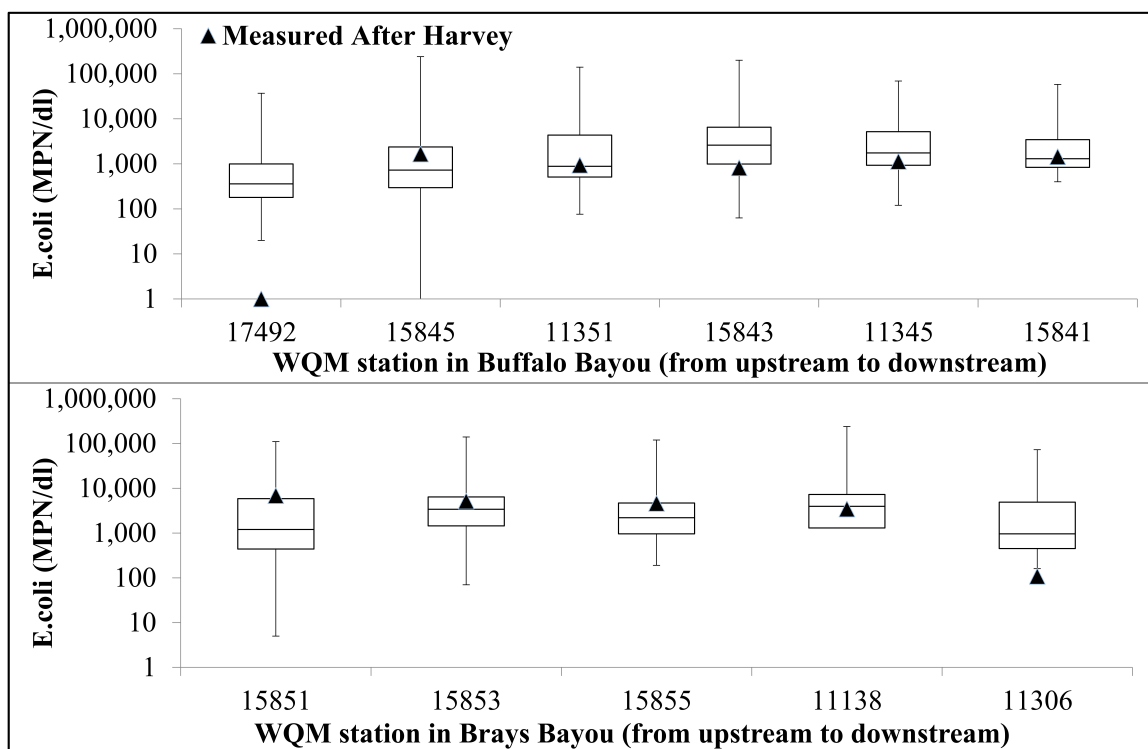


Figure 4. Historical *E. coli* data from 1983-2017 compiled from TCEQ's SWQMIS tool²¹ for different WQM stations along Buffalo and Brays Bayou and post Harvey measurements. The boxes span the interquartile range with the horizontal in the middle showing the median. The whiskers outside the boxes extend to minimum and maximum to represent the total range.

Dissolved and total metals. Table S3 in the SI shows total and dissolved trace metal concentrations at different sampling stations with the corresponding measured pH, and hardness values. Arsenic was detected in the dissolved phase in all collected samples (dissolved samples

were collected only when the water turbidity was low) and ranged from 1.80 to 3.62 µg/l. Analyses for all other metals showed results below the detection limit for the dissolved phase except for dissolved nickel, which was found in one sample collected five weeks after Hurricane Harvey and samples collected 10 weeks post Harvey when the flow rates returned to normal. None of the dissolved concentrations exceeded the TCEQ freshwater acute and chronic criteria (see Table S3 in the SI).

While the dissolved concentrations were below TCEQ criteria and almost non-detectable, total metal concentrations were slightly higher than their historical counterparts before Harvey in almost all sampled locations (see Table S3 and Table S4 in the SI). As noted before, historical data for trace metals is very limited; there are only seven WQM stations in the entire study area with trace metal records for 2017 prior to Hurricane Harvey reported by TCEQ. Among the four trace metals sampled in the study, total arsenic concentrations were detectable in all 23 samples, total lead in 18 samples, total nickel in six samples, and total chromium was only detected in three samples. It should be noted that pre-Harvey samples were collected in a normal flow regime with significantly less flow in Buffalo Bayou. Higher total metals concentration associated with higher flow rates is an important finding. With the presence of more water, dilution decreases the concentration. The fact that trace metals were detectable and at higher levels than in previous sampling and considering the sheer volume of water (and sediment) indicates a significant load of trace metals in runoff.

Effects of anthropogenic activities. No metals were detected in the dissolved phase in the sample collected from Peach Creek two month after Hurricane Harvey. For total concentrations, only arsenic and lead were detectable with total concentrations of 0.76 and 0.55 µg/l, respectively. The observed value for arsenic in Peach Creek was almost three times smaller than

the lowest measurement (1.99 µg/l in Station 15845, two weeks after Harvey, see Table S3 in the SI) in samples collected from the GHMA waterbodies. For lead, the value was similar to the lowest detectable value in GHMA samples.

Station 11296, Buffalo Bayou at Hirsch Rd, the most downstream sampling station in Buffalo Bayou, was the only station that exhibited all four trace metals two weeks after Hurricane Harvey when the flow rate was still high. However, all the measured values were below historical levels (1998-2017). Due to the absence of chromium and nickel in the upstream station (15845, see Figure 5), the source of the two metals may be associated with runoff generated from upstream industrial areas and superfund sites from Buffalo Bayou or White Oak Bayou drainage areas. This hypothesis is further supported when looking at the industries with chromium and nickel discharge permits close to Station 11296. As can be seen in Figure 5, there are more than 20 facilities with discharge permits for chromium and nickel upstream of the sampled station. In addition, subsequent samples collected 5 weeks after Hurricane Harvey showed nickel and chromium levels below detection limits. The decrease in concentrations indicated the source of these two metals was potentially the runoff from industrial areas in White Oak Bayou and downstream of Buffalo Bayou, as opposed to being associated with water releases from the reservoirs. The portion of the flow rate in Buffalo Bayou that originated from reservoir releases was 80.3% and 92%, two and five weeks after Hurricane Harvey, respectively. Lower levels of reservoir water means higher local runoff occurred which confirms the effect of local runoff on nickel and chromium concentrations. For Station 11296 in particular, samples were collected by TCEQ four months before Harvey in a downstream station (Station 11292, Table S4 in the SI), and chromium was not detected. This result also supports the hypothesis that chromium originated from industrial runoff.

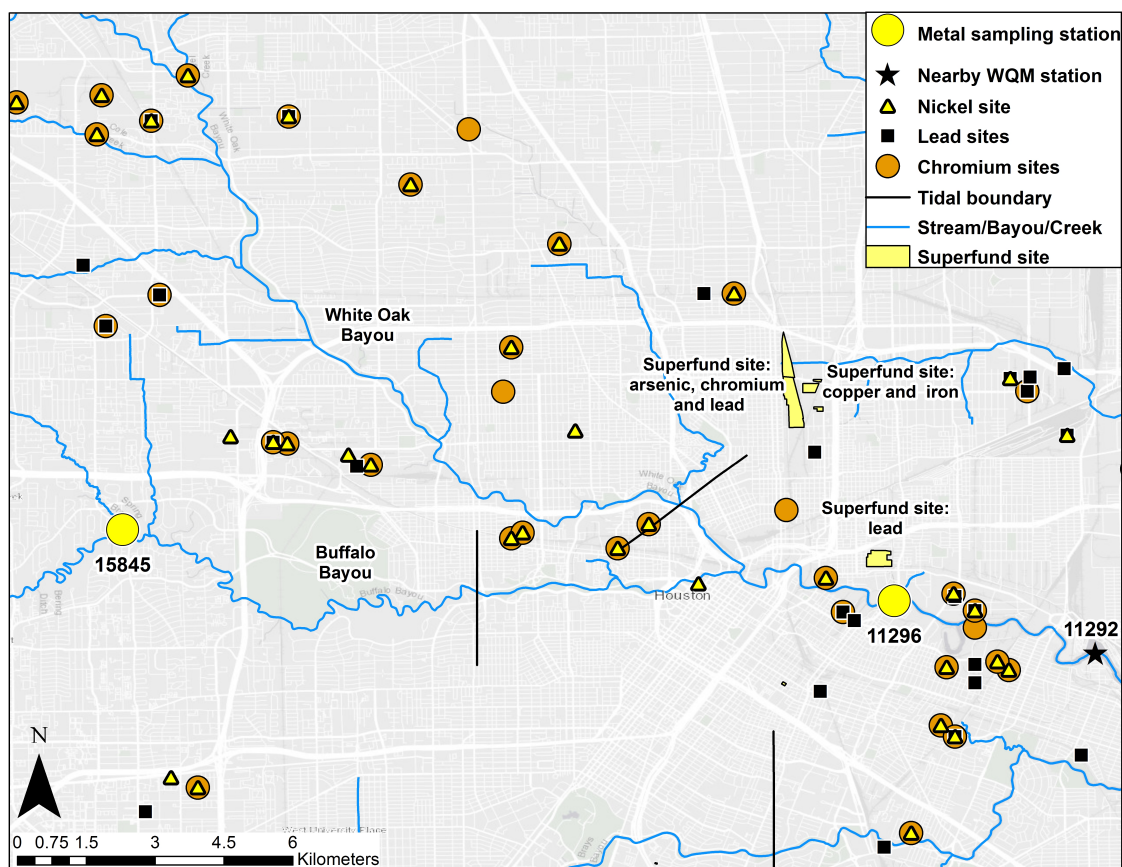


Figure 5. Location of industrial facilities with metals discharge permit and superfund sites close to Station 11296

The floodwater stored behind the Barker Reservoir and the discharged water from Barker (Station 11364, see Figure 1) both contained arsenic and lead a month after Hurricane Harvey. While the arsenic level was almost the same at both locations (see Table S4 in the SI), the lead level was almost 5 times higher in floodwater compared to the discharged water. Water stored behind Addicks Reservoir (Station 16428, see Figure 1) only contained arsenic a month after Hurricane Harvey at levels lower than the Barker Reservoir. In comparing metal concentrations in samples collected nine weeks post Hurricane Harvey at the discharge points of the two reservoirs with samples collected five weeks post Harvey, the effect of dilution especially for lead and nickel was evident. Lead concentrations were nine times higher and nickel was

detectable in water discharged from Barker Reservoir compared to samples collected a month before. This effect was mostly due to the lower volume of stored water in the Barker Reservoir.

Similar to pH, trace metal concentrations in Buffalo Bayou were a function of stored water behind the reservoirs in the absence of local runoff. Samples collected four days later (with no rainfall event in between and continuous discharge from both reservoirs) showed similar levels of arsenic and lead in Station 15485 and 11296 downstream of the reservoirs in Buffalo Bayou. However, the lead concentration was significantly lower (up to four times) as compared to its counterpart collected 20 days before in the presence of local runoff. Thus, it could be concluded that once the water in Buffalo Bayou was mainly controlled by the hydraulic structures and in the absence of local runoff, metal concentrations were a function of stored water behind the reservoirs.

Results presented in this work showed the significant effect of hydraulic flood control structures, local runoff from highly industrialized areas, and the presence of active superfund sites on the environmental impacts resulting from hurricanes and severe storms. The most acidic water after Hurricane Harvey was observed in a stream that is significantly affected by releases from flood control reservoirs. The presence of hydraulic structures increases the residence time which is typically beneficial for improving water quality. However, acidic soils covering the reservoirs, in addition to the fast storage rate during Hurricane Harvey, may have resulted in historically acidic reservoir discharges. The effect of industrial activities and superfund sites was observed in samples collected from high-density residential and industrial areas that showed higher concentrations of chromium and nickel. The source of the two metals was local runoff generated from industrial areas upstream of the sampling sites. At the watershed scale, the study demonstrated the exacerbation of water quality impacts post-hurricanes and severe storms within

376 watersheds with anthropogenic activities and their slower recoveries relative to watersheds with
377 minimal human alterations. While the study focused on water quality, companion studies
378 assessing impacts and recoveries of ecological systems need to be undertaken to fully understand
379 the impact of hurricanes and severe storms on environment.
380

ASSOCIATED CONTENT

Supporting Information

Acute and chronic criteria for trace metals in fresh and saline waters for aquatic life protection (values in $\mu\text{g/kg}$) (Table S1), Criteria for trace metals in water to protect human health (values in $\mu\text{g/l}$) (Table S2), Summary of post Harvey trace metal measurements in freshwater (Table S3), and Most recent measured historical trace metal concentrations at freshwater sampling stations and/or nearby stations (Table S4), Measured specific conductance extremes (red circles: minimum and black triangles: maximum) following Hurricane Harvey compared to historical data from 1983-2017 for different stations (from upstream to downstream) in six water bodies compiled from TCEQ's SWQMIS tool. The boxes span the interquartile range with the horizontal in the middle showing the median. The whiskers outside the boxes extend to minimum and maximum to represent the total range (Figure S1), Measured dissolved oxygen (DO) extremes (red circles: minimum and black triangles: maximum) following Hurricane Harvey compared to historical data from 1983-2017 for different stations (from upstream to downstream) in six water bodies compiled from TCEQ's SWQMIS tool. The boxes span the interquartile range with the horizontal in the middle showing the median. The whiskers outside the boxes extend to minimum and maximum to represent the total range (Figure S2), Correlation among pH values associated with released water from the reservoirs in Buffalo Bayou and the water in the Bayou (Figure S3).

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Notes

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