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Evaluation of spatial and temporal water and soil quality in the Buffalo and Brays Bayou watersheds of Houston, Texas

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ABSTRACT

The Buffalo and Brays Bayous are two of the primary drainage channels in the city of Houston. Both the Buffalo and Brays Bayou Watersheds (BBW, BrBW) are impacted by frequent flooding, rapid urbanization and intense land cover changes. The goal of this research is to assess and compare the soil and water quality and land cover changes in the BBW and BrBW. The specific objectives of the study are 1) to monitor and assess the nutrient and metal concentrations in the water and soil samples along the Buffalo and Brays Bayou, 2) to map the long-term land cover changes within these urban watersheds, and 3) to assess the effect of land cover changes on the bayou discharge, water and soil quality of the watersheds. Water and soil samples from several locations along the Brays and Buffalo Bayous were collected during multiple seasons and processed for chemical analysis. Our water sample analysis revealed that the Cu, As and Pb concentrations were higher in the fall compared to the summer and exceeded the critical limit in both the bayous. The soil analysis indicated that the Zn and Pb concentrations were higher in the fall over summer season and exceeded the background concentrations in both BBW and BrBW. The remote sensing analysis revealed that there was a 145% and 140% increase in impervious surface and 34.8% and 34.5% decrease in the vegetative surface in the BBW and BrBW, respectively, due to urbanization during 1984–2019. The contamination of soil and water in BrBW is substantially higher than the BBW. The results of this study provide insights for adoption of best sustainable management practices in urban watersheds.

1. Introduction

The rapid increase in population and industrialization of the greater Houston area has caused major urbanization to its local watersheds. The economy and size of the Houston-Galveston metropolitan region has aided Houston to become the fourth largest city in the United States. Houston is the world leader in chemical industry with 40% of US chemical production and is home for 405 chemical plants (City-Data, 2020; Bera et al., 2019). Urbanization resulted in the generous use of concrete and asphalt to transform vegetative and bare soil areas into impervious surfaces making it difficult for rainwater to infiltrate and absorb into the soil. An increase in the impervious surface lead to a direct decrease of natural infiltration areas. Other anthropogenic activities including the presence of hydraulic flood control structures, local runoff from wastewater facilities, superfund sites, and industrialized areas are recognized as key factors that can affect water and soil quality in the drainage areas (Kiaghadi and Rifai, 2019).

Hurricane Harvey severely flooded the greater Houston metropolitan area in September of 2017, with precipitation of 35.6 inches recorded, along Buffalo and Brays Bayou and about 47 inches of rain elsewhere in the city (HCFD, 2018). Buffalo Bayou Watershed (BBW) and Brays Bayou Watershed (BrBW) experienced 17,090 and 23,810 damaged houses, respectively (HCFD, 2018), as a result of Harvey flooding, which is the highest from the entire 22 watershed region of Harris county. The Memorial day flood in May 2015, Tax day flood in April 2016, and tropical storm Imelda in September 2019 are the other recent flood events recorded in this region. These major natural disasters caused increased levels of road flooding and inundation along the Buffalo and Brays Bayou. The urban flood water is often pumped off into the bayous in order to prevent further damage to the city's infrastructure which includes flooding of wastewater treatment plants, landfills, super fund sites, and industrial zones.

1.1. Buffalo and Brays Bayou

Buffalo Bayou runs across the city of Houston from the west towards

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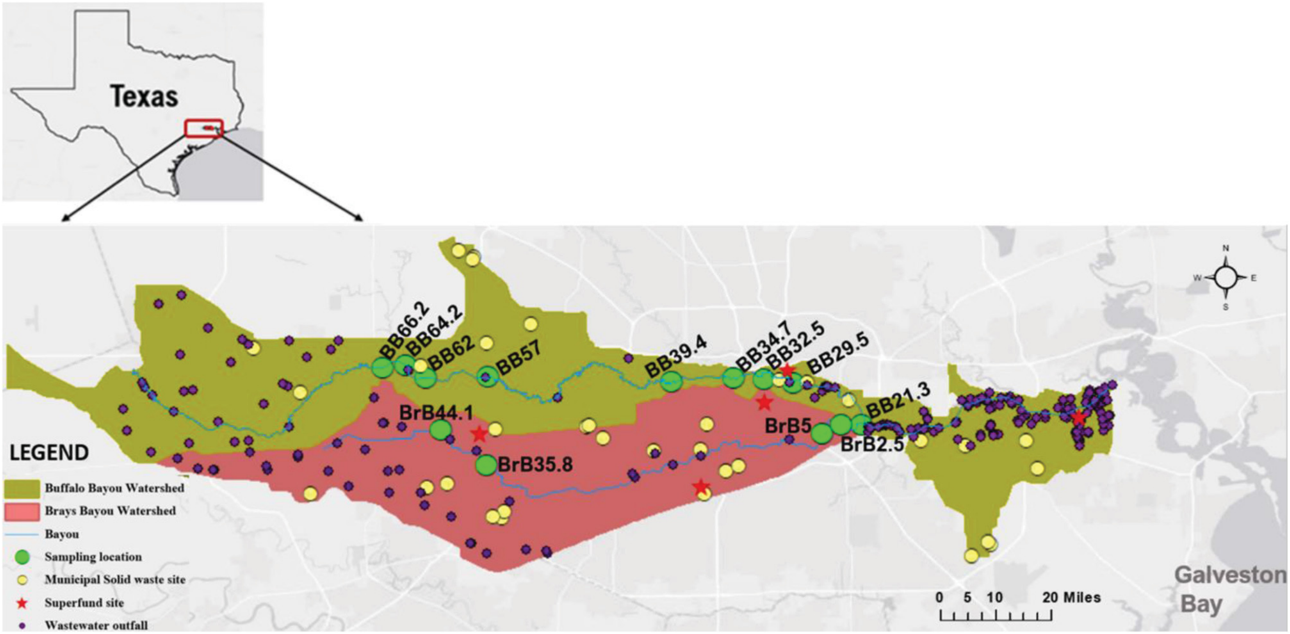

Fig. 1. The Buffalo and Brays Bayou watersheds along with the sampling locations. The sampling locations named as BB66.2, BB64.2, BB62, BB57, BB39.4, BB34.7, BB32.5, BB29.5, BB21.3 represents that they are 66.2, 64.2, 62, 57, 39.4, 34.7, 32.5, 29.5 and 21.3 km from the mouth of the Buffalo Bayou. Similarly, the locations BrB44.1, BrB35.8, BrB5, BrB2.5 represents that they are 44.1, 35.8, 5 and 2.5 km from the mouth of the Brays Bayou. Also shown are the municipal solid waste sites, superfund sites and wastewater outfalls in both the watersheds.

Katy and then flows further eastwards draining most of Houston area into the Galveston bay and further into the Gulf of Mexico. Buffalo Bayou is about 85 km in length and flanked on the west by the Addicks and Barker reservoirs. The watershed is home to many houses, highways and parks of Houston. The Buffalo Bayou is used as a paddle trail, biking and hiking trail, recreational fishing, and swimming area (HCFCD, 2020a). The population of Buffalo Bayou watershed is about 444,602 and drains about 102 Sq. Miles within Harris County (HCFCD, 2020a). There are 21 municipal solid waste sites, 183 waste-water outfalls and 2 active federally managed super fund sites located in this watershed (Fig. 1). Buffalo Bayou serves as a natural, economic, and social resource and is referred to as Houston's greatest natural treasure (HCFCD, 2020a).

The Brays Bayou runs parallel to the Buffalo Bayou from west to east and is 50.8 km in length. The population of Brays Bayou watershed is about 717,198, draining about 127 Sq. Miles and is the most populated of the 22 Harris county watersheds (HCFCD, 2020b). There are 14 municipal solid waste sites, 39 wastewater outfalls and 3 superfund sites located within the BrBW (Fig. 1). Both Buffalo and Brays Bayou are similar in size, land cover, population and urbanization pattern, but they have different flood management strategy, as Brays Bayou is channelized and Buffalo Bayou remains unchannelized (Juan et al., 2019). Channelization increases the carrying capacity of the stream by increasing the velocity of water flow and decreasing the water retention time and thereby allowing more economic development in the watershed (Juan et al., 2019). Both Buffalo and Brays Bayou are rainfed and serve as primary drainage channels in their watersheds with peak flows and occasional out-of-bank conditions during intense rain events (TCEQ, 2010).

Brays Bayou has been increasingly prone to flooding despite the channelization improvements while the Buffalo Bayou which is largely preserved in its natural state remains less affected by flooding (Juan et al., 2019). The impact of flooding on the environment can be observed in terms of changes in the physical, chemical and microbial water quality parameters of a watershed (Pardue et al., 2005). The release of heavy metals into the receiving waters and their increase in bioavailability will result in physical, chemical and biological disorders which may include decrease in mental development, reduced nervous system function, affecting lungs, kidneys, liver, heart, skin, blood composition and other organs in humans and other living organisms (Leland et al., 1978). Thus, chemical assessment and monitoring of bayou water characteristics is of high importance. The land use and land cover changes in an area are influenced by anthropogenic activities such as increase in residential, industrial, mining and other infrastructural facilities which in turn are associated with the economic growth of the area (Rawat et al., 2013).

Many highly urbanized cities such as Houston are vulnerable to flooding because of increased frequency of high intense rainfall in a short duration or sometimes continuous rainfall for a long duration (Kulkarni et al., 2014). Satellite images are an important source of data to monitor land use and land cover changes with remote sensing (Coppin and Bauer, 1996). This research focuses on characterization and comparison of the Buffalo and Brays Bayou watersheds of Houston in terms of the land cover changes, soil and water quality. The objectives of the study are 1) to monitor and assess the nutrient and metal concentrations in the water and soil samples along the Buffalo and Brays Bayou, 2) to map the long-term land cover changes within these urban watersheds, and 3) to assess the differential impact of land cover changes on the water and soil quality of the watersheds.

2. Material and methodology

2.1. *Water and soil sampling*

The seasonal water and soil sampling were conducted in Summer and Fall of 2019 along Buffalo Bayou and in Summer and Fall of 2017 along Brays Bayou. A total of 181 soil and 81 water samples were collected in triplicate from a total of 9 locations namely BB66.2, BB64.2, BB62, BB57, BB39.4, BB34.7, BB32.5, BB29.5, BB21.3 along the Buffalo Bayou and 4 locations namely BrB2.5, BrB5, BrB35.8 and BrB41.1 along the Brays Bayou (Fig. 1). The sample locations were named with letters followed by a number as suffix where the letters stand for the name of the bayou and the number represents the distance of the sample site in km from the mouth of the bayou. For example, the BB66.2 represents the

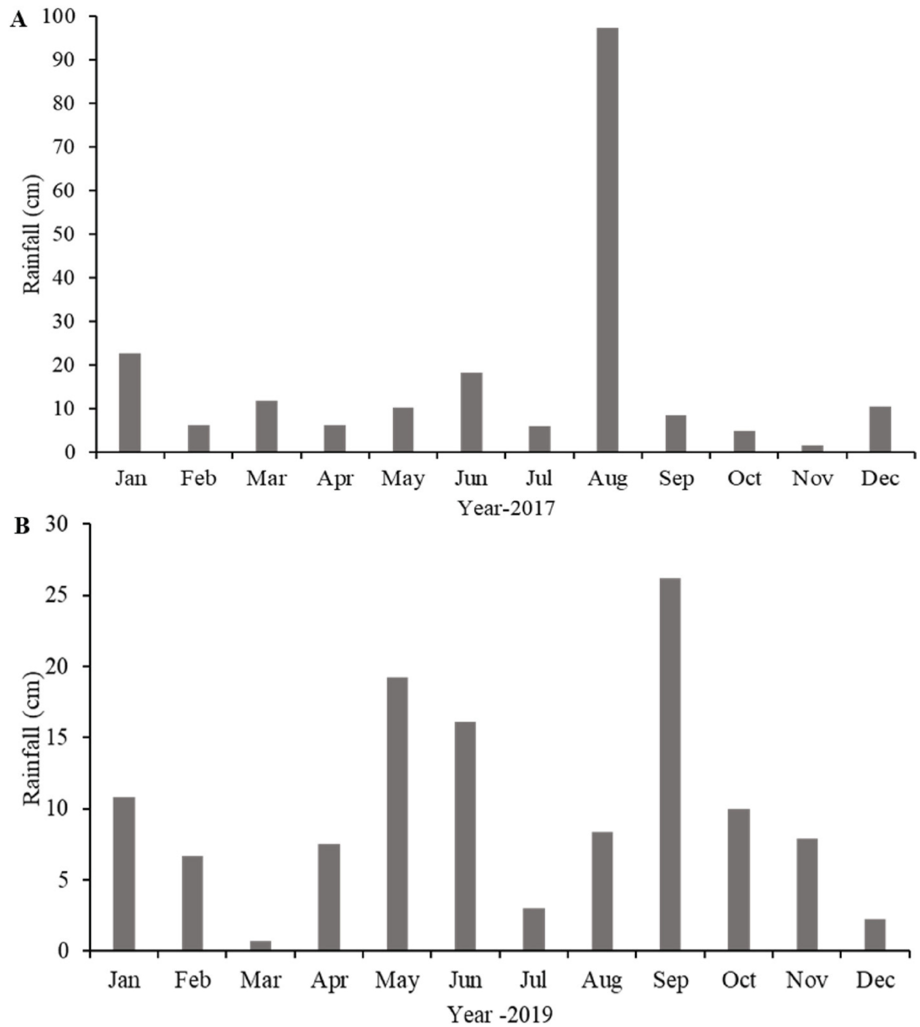

Fig. 2. Annual precipitation recorded in the Brays Bayou (A) and Buffalo Bayou watersheds during the water and soil sampling years of 2017 and 2019, respectively. The summer and fall sampling was conducted during the July and October months, respectively.

Buffalo Bayou sample site located at 66.2 km from mouth of the bayou.

The water samples were collected in 1-L sterile plastic bottles using a telescopic dipper. The soil samples were collected at three depths at 0–10, 10–20, and 20–30 cm using a soil core sampler and stored in plastic bags. Only the surface soil sample (0–10 cm) results are presented in this study. About three water and soil samples were collected from each of the sampling locations (Fig. 1) with a distance of at least 10m between the collected samples. All the soil samples were collected at least 3m away from the bank of the bayou. The summer and fall sampling was conducted during the July and October months, respectively. The longitude and latitude of each sampling location was recorded using a handheld Global Positioning System (GPS) receiver. The collected samples were immediately stored in a refrigerator set at −4 °C to keep fresh for chemical and bacterial analysis. The results of bacterial analysis will be published elsewhere. The annual precipitation recorded during the sampling years of 2017 and 2019 in the BBW and BrBW are shown in Fig. 2. The precipitation data was downloaded from Harris county flood warning system website (https://www.harriscountyfws.org/).

2.2. Chemical analysis

Soil samples were sieved, air dried and prepared for chemical analysis, where about 0.5 g of soil sample from each replicate was measured and microwave (Mars 6, CEM, Matthews, NC) acid digested in 10 ml of HNO_3 using EPA 3050B (USEPA, 1996) digestion method for soil. Similarly, about 10 ml of water samples were acidified with 0.6 ml of HNO_3 and 0.4 ml of HCl and then acid digested using the EPA 3015A method for water (Dirk et al., 1999). The digested samples were analyzed for Al, As, Ca, Cd, Cu, Cr, Fe, K, Mg, P, Pb, and Zn concentrations by using Inductive Coupled Plasma Mass Spectrometry (ICP-MS, Agilent 7500 Series, Santa Clara, CA). For air dried soil samples the Total C and N concentrations were analyzed using the Total Carbon and Nitrogen (TCN) Analyzer (TOC-V/SSM-5000A, Schimadzu, Columbia, Maryland, USA). All the samples were analyzed in triplicates and significant differences were evaluated through the analysis of variance (ANOVA). The Tukey's multiple range test was conducted using MINITAB statistical analysis software (MINITAB Inc., State College, PA).

An assessment index to measure the environmental concentrations of soil and water known as Single Element Pollution Index (SEPI) was applied (Pendias and Pendias, 2001; Kloke, 1979). The SEPI was calculated using the formula:

$$\text{SEPI} = \frac{\textit{Metal content in soil or water media}}{\textit{Permissible level of metal in the media}}$$

The Texas Human Health (THH) protection and Texas Commission on Environmental Quality (TCEQ) background criteria were adopted as permissible level for water and soil concentrations, respectively (TCEQ, 1999, 2014). The SEPI values of less than or equal to 1 was classified as low contamination, 1–3 as moderate contamination and more than 3 was considered as high contamination (Chen et al., 2005; Al Obaidy and

Table 1
Nutrient and other major elemental concentration in water samples collected from Buffalo and Brays Bayou (in mg L^{-1}). Given are mean values (n = 3) of three replicates.

Sampling Locations	C	N	P	K	Ca	Na	Mg	Al
Summer								
BB66.2	5.3	4.3 c	0.9 c	7.4 d	44.3 c	49.2 c	6.2 c	1.6 b
BB64.2	5.2	6.0 a	1.5 a	8.8 a	41.9 d	46.3 c	5.7 d	3.9 a
BB62	5.0	5.2 a	1.2 b	8.4 a	44.2 c	51.7 c	6.2 c	1.9 b
BB57	4.7	4.7 b	1.0 b	8.0 c	57.1 a	51.3 c	6.1 c	1.5 b
BB39.4	5.4	4.7 b	0.9 c	8.2 b	48.9 b	50.4 c	6.3 c	1.2 b
BB34.7	4.9	5.7 a	1.1 b	9.3 a	64.1 a	69.8 a	8.2 b	0.7 c
BB32.5	4.0	5.1 a	1.0 b	9.2 a	65.3 a	69.1 ab	8.5 b	0.1 c
BB29.5	13.6	5.2 a	0.9 c	9.0 a	65.3 a	69.8 a	8.1 b	0.1 c
BB21.3	3.8	5.3 a	0.7 d	9.0 a	65.3 a	63.6 b	9.2 a	0.1 c
Fall								
BB66.2	2.4 c	10.6 b	2.3 b	13.2 b	52.4 c	138.5 c	11.8 c	0.3 a
BB64.2	2.4 c	12.1 a	2.8 a	14.7 b	47.9 e	114.9 c	9.8 c	0.2 a
BB62	3.6 a	13.7 a	2.3 b	13.6 b	50.6 d	117.5 c	10.7 c	0.1 b
BB57	2.4 b	11.3 a	2.0 c	13.5 b	54.5 c	113.9 c	10.4 c	0.1 b
BB39.4	2.6 b	11.1 b	2.0 c	12.1 c	60.7 b	103.8 c	10.8 c	0.1 b
BB34.7	3.5 a	10.4 b	1.8 c	11.8 c	63.5 b	100.3 c	11.1 c	0.02 c
BB32.5	3.5 a	8.9 c	1.5 d	11.5 d	63.2 b	116.3 c	14.3 c	0.03 c
BB29.5	4.1 a	9.1 c	1.5 d	15.3 b	66.7 a	206.7 b	28.8 b	0.02 c
BB21.3	3.7 a	9.1 c	1.1 e	21.3 a	69.2 a	340.5 a	51.1 a	0.04 c
Summer								
BrB44.1	11.0 b	5.1 c	0.6 c	7.2 c	46.1 c	56.6 c	9.9 c	0.4 a
BrB35.8	10.5 c	14.5 a	2.2 a	11.9 c	51.4 b	72.7 c	8.5 c	0.3 ab
BrB5	11.4 a	8.1 b	1.6 b	15.9 b	57.3 b	208 b	25.9 b	0.2 b
BrB2.5	11.6 a	8.1 b	1.7 b	21.5 a	62.7 a	339 a	43.1 a	0.1 b

† Means followed by a different letter are significantly different at the 0.05 probability level, grouped into classes a, b, and c. The underlined values exceed the proposed critical limits.

Al Mashhadi, 2013). A Combined Pollution Index (CPI) was calculated, to identify the effect of multi-element contamination, where CPI was calculated using the formula:

$$CPI = \frac{(Metal\ content\ in\ media\ /Permissible\ level\ of\ metal\ in\ the\ media)}{Number\ of\ metals}$$

The CPI values of less than or equal to 1 was classified as low contamination, 1–2 as moderate contamination and more than 2 was considered as high contamination (Al Obaidy and Al Mashhadi, 2013).

2.3. Geospatial analysis

The flow lines, and watershed boundary layers were extracted from the National Hydrography Dataset (NHD) (https://www.usgs.gov/core-science-systems/ngp/national-hydrography/) and Houston-Galveston Area Council GIS datasets (http://www.h-gac.com/gis-applications-and-data/datasets.aspx). Water and soil sampling points of the study area were imported into GIS as separate vector layer. The data were downloaded and processed using the Arc GIS Version 10.5 software (ESRI, 2014).

Cloud free, Landsat imagery of the study area falling in Path 25 and Row 39 obtained over a period of 1984–2019, with at least 10-year intervals were downloaded and processed for land cover change analysis. Landsat imagery were downloaded from USGS Earth Explorer (https://earthexplorer.usgs.gov/) website, and processed using the ER Mapper V16.6 software (Hexagon Geospatial, 2020).

The vector outlines of BBW and BrBW were overlaid, clipped on the Landsat images and the study area subsets were extracted. The land cover changes were evaluated by mapping the vegetative and impervious surface characteristics as environmental indicators to map and monitor the landscape changes in BBW and BrBW. Land cover maps of the study areas were created using the unsupervised classification method which utilizes a maximum likelihood algorithm to classify pixels of the satellite imagery. Temporal and spatial images for the years 1984–2019 showing vegetation and impervious surface area change for each watershed were quantified and mapped. The land cover change data were mapped against the discharge flow rate of each bayou using

Table 2
Heavy metal concentrations in the water samples collected from the different locations along the Buffalo and Brays Bayou (in μg L^{-1}). Given are mean values (n = 3) of three replicates. Also given are the proposed critical limits for human health protection in water for specific metals (TCEQ, 2014; USEPA, 2018). THH = Texas Human Health protection criteria.

Sampling Locations	Fe	Cu	Zn	As	Pb	Cd
Summer						
BB66.2	753 b	3.6	75.2	3.7 b	7.8	2.8
BB64.2	1793 a	4.0	104.5	9.3 ab	8.2	0.7
BB62	873b	2.9	62.4	15.2 a	5.5	2.7
BB57	708b	2.9	76.4	6.5 ab	7.5	0.6
BB39.4	565bc	3.1	214	8.4 ab	5.3	1.7
BB34.7	330 c	3.2	70.4	1.6 b	4.8	1.4
BB32.5	51 c	3.6	43.4	12.5 a	3.2	1.7
BB29.5	63 c	3.9	142	17.1 a	2.5	1.2
BB21.3	43 c	3.0	43.7		3.5	2.0
Fall						
BB66.2	136 a	4.5	21.3 c	10.9	6.5	0.2
BB64.2	117 a	4.6	31.3 a	18.4	7.3	0.7
BB62	64.5 b	3.9	25.6 b	12.1	15.7	0.4
BB57	43.3 b	3.8	24.6 b	14.2	16.2	0.3
BB39.4	42.5 b	3.5	20.2 c	13.8	16.4	0.6
BB34.7	21.1 c	2.6	17.4 d	17.4	7.8	0.3
BB32.5	26.2 c	2.6	17.5 d	18.9	7.9	0.5
BB29.5	15.7 c	1.1	15.1 e	16.5	6.8	0.9
BB21.3	26.0 c	3.4	15.8 e	12.2	13	0.5
Summer						
BrB44.1	780	48.5	172	1.9 a	21.3	26.7
BrB35.8	370	42.6	85.5	1.2 b	9.6	7.3
BrB5	520	42.4	62.4	1.1 b	8.5	7.0
BrB2.5	570	40.0	99.5	1.0 b	7.2	12.1
Criteria						
THH				10	1.15	5
EPA	1000	2		10	10	5

† Means followed by a different letter are significantly different at the 0.05 probability level, grouped into classes a, b, and c. The underlined values exceed the proposed critical limits.

Table 3
Nutrient and other major elemental concentration in flood plain soil samples collected from Buffalo Bayou (in mg kg^{-1}). Given are mean values (n = 3) of three replicates.

Sampling Locations	C	N	P	K	Ca	Mg	Fe
Summer							
BB66.2	4193 b	390 a	93	648 ab	2011	696b	3908 b
BB64.2	4117 b	310 b	87	465 ab	3464	663 b	3034 b
BB62	3447 b	254 b	71	802 a	2800	896 b	3627 b
BB57	2753 b	193 b	48	438 ab	2369	532 b	2240 b
BB39.4	2317 b	195 b	52	430 ab	2070	564 b	2140 b
BB34.7	4543 b	330 b	84	509 ab	2716	620 b	2542 b
BB32.5	4663 b	220 b	62	422 ab	2965	508 b	2038 b
BB29.5	5320 ab	273 b	64	296 b	3089	384 b	1910 b
BB21.3	10,750 a	735 a	117	925 a	7573	1468 a	6475 a
Fall							
BB66.2	1803 b	163 b	48	324b	1415	472	2734
BB64.2	3720 b	286 b	132	582.3 ab	2815	747	3539
BB62	1720b	103 b	52	429.3b	1843	544	2524
BB57	2970b	200 b	63	446.9b	2735	513	2964
BB39.4	4997 ab	300 b	91	684 ab	2939	880	3784
BB34.7	3740b	213 b	96	558.1 ab	2579	675	2900
BB32.5	1883 b	97 b	57	334b	2045	407	1826
BB29.5	3947 b	190 b	61	322.3b	3526	405	2071
BB21.3	8080 a	637 a	88	966a	2333	844	3949

† Means followed by a different letter are significantly different at the 0.05 probability level, grouped into classes a, b, and c.

Table 4
Heavy metal concentrations in the soil samples collected from the different locations along the Buffalo Bayou (in mg kg^{-1}). Given are mean values (n = 3) of three replicates. Also given are the proposed Texas specific soil background concentrations (TCEQ, 1999).

Sampling Locations	Cr	Cu	Zn	As	Pb	Cd
Summer						
BB66.2	8.8 a	2.2 b	19.6		5.0 ab	0.3 a
BB64.2	5.8 b	3.7 b	21.7	2.7	4.5 ab	0.2 b
BB62	9.4 a	7.0 ab	26.4	2.0	2.0 b	0.3 a
BB57	5.3 b	2.5 b	18.7	3.8	2.8 ab	0.2 b
BB39.4	5.1 b	3.5 b	34.2	1.1	0.9 ab	0.2 b
BB34.7	6.2 b	3.7 b	24.4	2.2	2.3 ab	0.1 b
BB32.5	4.2 b	4.4 ab	19.3	2.3	5.6 ab	0.1 b
BB29.5	4.8 b	4.2 ab	27.9	1.1	5.7 ab	0.1 b
BB21.3	12.1 a	11.7 a	47.5	1.7	10.6 a	0.5 a
Fall						
BB66.2	5.2	6.7	13.0 b	2.9	4.8 c	0.2
BB64.2	7.1	10.6	22.5 ab	3.5	5.4 b	0.2
BB62	4.9	8.6	11.1 b	4.9	4.5 c	0.1
BB57	5.9	3.2	12.8 b	5.3	3.8 c	0.2
BB39.4	8.8	4.1	21.9 ab	3.3	7.1 ab	0.3
BB34.7	7.2	4.6	19.7 ab	3.5	6.3 b	0.6
BB32.5	4.1	4.0	13.7 b	4.8	8.8 ab	0.1
BB29.5	4.7	5.4	22 ab	4.1	12.8 a	0.2
BB21.3	9.7	6.5	42.7 a	2.9	10.9 a	0.4
Criteria						
Background	30	15	30	5.9	15	

† Means followed by a different letter are significantly different at the 0.05 probability level, grouped into classes a, b, and c. *Not significantly different.

bayou discharge data obtained from the USGS monitoring stations for the same period (https://txpub.usgs.gov/txwaterdashboard/index.html). Finally, the chemical analysis data, spatial and temporal data were integrated to analyze the overall landscape change pattern, in BBW and BrBW. Landsat image classification accuracy assessment was conducted with reference of 182 and 101 random ground truth sampling points for BBW and BrBW, respectively, that were collected with GPS device in the field and using high resolution google earth imagery for assessment of every classified image. The data is summarized and quantified by using error matrices.

3. Results

3.1. Buffalo Bayou water sample analysis

The elemental concentrations in the Buffalo and Brays Bayou water samples collected in different seasons are given in Tables 1 and 2. Our results show that the N, K, Na, Mg, As and Pb concentrations in water were higher in the fall compared to summer in Buffalo Bayou (Tables 1 and 2). Concentrations of K, Ca, Mg in water increased significantly from upstream (BB66.2, BB64.2, BB62) to downstream (BB29.5, BB21.3) in both the seasons (Table 1) while Fe concentrations were higher in upstream compared to downstream of Buffalo Bayou (Table 2).

The N concentrations in water at BB66.2, BB64.2, BB62, BB57, BB39.4 and BB34.7 in the fall exceeded the Texas Human Health (THH) criteria of 10 ppm concentration in water samples. The P concentrations in water at all the sampling locations of Buffalo Bayou were well above the recommended maximum level of 0.1 ppm which is the proposed critical limit of EPA for algal bloom occurrence in surface water (Table 1). The Cu, As and Pb concentrations in Buffalo Bayou water samples collected during both seasons remained above their THH or EPA criteria of 2, 10 and 1.15 ppb, respectively (Table 2). The Cd concentration remained below the THH and EPA criteria of 5 ppb at all the locations while the Fe concentration at BB64.2 in summer exceeded the EPA criteria of 1000 ppb in water (Table 2).

3.2. Brays Bayou water sample analysis

The elemental concentrations of Brays Bayou water samples are shown in Tables 1 and 2, no water samples were collected in the fall season. Concentrations of K, Ca, Na and Mg increased significantly from upstream (BrB44.1, BrB35.8) to downstream (BrB5, BrB2.5) while no specific trend was observed for rest of the elements in Brays Bayou (Tables 1 and 2). The N concentrations in BrB35.8 exceeded the Texas Human Health (THH) criteria of 10 ppm concentration in water samples. The P concentrations in all the sampling locations of Brays Bayou exceeded the 0.1 ppm which is the proposed critical limit of EPA for algal bloom occurrence in surface water (Table 1). The Cu, Pb and Cd concentrations in all the Brays Bayou water samples exceeded the THH or EPA criteria of 2, 1.15 and 5 ppb, respectively (Table 2). The Cu and Fe concentration remained below the EPA criteria of 2 and 1000 ppb, respectively, at all the locations of Brays Bayou (Table 2).

3.3. Buffalo Bayou soil analysis

The concentrations of C, N, P, K, Ca, Mg, and Fe in Buffalo Bayou soil samples increased significantly from upstream (BB66.2, BB64.2, BB62) to downstream (BB29.5, BB21.3) in both the seasons (Table 3). No significant seasonal difference was seen in the soil chemical concentrations (Table 3). The concentrations of Cr, Cu, Zn, Pb and Cd increased significantly from upstream to downstream (Table 4) along the bayou. The Cr, Cu, As, and Pb soil concentrations remain below the soil background concentrations during both the seasons (Table 4). No significant temporal differences were found between the sampling locations

Table 5
Nutrient and other major elemental concentration in flood plain soil samples collected from Brays Bayou (in mg kg^{-1}). Given are mean values (n = 3) of three replicates.

Sampling Locations	C	P	K	Ca	Mg	Fe
Summer						
BrB41.1	40,640	160	455 ab	13,154 a	1240 a	2522 a
BrB35.8	10,420	88	522 a	10,821 b	1181 a	2068 a
BrB5	15,760	206	215 b	10,253 b	566 b	1518 b
BrB2.5	8620	75	104 b	4412 c	269 b	1155 b
Fall						
BrB41.1	13,100 a	163 b	758 a	13,415 b	1678	4853
BrB35.8	4200 ab	546 a	500 a	20,369 b	1354	3705
BrB5	10,400 ab	281 a	455 ab	42,134 a	1573	2896
BrB2.5	1000 c	165 b	217 b	46,735 a	1244	2907

† Means followed by a different letter are significantly different at the 0.05 probability level, grouped into classes a, b, and c.

Table 6
Heavy metal concentrations in the soil samples collected from the different locations along the Brays Bayou (in mg kg^{-1}). Given are mean values (n = 3) of three replicates. Also given are the proposed Texas specific soil background concentrations (TCEQ, 1999).

Sampling Locations	Cr	Cu	Zn	As	Pb	Cd
Summer						
BrB41.1	2.5 a	3.3 b	25.1 ab	0.8 ab	6.9	0.1 a
BrB35.8	2.2 b	1.7 b	16.2 b	0.4 b	7.2	0.04 b
BrB5	2.9 a	5.7 a	45.2 a	0.5 ab	17.4	0.1 a
BrB2.5	2.2 b	2.9 b	29.6 ab	0.3 b	16.1	0.1 a
Fall						
BrB44.1	5.3	6.1	56.1	0.6	11.7	1
BrB35.8	4.4	8.9	92.4	0.7	11.5	1.4
BrB5	9.9	34.3	107.4	0.7	38.2	0.4
BrB2.5	6.9	28.7	66.5	0.7	30.6	0.9
Criteria						
Background	30	15	30	5.9	15	

† Means followed by a different letter are significantly different at the 0.05 probability level, grouped into classes a, b, and c. *Not significantly different.

(Table 4). The Zn soil concentrations at BB21.3 remained above the soil background levels of 30 ppm during both the seasons (Table 4).

3.4. Brays Bayou soil analysis

The concentrations of C, P, K, Ca, Mg, and Fe in Brays Bayou soil samples decreased significantly from upstream (BrB41.1, BrB35.8) to downstream (BrB5, BrB2.5) in both the seasons (Table 5). The soil chemical concentrations were higher in the fall season compared to the summer (Table 5). The concentrations of Cr, Cu, Zn, Pb and Cd increased significantly from upstream to downstream (Table 6). The Cu, Zn and Pb soil concentrations were higher in the fall compared to the summer. The Cr and As soil concentrations remain below the soil background concentrations during both the seasons (Table 6) along the bayou. The Cu and Pb concentrations along the downstream locations of BrB5 and BrB2.5 remained above the soil background levels of 15 ppb. The Zn concentrations at all the locations in fall and at BrB5 in summer remained above the background soil concentration of 30 ppm (Table 6).

The SEPI values of water samples for Cu and Pb were higher in both Brays and Buffalo Bayous during both the seasons compared to the As and Cd concentrations (Table 7). The As values in Brays Bayou were lower than Buffalo Bayou while Cd values remain higher (Table 7). The As and Cu values in Buffalo Bayou during the fall season were higher and are classified as moderately contaminated, as their SEPI values were in the range of 1–3. The Pb contamination all along the Buffalo Bayou sampling locations were classified as of higher contamination with SEPI values exceeding 3. The Cd contamination was classified as low in both

Table 7
Single Element Pollution Index (SEPI) and Combined Pollution Index (CPI) of water samples collected from the different locations along the Buffalo and Brays Bayou (in μg l^{-1}). Given are mean values (n = 3) of three replicates.

Sampling Locations	Cu	As	Pb	Cd	CPI
Summer					
BB66.2	1.8	0.4	6.8	0.6	0.2
BB64.2	2.0	0.9	7.1	0.1	0.3
BB62	1.5	1.5	4.8	0.5	0.4
BB57	1.5	0.7	6.5	0.1	0.2
BB39.4	1.6	0.8	4.6	0.3	0.3
BB34.7	1.6	0.2	4.2	0.3	0.2
BB32.5	1.8	1.3	2.8	0.3	0.3
BB29.5	2.0	1.7	2.2	0.2	0.3
BB21.3	1.5		3.0	0.4	0.1
Fall					
BB66.2	2.3	1.1	5.7	0.0	0.3
BB64.2	2.3	1.8	6.3	0.1	0.4
BB62	2.0	1.2	13.7	0.1	0.4
BB57	1.9	1.4	14.1	0.1	0.5
BB39.4	1.8	1.4	14.3	0.1	0.5
BB34.7	1.3	1.7	6.8	0.1	0.4
BB32.5	1.3	1.9	6.9	0.1	0.4
BB29.5	0.6	1.7	5.9	0.2	0.3
BB21.3	1.7	1.2	11.3	0.1	0.4
Summer					
BrB44.1	24.3	0.2	18.5	5.3	1.4
BrB35.8	21.3	0.1	8.3	1.5	0.8
BrB5	21.2	0.1	7.4	1.4	0.8
BrB2.5	20.0	0.1	6.3	2.4	0.8

Table 8
Single Element Pollution Index (SEPI) and Combined Pollution Index (CPI) of soil samples collected from the different locations along the Buffalo and Brays Bayou (in mg kg^{-1}). Given are mean values (n = 3) of three replicates.

Sampling Locations	Cu	Zn	Pb	CPI
Summer				
BB66.2	0.1	0.7	0.3	0.1
BB64.2	0.2	0.7	0.3	0.2
BB62	0.5	0.9	0.1	0.2
BB57	0.2	0.6	0.2	0.1
BB39.4	0.2	1.1	0.1	0.2
BB34.7	0.2	0.8	0.2	0.2
BB32.5	0.3	0.6	0.4	0.2
BB29.5	0.3	0.9	0.4	0.2
BB21.3	0.8	1.6	0.7	0.4
Fall				
BB66.2	0.4	0.4	0.3	0.1
BB64.2	0.7	0.8	0.4	0.2
BB62	0.6	0.4	0.3	0.1
BB57	0.2	0.4	0.3	0.1
BB39.4	0.3	0.7	0.5	0.2
BB34.7	0.3	0.7	0.4	0.2
BB32.5	0.3	0.5	0.6	0.1
BB29.5	0.4	0.7	0.9	0.2
BB21.3	0.4	1.4	0.7	0.3
Summer				
BrB44.1	0.2	0.8	0.5	0.2
BrB35.8	0.1	0.5	0.5	0.1
BrB5	0.4	1.5	1.2	0.4
BrB2.5	0.2	1.0	1.1	0.3
Fall				
BrB44.1	0.4	1.9	0.8	0.4
BrB35.8	0.6	3.1	0.8	0.6
BrB5	2.3	3.6	2.5	1.0
BrB2.5	1.9	2.2	2.0	0.7

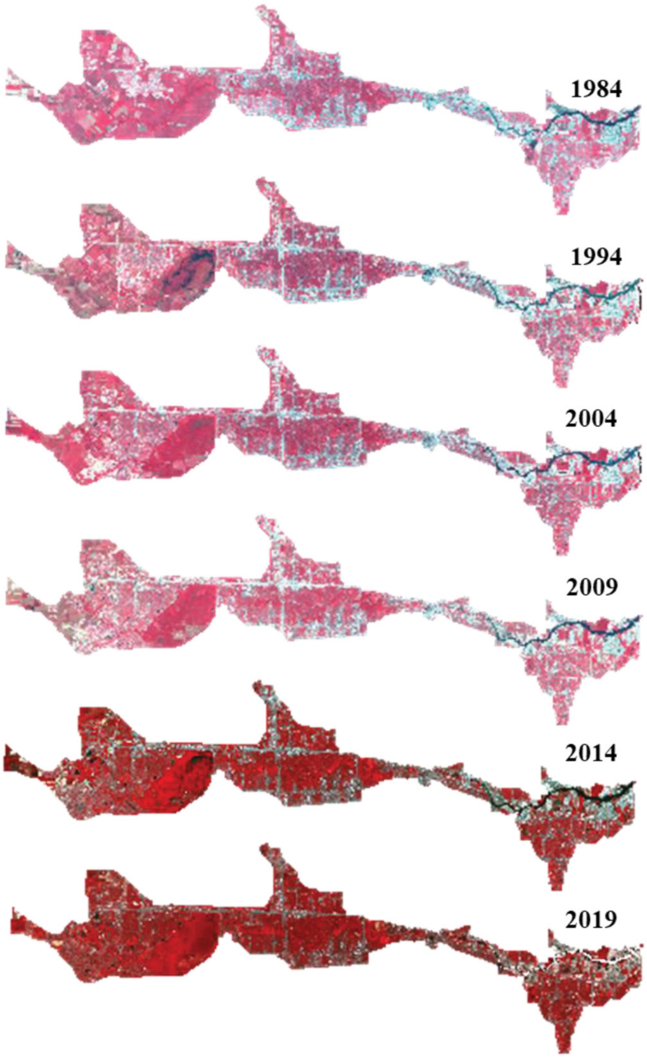

Fig. 3. The pseudo color image of the Buffalo Bayou watershed where Landsat 5 bands 2, 3, 4 were shown in blue, green and red, respectively, while the Landsat 8 bands 3, 4, 5 were shown in blue, green and red, respectively. The vegetation appears in shades of red while the urban areas appear in pale white to lighter shades, the wetland areas and water appear dark. The eastern part of the study area is dominated by urban impervious surface while the western part by vegetation. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

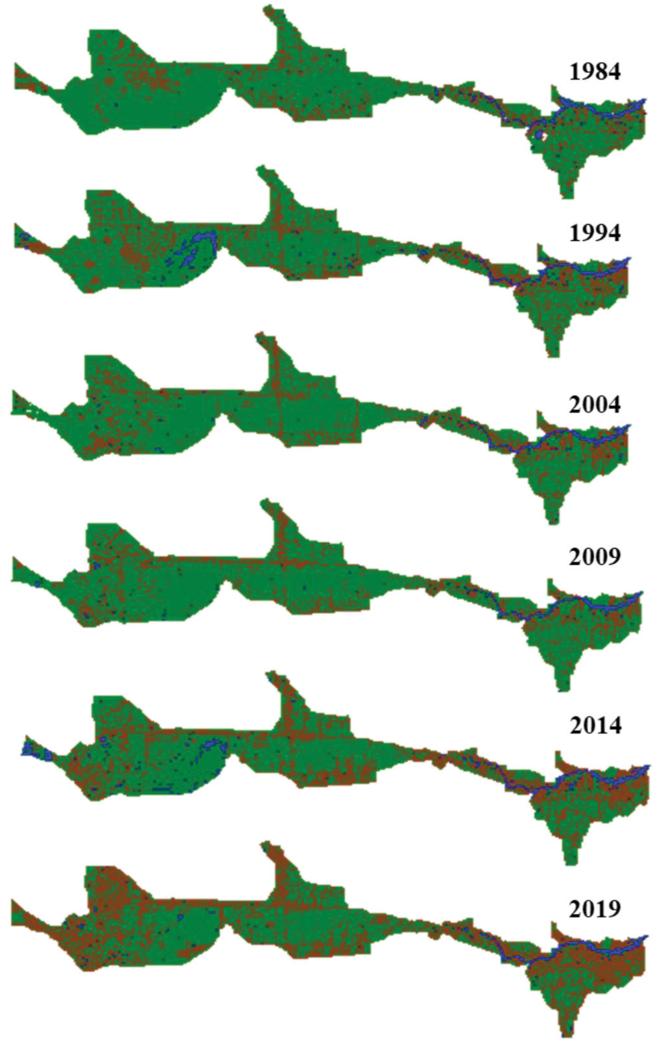

Fig. 4. The unsupervised classification images of the Buffalo Bayou watershed (BBW) where the areas covered with vegetative surface, and impervious were shown in green, and brown, respectively. The impervious surface areas increased at the expense of the vegetative cover during the period of 1984–2019. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the Bayous as the SEPI values remain mostly below 1 (Table 7). The Cu and Pb values of Brays Bayou were higher than the Buffalo Bayou water samples and are classified as of higher contamination as their SEPI values exceeded 3. The CPI values of the water indicate that the combined metal contamination value of the water is low, as the values remain below 1, during both the seasons in the Buffalo and Brays Bayou (Table 7). However, the Brays Bayou is relatively more contaminated than Buffalo Bayou with CPI values ranging from 0.8 to 1.4 (Table 7).

The SEPI value of Zn in the downstream soil samples of Buffalo and Brays Bayou remain high during both the seasons (Table 8). All the soil samples along the Brays Bayou during fall were moderately polluted with Zn as the SEPI values remain mostly in the range of 1–3. The Cu and Pb values of soil at BrB5 and BrB2.5 locations along the downstream of Brays Bayou during fall are of moderate contamination as their SEPI values remain in the range of 1–3 (Table 8). The CPI values of soil ranged from 0.1 to 0.4 along Buffalo Bayou and 0.1 to 1.0 along Brays Bayou indicating lower level of contamination in their flood plain soils.

3.5. Land cover change in Buffalo Bayou watershed (BBW)

A pseudo color image of the BBW corresponding to the periods of 1984, 1994, 2004, 2014 and 2019 (Fig. 3) shows the vegetation in shades of red color and the impervious surfaces such as roads, parking lots, and roof tops in white to grey color and the surface waters in dark blue to black color in the imagery. Land cover changes in BBW during 1984–2019 are shown in Fig. 4. The brown color in the image is indicative of impervious surfaces in the watershed while the vegetative surfaces were represented in green color. With the progression of time from 1984 to 2019, a clear increase in the impervious surface is seen along the western and eastern parts of the BBW. Most of the impervious surface increase happened at the expense of the vegetative surface. About 34.8% decrease in vegetative land cover and a 145.3% increase in impervious area was observed from 1984 to 2019 (Fig. 5). The increase in impervious surface area and decrease in vegetation remain consistent and gradual throughout the time period.

The changes in BBW land cover was further mapped against discharge flow of the bayou over time. The results indicated that an increase in the impervious surface area over the last three decades is proportional to the increase in the maximum water discharge in the

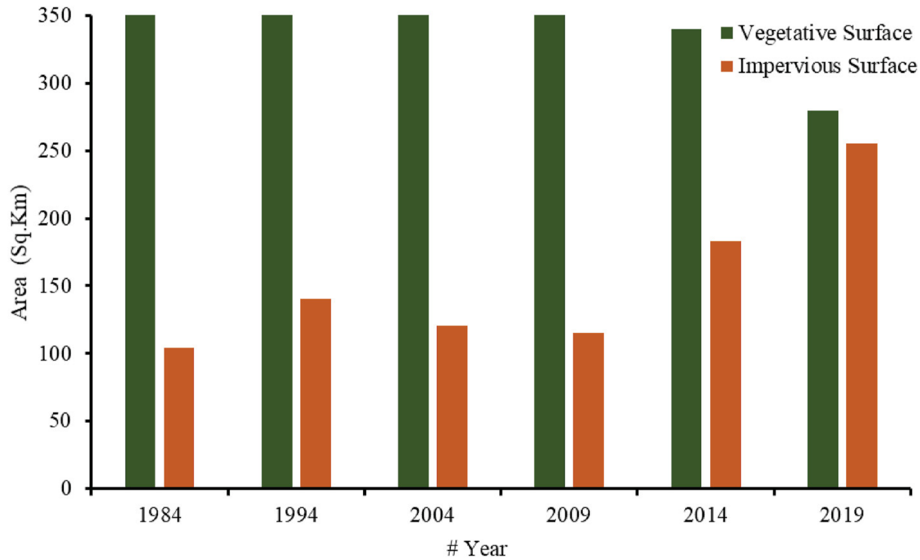

Fig. 5. Change in the area of impervious and vegetative suface over the period of 1984–2019 in the Buffalo Bayou Watershed (BBW).

bayou. The change in vegetative surface is negatively correlated to the flow rate of bayou which clearly indicates that the decrease in vegetative cover was decreasing the infiltration rate within the bayou. The maximum discharge in the Buffalo Bayou increased significantly while the impervious surface within the watershed increased by 145.3% and the vegetative surface decreased by 34.8% during the period of 1984–2019 (Fig. 9).

3.6. Land cover changes in Brays Bayou watershed (BrBW)

The pseudo color (Fig. 6) and the land cover classification images (Fig. 7) of BrBW showed that with the progression of time from 1984 to 2019, a clear increase in the impervious surface and decrease in vegetative cover was seen along Brays Bayou. Most of the impervious surface increase happened at the expense of the vegetative surface, where a 34.5% decrease in vegetative land cover and a 140.4% increase in impervious area occurred between 1984 and 2019 in the BrBW (Fig. 8). The increase in the impervious surface area and decrease in the vegetative cover remain consistent and rapid during the time period compared to the BBW. The maximum discharge in the Brays Bayou increased significantly while the impervious surface area within the watershed increased by 140.4% and the vegetative surface decreased by 34.5% during the period of 1984–2019 (Fig. 10).

The accuracy assessment of each classified Landsat image of BBW and BrBW from 1984 to 2019 are given in Table 9 and Table 10, respectively. The overall accuracy of the BBW and BrBW imagery ranged from 96.1% to 100% and 83.2%–99%, respectively. The kappa statistic ranged from 0.93 to 0.99 and 0.72 to 0.88 for the selected imagery of BBW and BrBW, respectively (Tables 9 and 10).

4. Discussion

The N and P concentration in the Buffalo and Brays Bayou water ranging at 4.3–14.5 mg l^{-1} and 0.6–2.8 mg l^{-1}, respectively, during both the seasons exceeded the typical U.S. urban storm water concentration of 2.0 mg l^{-1} for N and 0.26 mg l^{-1} for P (Schueler, 2003; Carey et al., 2013). The P concentration in the range of 0.01–0.75 mg l^{-1} is the appropriate level to control the nuisance algal blooms in fresh water (USEPA, 2002). High N, P and other nutrient concentrations in the bayou water in fall over the summer (Table 1) can be attributed to the domestic and municipal waste water disposal as well as intensification of runoff from residential yards, roads, agricultural and industrial activities within the watersheds. The precipitation and storm water runoff in both BBW and BrBW is generally higher in fall over summer seasons (Fig. 2). The discharge from Waste Water Treatment Plants (WWTP) is a major factor affecting the nutrient loads in urban streams (Andersen et al., 2004; Ekka et al., 2006; Carey et al., 2013). Sanitary sewer overflows are a major problem in both Brays and Buffalo Bayous. About 390 sanitary sewer overflows were reported in Brays Bayou watershed during 2001–2003 (TCEQ, 2010). The high concentration of Na in downstream locations of Buffalo Bayou (BB29.5, BB21.3) in fall and in Brays Bayou downstream at BrB5 and BrB2.5, remained above the EPA criteria limit of 200 ppm, can be attributed to the slow drainage and backing up of estuary into the bayou. The high Na concentration in fall compared to summer season in Buffalo Bayou can be attributed to slow drainage and backing up of estuary water at the confluence with the Houston Ship Channel.

The concentration of As (Table 2) was significantly higher all along the Buffalo Bayou during both seasons and is also higher than the general range of As in natural water which is 1–2 ppb (Hindmarsh and McCurdy, 1986; USNRC, 1999; WHO, 2011a). Exposure to high As concentration in water increases the risk of cancer to the skin, lung, bladder, kidney and increase cardiovascular and neurological disorders (IPCS, 2001; Milton et al., 2001) The concentration of Pb is higher than the THH criteria of 1.15 ppb and getting close to the EPA proposed maximum critical limit of 10 ppb in both the bayous (Table 2). High concentration of Pb in water is poisonous affecting the health of infants, and children affecting the brain development and functions of central nervous system (WHO, 2011b; Jakubowski, 2011). The high concentration of As and Pb in fall over the summer can be attributed to the high seasonal flooding during which the industrial and WWTP released high volumes of untreated effluents into the bayous. High concentration of Pb and As cause nervous and reproductive disorders, skin cancer and endocrinal disruptions (WHO, 2011a; Cobbina et al., 2015). Kiaghadi and Rifai (2019) showed high levels of As and Pb in bayou waters after the Hurricane Harvey in Houston. High metal and nutrient concentration in Buffalo and Brays Bayou can be attributed to the presence of several WWTP outfalls, large and small-scale industries and high impervious surface area within the drainage watershed. WWTP and storm water runoff are considered as large sources of surface water pollution in urban areas (Paul and Meyer, 2001). The concentration of Cu and Cd (Table 2) was significantly higher all along the Brays bayou and was higher than the EPA criteria of 2 and 5 ppm, respectively. Cadmium at low exposure levels will cause kidney damage, bronchitis and at high levels will damage nervous and immune system and causes cancer (Cobbina et al., 2015). The high concentration of Fe at BB64.2 in

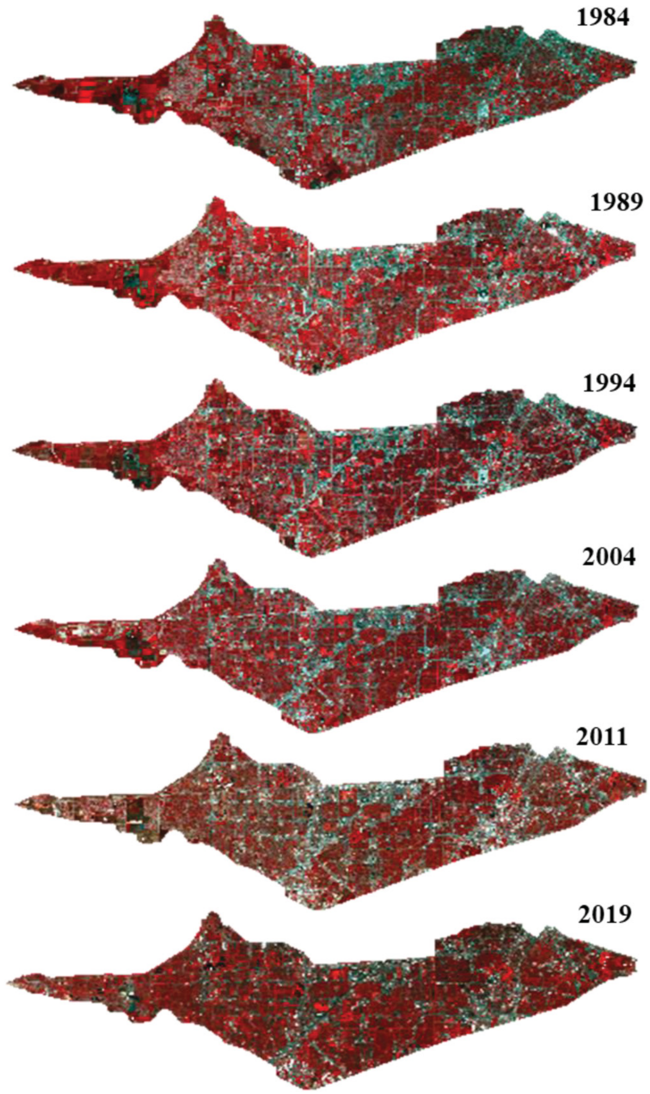

Fig. 6. The pseudo color image of the Brays Bayou watershed where Landsat 5 bands 2, 3, 4 were shown in blue, green and red, respectively, while the Landsat 8 bands 3, 4, 5 were shown in blue, green and red, respectively. The vegetation appears in shades of red while the urban areas appear in pale white to lighter shades. Gradual urbanization is seen in the images from 1984 to 2018. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

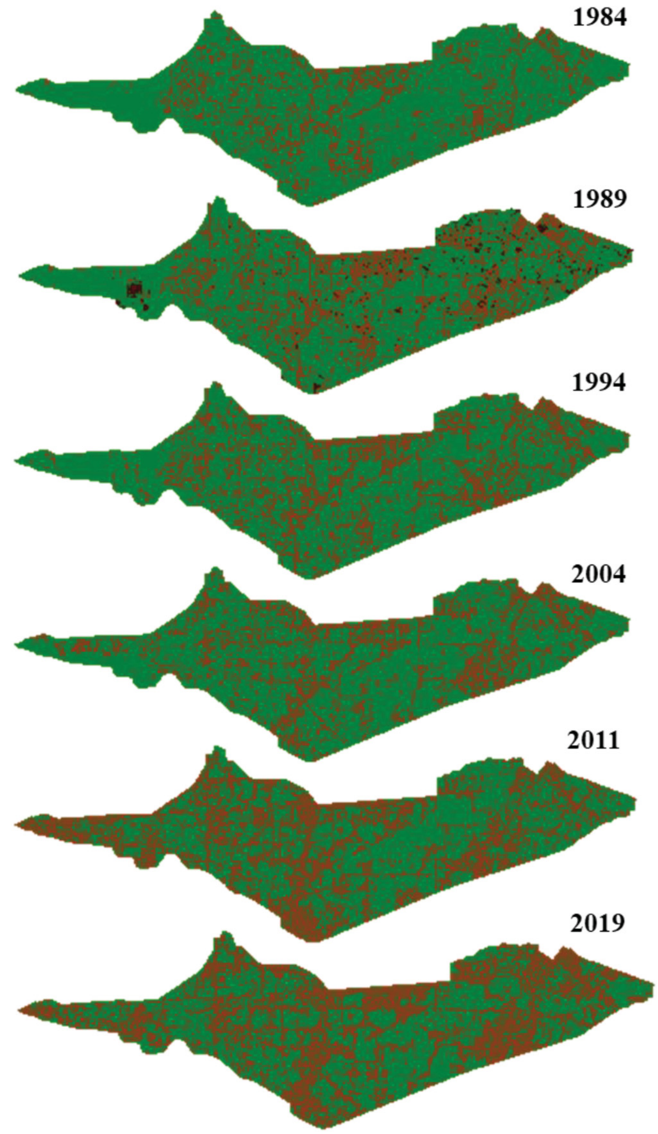

Fig. 7. The unsupervised classification images of the Brays Bayou watershed (BBW) where the areas covered with vegetative surface, and impervious were shown in green, and brown, respectively. The impervious surface areas increased at the expense of the vegetative cover during the period of 1984–2019. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Buffalo Bayou and Zn at BrB44.4 and BB29.5 of Brays and Buffalo Bayou, exceeding the EPA criteria, can be the result of the localized contamination sources in the respective bayous (Table 2). Houston is the second largest petrochemical hub in the world and many of these facilities flood during heavy rain events resulting in accidental leak or release of pollutants into the bayous and streams (Santschi et al., 2001; Du et al., 2020).

The soil nutrient and metal concentration increased from upstream to downstream among the sites of Buffalo Bayou (Table 3). All the metal concentration remained below the background soil concentrations except for the Zn which exceeded the background soil concentration at BB21.3 during both the seasons (Table 4). The soil nutrient concentrations showed less variation among the sites of Brays Bayou during both the seasons (Table 5). The Brays Bayou soil metal concentrations were higher during fall compared to summer season, where the Cu, Zn and Pb soil concentrations exceeded the background soil criteria of their respective elements, especially in the downstream locations of BrB5 and BrB2.5 (Table 6). Soils become contaminated with heavy metals by disposal of metal wastes, leaded gasoline and paints, insecticide and pesticide application, petrochemical spills and atmospheric deposition (Wuana and Okieimen, 2011; Khan et al., 2008; Zhang et al., 2010).

The Cu, Pb and Cd concentrations of Brays Bayou water were higher than the Buffalo Bayou samples and were at least about 20, 6 and 1.5 times higher than the criteria limit of the elements (Table 7). The combined metal contamination of Brays Bayou water is classified as low to moderately contaminated compared to lower contamination of Buffalo Bayou water. The Cu, Zn and Pb concentration of Brays and Buffalo Bayou soils at the downstream locations were higher than the existing background concentration of the respective elements (Table 8). The combined metal contamination of BrBW and BBW were classified as of lower contamination (Table 8). Brays Bayou became increasingly prone to flooding in the last three decades resulting in severe inundation of its flood plain soils (Bass et al., 2017). The frequent flooding might have contributed to increase in the metal contaminant accumulation along the flood plain soils of Brays Bayou.

The overall Landsat classification accuracy of BBW is in the range of

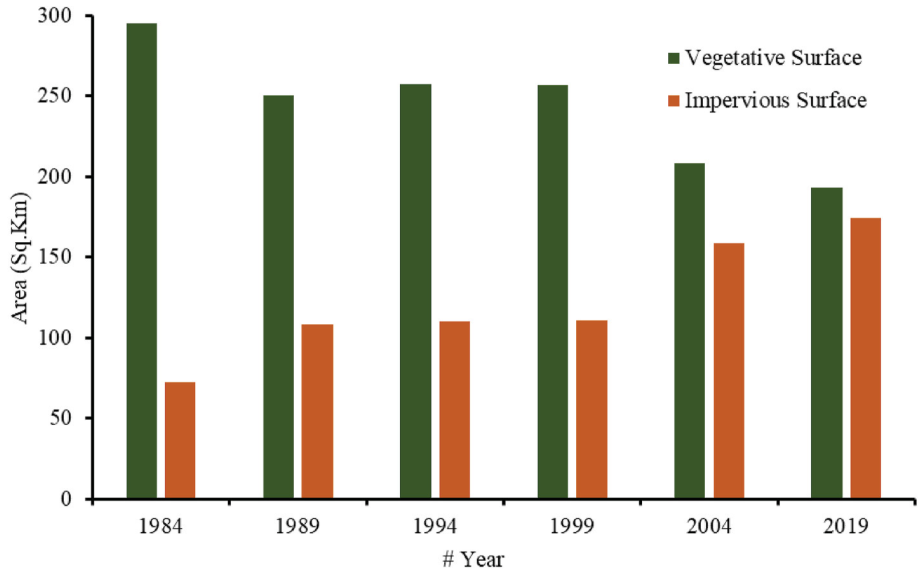

Fig. 8. Change in the area of impervious and vegetative suface over the period of 1984–2019 in the Brays Bayou Watershed (BrBW).

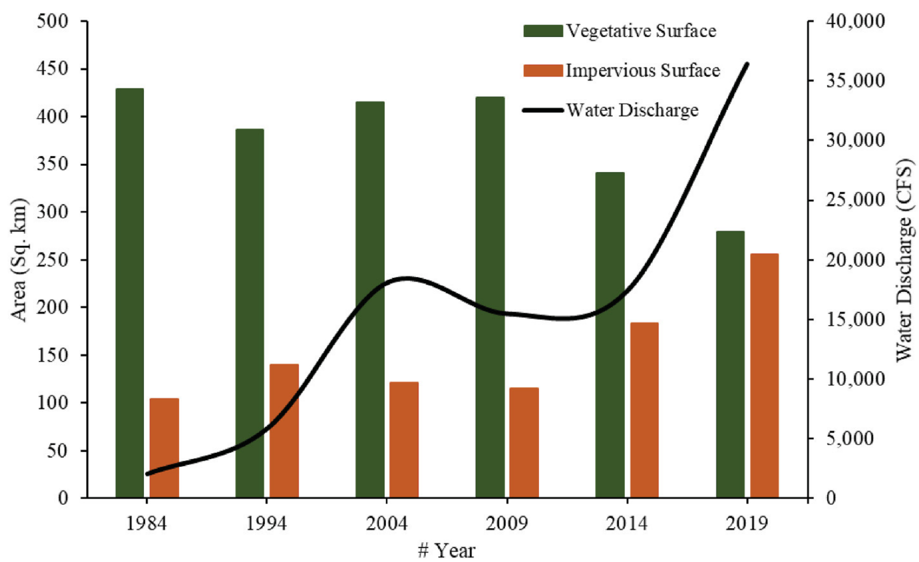

Fig. 9. Land cover changes in the Buffalo Bayou Watershed (BBW) and the water discharge in the Buffalo bayou during the period of 1984–2019.

95.1%–99.4% for the imagery of 1984–2019 (Table 9) is higher than the suggested minimum level of interpretation accuracy of 85% (Anderson et al., 1976). In case of BrBW, the overall Landsat classification accuracy of BBW is in the range of 86.2%–99% for the imagery of 1984–2019 (Table 10), which is also within the acceptable range of interpretation accuracy of 85% (Anderson et al., 1976). The low overall classification accuracy of 86.2% and kappa statistic of 0.72 was found in case of 2011 imagery of BrBW because of the slight cloud cover found in the western most part of the watershed (Table 10; Fig. 5). The user's and producer's accuracy for the vegetative and impervious surface cover land cover was found to be high for BBW imagery (Table 9) and BrBW imagery (Table 10), which is sufficient to produce an overview of the landscape change pattern within the watershed.

The land cover change analysis revealed that the impervious surface increased by 145.3% and the vegetative surface decreased by 34.8% in the BBW while the impervious surface increased by 140.4% and vegetative surface decrease by 34.5% in BrBW during the period of last three decades (Figs. 5 and 8). The total impervious surface percentage, which is the ratio percentage of total impervious surface to the total area of the BBW increased from 19.5% in 1984 to 47.7% in 2019 while in BrBW it increased from 19.7% in 1984 to 47.4% in 2019. According to Juan et al. (2019) Brays Bayou had significantly higher development change and increased urban runoff compared to Buffalo Bayou during 1970–2011. The channelized Brays Bayou has lower vegetation on either side of its banks compared to Buffalo Bayou which is preserved in its natural state (Juan et al., 2019). Higher vegetative cover can decrease soil and water contamination and flooding. A 5–10% increase in total impervious surface (Schiff and Benoit, 2007) in a watershed can impair water quality while 10–20% (Exum et al., 2005) will cause significant aquatic degradation (Carey et al., 2013). The land cover results for BBW and BrBW are consistent with the vegetative surface loss findings of Zhu et al. (2015) which showed that the Houston metropolitan area has changed dramatically with watersheds experiencing up to 40% increase in developed areas and vegetation loss from 20 to 60% between 1980 and 2006.

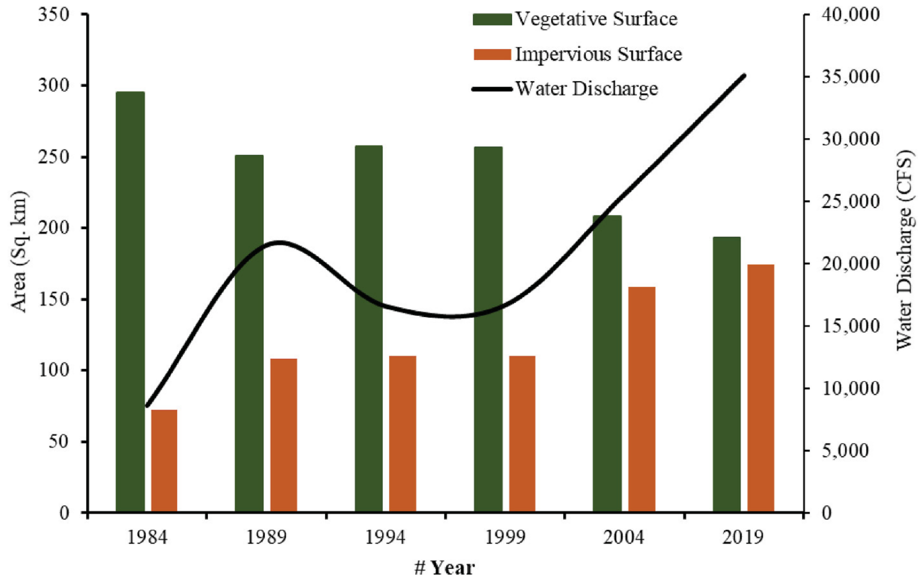

Fig. 10. Land cover changes in the Brays Bayou Watershed (BrBW) and the water discharge in the Brays bayou during the period of 1984–2019.

Table 9
Summary of user's (U), producer's (P), overall accuracy (%) and kappa statistic of land cover change maps of Buffalo Bayou Watershed.

Land Cover	1984		1994		2004		2009		2014		2019	
	U	P	U	P	U	P	U	P	U	P	U	P
Vegetative Surface	98.1	100	98	98	100	90	100	90	100	100	96.2	98
Impervious Surface	100	100	95.7	86.5	89.7	100	89.6	100	100	98.1	96.1	96.2
Water	100	100	100	98	98	96.1	100	98	98.1	100	100	98
Overall Accuracy	99.4		95.1		96.2		96.7		99.3		97.4	
Kappa Statistic	0.99		0.93		0.94		0.95		0.99		0.96	

Table 10
Summary of user's (U), producer's (P), overall accuracy (%) and kappa statistic of land cover change maps of Brays Bayou Watershed.

Land Cover	1984		1989		1994		2004		2011		2019	
	U	P	U	P	U	P	U	P	U	P	U	P
Vegetative Surface	98.1	100	92	90.2	97.9	98	91.1	100	86.3	86.2	98.1	100
Impervious Surface	100	98	92	92	92.6	92	100	90	86	86	100	98
Overall Accuracy	99		90.2		95.1		95		86.2		99	
Kappa Statistic	0.98		0.81		0.90		0.91		0.72		0.98	

5. Conclusions

Land cover change due to human activities is an important parameter that impacts the global environmental and ecological change by altering complex biophysical processes at global, regional and local scales (Wasige et al., 2013; Wu et al., 2003). Impervious surface increase in BBW and BrBW effectively alters hydrological pathways, enhance nutrient transport and thus impact the natural biogeochemical cycle of the region. High concentration of N, P, K, Na, As and Pb in fall over summer Buffalo Bayou water samples can be attributed to seasonal flooding which overwhelms the waste water treatment and industrial plants along the bayou. The Cu, Zn and Pb concentration built up in BrBW and BBW soils is evident as the metal concentrations exceeded the background soil concentrations. Similarly, the concentrations of As, Cu, Cd and Pb in water exceeded the safety limits for human health. The nutrient and metal increase in water and soils of BBW and BrBW can be attributed to several point and non-point pollutant source locations in the downstream, as several waste water outlets dump all along the length of the Buffalo and Brays bayou. The total N and P concentrations in our water samples exceeds the EPA nutrient criteria for rivers and streams which is 0.76 ppm for total N and 0.128 ppm for total P, exceeding which results in eutrophication of waterbodies. The seasonal variation is more prominent in the water samples compared to soil samples. Continuous in situ sensors of water quality parameters will promote the better understanding of the urban bayou systems.

The increasing impervious surface and decreasing vegetative surface in both the watersheds are increasing the velocity and volume of surface water runoff. Optimizing watershed management practices to reduce chemical inflow and decrease in the flood water runoff is critical to improve the water and soil quality of BBW and BrBW. This study improves the understanding of the land cover change in BBW and BrBW which is recognized as a critical gap in the knowledge of vegetation loss, soil and water degradation, and eutrophication of Galveston Bay. Further research involving the use of high resolution satellite and aerial imagery along with a comprehensive water analysis for extensive inorganic and organic contaminants covering the entire watershed will be greatly beneficial. Urban growth with environmental sustainability is key to the future economic growth in the region where urban development should be planned by conserving the natural resources. Conservation of the wetland areas, reducing the inflow of domestic sewage and industrial effluents, developing and preserving the vegetative buffer strips around the drainage streams, along with the control of point and non-point source pollution is crucial to prevent the decline in the water quality and to promote urban watershed sustainability.

Credit author statement

Titilope Bukunmi-Omidiran: Data curation, Writing – original draft, Visualization, Investigation. Maruthi Sridhar: Conceptualization, Methodology, Writing- Reviewing and Editing, Funding acquisition, Project Supervision and Administration

Ethical statement

We declare that all ethical practices have been followed in relation to the development, writing, and publication of the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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