Water Air Soil Pollut (2017) 228:336
DOI 10.1007/s11270-017-3538-7

Effect of Land Cover Changes on the Sediment and Water Quality Characteristics of Brays Bayou Watershed

Sharmila Bhandari · B. B. Maruthi Sridhar · Bobby L. Wilson

Received: 24 May 2017 / Accepted: 11 August 2017

Abstract Rapid increase in impervious surfaces due to urbanization often intensifies the frequency of flooding which in turn increases runoff of environmental pollutants. The Brays Bayou watershed (BBW) is a heavily urbanized and densely populated watershed located mostly in Harris County, TX. The objectives of our study are (1) to analyze and interpret the spatial and temporal land use and land cover changes in BBW and (2) to determine nutrient, heavy metal, and bacterial contamination in the Brays Bayou. Water and sediment samples were collected from selected sampling locations along the Brays Bayou and analyzed for various nutrient and metal concentrations. Bacterial analysis was conducted to enumerate the fecal coliform bacteria in water samples. Landsat Thematic Mapper (TM) satellite images sampled from over three decades (1980–2010) for the BBW study area were processed and analyzed for land use and land cover changes. Our remote sensing analysis revealed that the BBW lost about 28.4% (9463 acres) vegetation during the period of 1984 to 2010. The loss in vegetative areas resulted in increased impervious surface areas. In sediment samples, increasing trends for Al, Cu, Fe, Pb, and Zn were observed towards the downstream of Brays Bayou. Lead concentrations were found at the highest concentration (70 mg/kg) in certain Brays Bayou sampling locations. *Escherichia coli* concentrations decreased towards the downstream of Brays Bayou and were found below 200 maximum probable numbers/100 ml. Integration of remote sensing along with the chemical and biological analysis helped to understand the impact of land cover changes on the bayou water quality.

Keywords Urban watersheds · Flooding · Water quality · Remote sensing · Geographic information systems (GIS)

S. Bhandari · B. B. Maruthi Sridhar (✉)
Department of Environmental and Interdisciplinary Sciences, Texas Southern University, Houston, TX 77004, USA
e-mail: bhaskarm@tsu.edu

B. L. Wilson
Department of Chemistry, Texas Southern University, Houston, TX 77004, USA

1 Introduction

As the world population increases, more people are gravitating towards urban areas. Natural resources in rapidly growing urban regions are increasingly being transformed to accommodate the demand of developmental expansion. Urbanization often results in increase of infrastructure facilities, industrial expansion, construction of roads to support the economic and social developmental activities (Alsaaideh et al. 2011), and thus causing an expansion of watershed impervious surface and resulting in a decline of ecological sustainability. World urban population is estimated to reach 9.8 billion in 2050 (United Nations 2017). Impervious surfaces such as roads, rooftops, parking lots, buildings, and sidewalks alter the surface runoff affecting the water quality, habitat, aquatic ecosystems, public health, and esthetic appearance of waters (Uygun and Aldek 2015; Wissmar et al. 2004). Urban land cover changes also

Published online: 18 August 2017

result in increase of urban heat islands (Xiao et al. 2007). Excessive heat and increase in air temperature can alter the weather and rainfall patterns by decreasing or increasing the amount of surface water over extended periods of time. Excessive amounts of water received in the form of heavy rain over a short period of time can lead to flash flooding events. Urban impervious surfaces enhance flash flooding by reducing infiltration and surface storage of precipitation (Arnold and Gibbons 1996). Also, the litter being transported in the flood water can clog man-made drains and prolong flooding on surfaces by diminishing drainage capacity.

Floods can cause socio-economic and environmental damages to the ecosystem. During the past 30 years, flooding killed more than 200,000 people and affected more than 2.8 billion people worldwide (Menne and Murray 2013). In 2006, the USA experienced on average a total of $6 billion in damage and 140 deaths per year (USGS 2006). Floods also have negative impacts on mental health (Fernandez et al. 2015). The flood waters that penetrate the walls of homes and businesses promote the growth of mold and fungal infection by increasing the indoor dampness (IOM 2011; Rao et al. 2007; Belanger et al. 2003; Portnoy et al. 2001; Solomon et al. 2006). Individuals living in flooded houses often experience increase in respiratory-related problems such as allergies and asthma (Emerson et al. 2015; Hoppe et al. 2012; IOM 2011). When flooding occurs, water bodies receive biological, physical, radioactive, and chemical contaminants from both point and non-point sources of pollution (Eisakhani et al. 2009) resulting in adverse health impacts within urban environments (Brezonik and Stadelmann 2002). Though heavy metals occur naturally at very low concentrations, anthropogenic activities such as smelting, mining, and sewage irrigation are affecting the natural distribution of these metals in air, aquatic, and terrestrial environments (Kim et al. 1998; Niu et al. 2013). Heavy metals are considered toxic, persistent, and bioavailable pollutants because they pose serious health hazards to living organisms and ecosystem (Fu et al. 2010; Song et al. 2014; Zhang et al. 2015).

Appropriate design and sampling plans are required to provide information that can be useful to manage urban watersheds. Environmental indicators are specific physical, chemical, and biological parameters which can provide a relationship between environmental stressors and the response on the living organisms (Niemi et al. 2007). A few examples of indicators for land use and land cover change include vegetation and impervious surface areas. Additionally, trace metal contaminants are indicators of aquatic pollution.

The objectives of our study are (1) to analyze and interpret the spatial and temporal land use and land cover changes in Brays Bayou watershed (BBW) and (2) to determine nutrient, heavy metal, and bacterial contamination in the Brays Bayou. This research uses an innovative and integrated approach of remote sensing, geographic information systems (GIS), and field analysis to create a link between stressors, environmental indicators, and pollutants. It is significant because it contributes to the limited amount of data that currently exists on BBW in terms of historical changes and pollution levels.

2 Materials and Methods

2.1 Brays Bayou Watershed

The BBW is a highly urbanized and densely populated watershed that serves as a drainage basin for Brays Bayou which runs from the west fork of Katy to the Houston Ship Channel. About 87% of BBW is located in the southwest part of Harris County and the remaining portion lies in the Fort Bend County (TCEQ 2009). A larger portion of the land surrounding Brays Bayou was already developed prior to the existence of detailed floodplain mapping (Lester and Gonzalez 2005). This urban sprawl has not occurred without some environmental impacts such as increased pollution and flooding in bayous and the surrounding watersheds that are designed to hold the excess water until it drains into larger water bodies such as the Houston Ship Channel and Galveston Bay. Pollution has been introduced into the waterways from known and unknown sources. These sources include factories situated near the waterways; pollutants released as a result of combustion from the boats, ships, and other recreation vehicles; littering; effluents released from sewage pipes; storm water runoff; and tires from automobiles.

There are several open space and recreational parks in this BBW region. Approximately 95 sq. miles of this watershed is densely populated and highly developed (Bedient et al. 2002). It flows through cities of Houston, Missouri City, Stafford, and Bellaire and drains into a common outlet, Houston Ship Channel, and it has three primary streams: Brays Bayou, Keegans Bayou, and

Willow Waterhole Bay (HCFCD 2016). There are about 121 miles of open streams within the watershed, and it receives an average annual rainfall of 47.7″ per year (TCEQ 2009). Along its journey, it receives inflows from industrial and residential sources and other waterways.

From 1997 to 2001, Harris County, TX, alone had 26 flood events which caused about 1.6 billion dollars in property damage (Brody et al. 2008). In recent years, BBW has experienced more frequent flooding events. The Memorial Day flood occurred on May 25, 2015 (Hamilton 2015), and the Tax Day flood occurred on April 18, 2016 (Mulligan 2016). Based on the floods that devastated many neighborhoods that are located along the BBW, it is necessary to identify the areas that are prone to flooding in order to implement future remediation plans. At present, the lower part of the bayou is mostly paved but little to no work has been done towards the upper portion of the watershed, thus leaving it in natural conditions.

2.2 Sampling Locations Along BBW

The water and sediment sampling locations distributed across the BBW are given in Fig. 1. A total of 21 water samples and 21 sediment samples were collected from 7 different sampling locations along the Brays Bayou. At each of the 7 sampling locations, the water and sediment samples were collected in triplicate. The samples B1 to B9 were collected in the upper BBW (UBBW) and B10 to B21 were collected from the lower BBW (LBBW). The sampling locations were recorded using a handheld Global Positioning System (GPS) receiver. Samples were stored and transported immediately to the laboratory and kept at −4 °C until further environmental analysis was performed.

2.3 Heavy Metal Analysis

Water and sediment samples collected were acid digested using a microwave digestion unit (Mars 6, CEM, Matthews, NC) using EPA 3015a and 3051a method, respectively. For water samples, 5 ml of HNO_3 was mixed with 45 ml of water sample for acid digestion. For sediment samples, 0.5 g air-dried, sieved sediment sample was mixed with 10 ml of HNO_3 for microwave acid digestion. Each sample was filtered using the Glass Fiber Filter (GFF) paper. The water and sediment samples were analyzed for Al, As, Ca, Cd, Cu, Fe, Hg, K, Mg, Na, Pb, and Zn by using the inductive coupled plasma mass spectrometry (ICP-MS, Agilent 7500 Series, Santa Clara, CA). Results of soil and sediment samples were statistically analyzed and Pearson's correlation coefficients were calculated to identify the relationship among analyzed heavy metals.

2.4 Analysis of *Escherichia Coli* Concentration in Water Samples

Bacterial *E. coli* concentration was enumerated using EPA 1604 method for all the 21 water samples collected from Brays Bayou. About 100 ml of the water sample was filtered using a membrane filter. The membrane filter was rolled on the agar pre-plated media and made sure that the membrane filter was properly placed on the agar. Petri plates were placed in an inverted position for incubation at 37 ± 0.5 °C for 24 h. After incubation, content of *E. coli*/100 ml water was counted using the equation: *E. coli*/100 ml = (No. of E-coli colonies/ Volume of sample filtered) * 100.

2.5 Landsat Image Analysis and Interpretation

Six Landsat Thematic Mapper (TM) images corresponding to the time periods of (1) Aug 17, 1984, (2) June 9, 1988, (3) Aug 5, 1997, (4) Aug 27, 1999, (5) Aug 3, 2002, and (6) Aug 25, 2010, all having 0% cloud cover were selected for this study. Images were then downloaded from the USGS Global Visualization viewer, GLOVIS (http://glovis.usgs.gov) website, and processed using the ERDAS ER Mapper image software. Several spectral ratio and single-band combinations were derived from the dark-object-subtracted (DOS) values for each of the seven bands. A DOS value of a band is defined as one value lower than the minimum digital number found in all pixels of that particular image for that band (Vincent et al. 2004; Sridhar et al. 2009, 2011). The vector layers of BBW study areas were overlaid and extracted from each of the downloaded satellite images and then used for further image analysis. The land use and land cover changes were analyzed by choosing the vegetation and impervious surface parameters as environmental indicators to monitor the natural and human-induced disturbances in BBW. Normalized Difference Vegetation Index (NDVI) was calculated by using the formula NDVI = ((Band 4 − Band3)/Band 4 + Band 3) (Rouse et al. 1974). An NDVI mask value of greater than 0.2 was used to map the

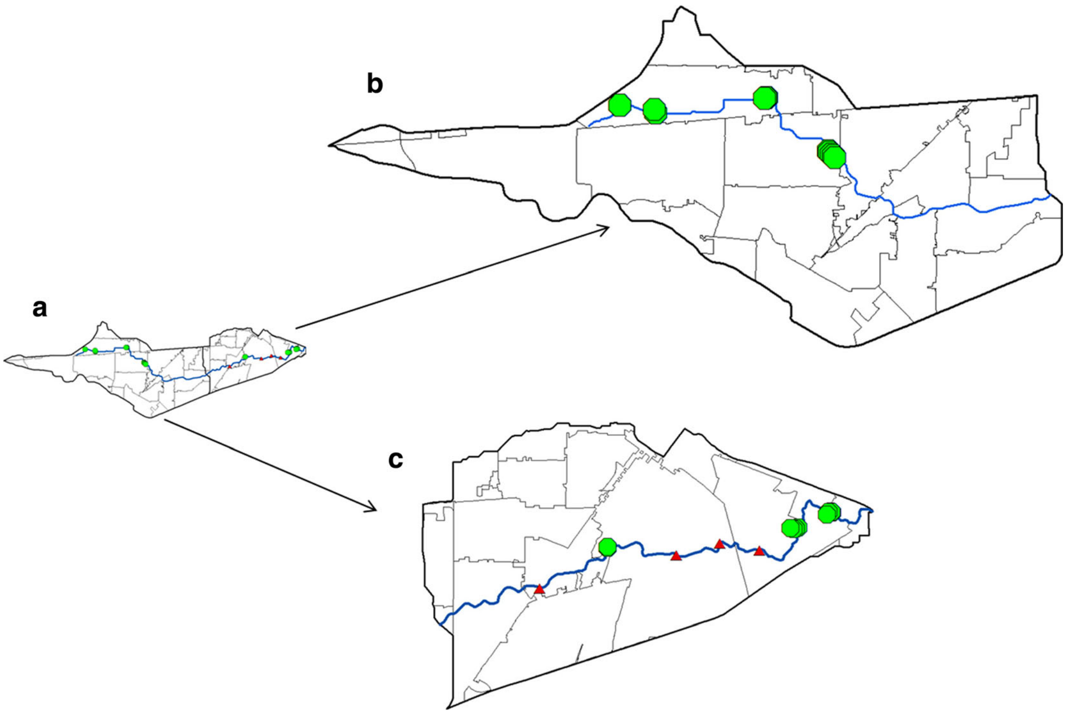

Fig. 1 Water and sediment sampling locations along Brays Bayou. The Brays Bayou watershed (a) is shown along with the upper Brays Bayou watershed (b) and lower Brays Bayou watershed (c). The water and sediment sampling locations are shown as green dots while the USGS historical sampling locations are shown as red triangles. At each of the seven sampling locations, the water and sediment samples were collected in triplicate. The blue flow line represents the Brays Bayou along with the regions of zip codes in the back ground

vegetation. The temporal and spatial changes in vegetation and impervious surface areas from 1984 to 2010 were quantified and mapped individually for all the selected Landsat images for BBW.

GIS data was collected and assembled from numerous sources for the geospatial analysis. These include Houston Galveston Area Council (http://www.h-gac.com/rds/gis-data/gis-datasets.aspx), Census Bureau (http://factfinder.census.gov/faces/nav/jsf/pages/ index.xhtml), Texas Commission of Environmental Quality (TCEQ; http://www.tceq.state.tx.us/gis/download-tceq-gis-data), EPA (https://www.epa.gov/ geospatial), and USGS National Land Cover database (NLCD; http://www.mrlc.gov/nlcd11_data.php). Study areas were extracted and separated into upper and lower watersheds (UBBW and LBBW). Sampling points, bayous, and bayou watersheds were imported as separate layers. A buffer of 1 km was created for the bayou (with 500 m on each side), and the surrounding land use and land cover pattern were analyzed from the downloaded Landsat imagery for the past three decades.

Historical data for trace metals, nutrients, and bacterial content were downloaded from TCEQ (https://www.tceq.texas.gov/assets/public/waterquality) and United States Geological Survey (USGS; http://waterdata.usgs.gov). Finally, field data, historical data, and spatial temporal data were combined to evaluate the overall change pattern, to compare the trends in contamination levels around study sites.

3 Results

3.1 Land Use and Land Cover Change Analysis of Brays Bayou Watershed and Brays Bayou

The natural color image of BBW where bands 1, 2, and 3 are displayed in blue, green, and red color is shown in Fig. 2. The vegetation appears in green color and the impervious surface such as roads, parking lots, and roof tops appear in white to gray color (Fig. 2). The NDVI images showing the robust vegetation for the UBBW (Fig. 3a, b) and LBBW (Fig. 3c, d) are shown for the

Fig. 2 A natural color image of the study area where Landsat bands 1, 2, and 3 are shown in blue, green, and red, respectively. The satellite image was obtained on Aug 25, 2010. The white line represents the Brays Bayou along with a 1-km buffer

1984 and 2010 time periods. Heavily vegetated areas appear as red to bright yellow in color while impervious surface areas appear as light to dark blue or black in color (Fig. 3). The vegetation has decreased overtime throughout the UBBW as indicated by the reduction in the red and bright yellow colors (Fig. 3). The UBBW shows a clear increase in the impervious surface area such as expansion of the roads and highways in 2010 (Fig. 3b) compared to 1984 (Fig. 3a). Towards the west corner of UBBW (towards Fort Bend County), Grandpark Tollway and Westpark Tollway were constructed after 2000 (FBCTRA 2016). Figure 3c, d shows a comparison between NDVI images taken from 1984 and 2010 for LBBW. The spread of the impervious surface area from north to south of lower Brays Bayou can be visualized as most of the vegetation in the southern part of the LBBW (Fig. 3c) starts to disappear by 2010 (Fig. 3d).

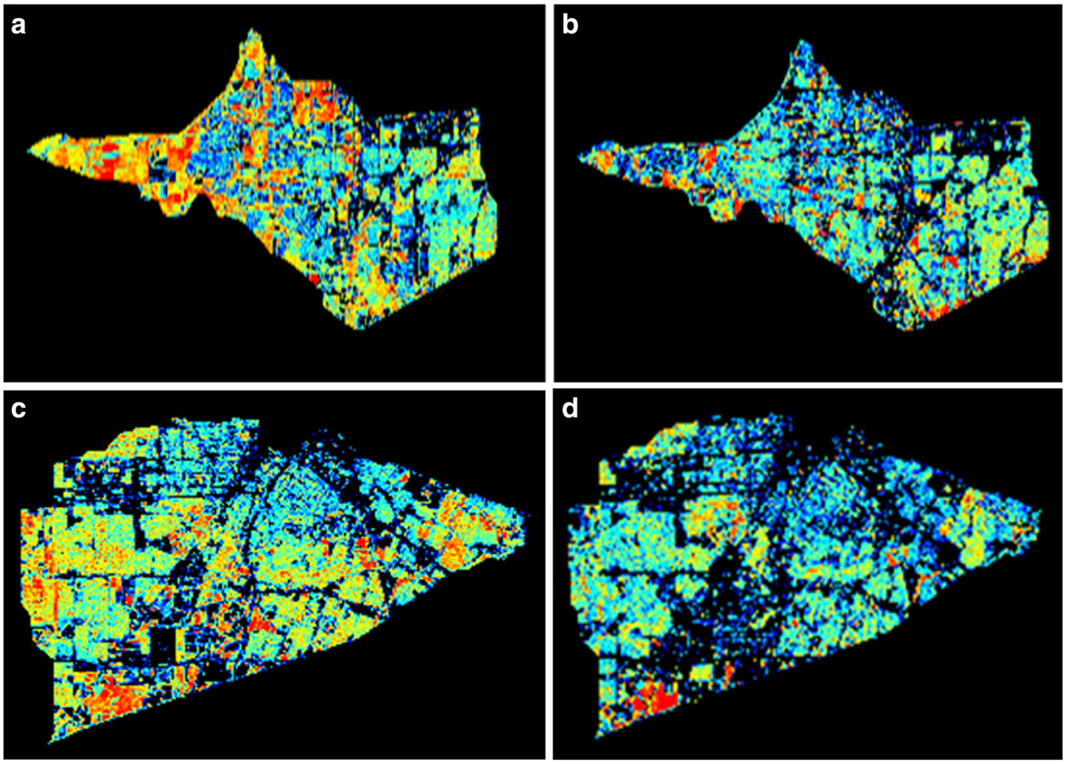

Fig. 3 Normalized Difference Vegetative Index (NDVI) of Landsat TM images of the upper and lower Brays Bayou watershed (UBBW and LBBW) for 1984 and 2010. The UBBW shows a decrease in vegetation and increase in impervious surface from 1984 (**a**) to 2010 (**b**). The LBBW shows an increase in impervious surface from 1984 (**c**) to 2010 (**d**). UBBW in 1984 (**a**), UBBW in 2010 (**b**), LBBW in 1984 (**c**), and LBBW in 2010 (**d**). Robust vegetation appears in red and yellow colors and impervious surface appears in different shades of blue to black. A mask of NDVI < 0.2 was applied to the image

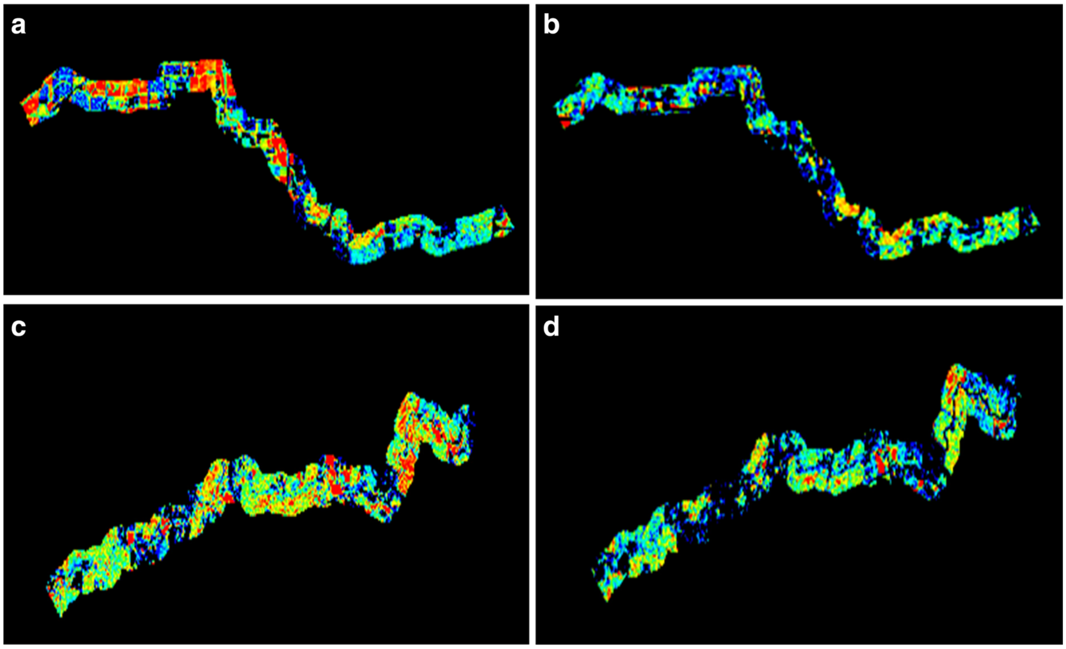

Fig. 4 Normalized Difference Vegetative Index (NDVI) of Landsat TM images of the upper and lower Brays Bayou flood plain regions (UBB and LBB) for 1984 and 2010, where only the flood plain areas within 1 km of the Brays Bayou are shown. The UBB region shows a decrease in vegetation and increase in impervious surface from 1984 (**a**) to 2010 (**b**). The LBB region shows an increase in impervious surface from 1984 (**c**) to 2010 (**d**). UBBW in 1984 (**a**), UBBW in 2010 (**b**), LBBW in 1984 (**c**), and LBBW in 2010 (**d**). Robust vegetation appears in red and yellow colors and impervious surface appears in different shades of blue to black. A mask of NDVI < 0.2 was applied to the image

A 1-km buffer area was created surrounding the Brays Bayou to see how the land cover has changed from 1984 to 2010, in the immediate vicinity within the flood plain area of the bayou. The vegetation change in UBB is shown in Fig. 4a, b, and vegetation change in LBB is shown in Fig. 4c, d for the 1984 and 2010 time periods. Dense vegetation was changed into lightly sparse vegetation in all portions of the bayous from 1984 to 2010. Vegetation loss in the UBB was mostly seen towards the upper end of the bayou (Fig. 4a, b). The LBB flood plain showed a significant decrease in the vegetation as we move from east to west along the bayou (Fig. 4c, d). Some parts of the LBB show complete imperviousness because of the complete paving of the bayou along the bank channels. Significant increase in imperviousness was shown in the middle part and lower part of the UBB (Fig. 4b).

3.2 Surface Area Change in Brays Bayou Watershed and Brays Bayou Flood Plain

The increase in impervious surface area and decrease in vegetation during 1984 to 2010 for UBBW are quantified in Fig. 5a and for LBBW in Fig. 5b. The impervious area increased by 3402 acres in UBBW and by 6601 acres in LBBW from 1984 to 2010. The increase in impervious surface for LBBW is about twice that of UBBW during the three-decade time period. Vegetation lost for UBBW was 5589 acres and for LBBW was 3474 acres from 1984 to 2010.

In the 1-km buffer region of flood plains of UBB (Fig. 5c) and LBB (Fig. 5d), approximately 550 acres and 750 acres of vegetative land were lost from 1984 to 2010, respectively. Overall decrease in vegetation within the 26-year period in UBB and LBB was 10 and 16% (Fig. 5c, d), respectively. The increase in impervious area for UBB and LBB was in contrast to the decrease in vegetation content (Fig. 5c, d) during the same period. The LBB had experienced more percentage of vegetation loss than the UBB. The reason being that the LBB is in close proximity to the city of Houston and the urban sprawl has more impact on the vegetation and ecological characteristics of this part of the bayou. Overall increase in impervious surface area in UBB over the 26-year time period was 249 acres (Fig. 5c). LBB has a 1126-acre increase in impervious surface area from 1984 to 2010 (Fig. 5d).

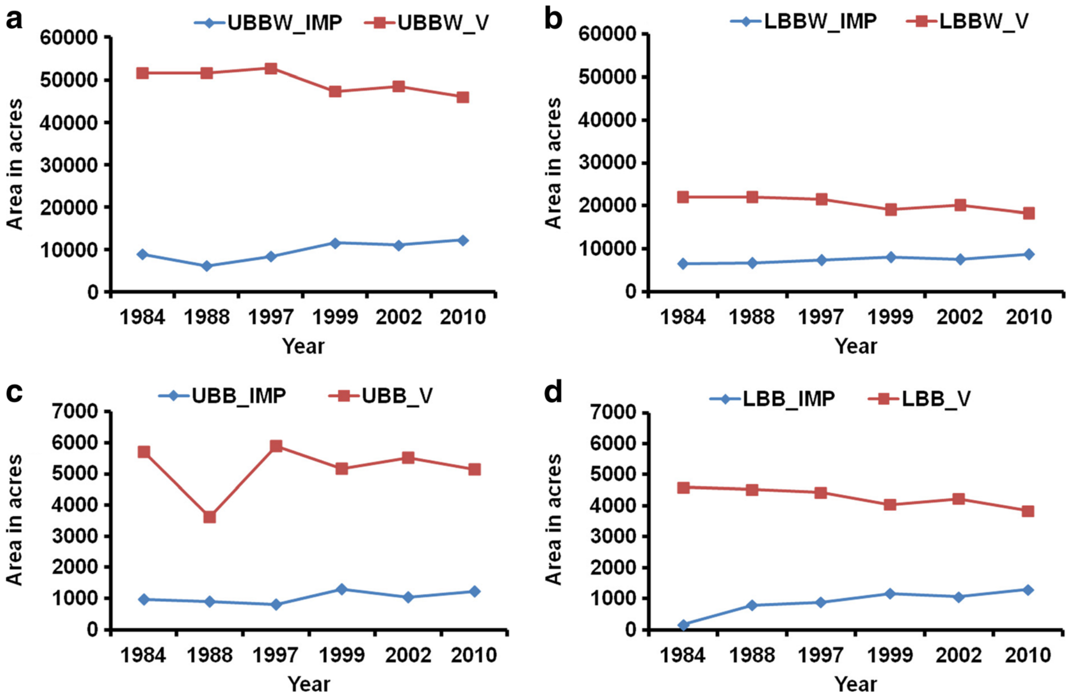

Fig. 5 Changes in the total areas of vegetation and impervious surface from 1984 to 2010 within the upper Brays Bayou watershed—UBBW (**a**), lower Brays Bayou watershed—LBBW (**b**), flood plain region within 1 km of upper Brays Bayou—UBB (**c**), and flood plain region within 1 km of lower Brays Bayou—LBB (**d**)

3.3 Historical Stream Flow Data for Brays Bayou

The historical stream flow data of Brays Bayou recorded at USGS station USGS08075000 was downloaded and compared with the change in the impervious surface of BBW. The stream flow pattern showed an increasing trend in a stream flow discharge pattern during the period of 1984 to 2010 (Fig. 6). The annual peak stream flow was increased by 11,500 cubic feet per second (CFS) in Brays Bayou for the study period from 1984 to 2010 for which the satellite imagery was analyzed. Correlation between approximate annual stream flow rate and impervious surface was recorded for each study year for BBW (Fig. 6). A significant positive correlation between stream flow discharge and impervious surface was shown during the period of 1984 to 2010 (Fig. 6).

3.4 Chemical Analysis

3.4.1 Metal Concentrations in Water Samples

The concentrations of Na, Mg, K, Fe, and Al were found to be significant compared to other metals in the waters of Brays Bayou (Fig. 7). The highest concentration of Al and Fe reported were 2.77 and 4 mg/l, respectively. The Na, K, and Mg were abundant either towards the upper or lower stream of Brays Bayou. However, Al and Fe were distributed all along the bayou and show no particular trend. The Na, K, and Mg were reported low towards the middle of Brays Bayou. Concentrations were slightly increased in the lower part than the upper part of the bayou.

3.4.2 Metal Concentrations in Sediment Samples

The concentrations of heavy metals like Al, Cu, Zn, Hg, and Pb in sediment samples were found to be present in significant concentrations compared to other metals (Fig. 8). The concentrations of As was found below 2.25 ppm, and Hg ranged from 0.2 to 1.252 ppm (Fig. 8). Concentrations of Cu, Zn, and Pb were found higher towards the downstream of Brays Bayou (Fig. 8). Metal concentrations were higher in sediment than water. The Ca concentrations were abundant and found to be at the greatest concentration. Cd was not detected in any samples except B1 and B2 and hence was not reported. Concentration of the heavy metals and

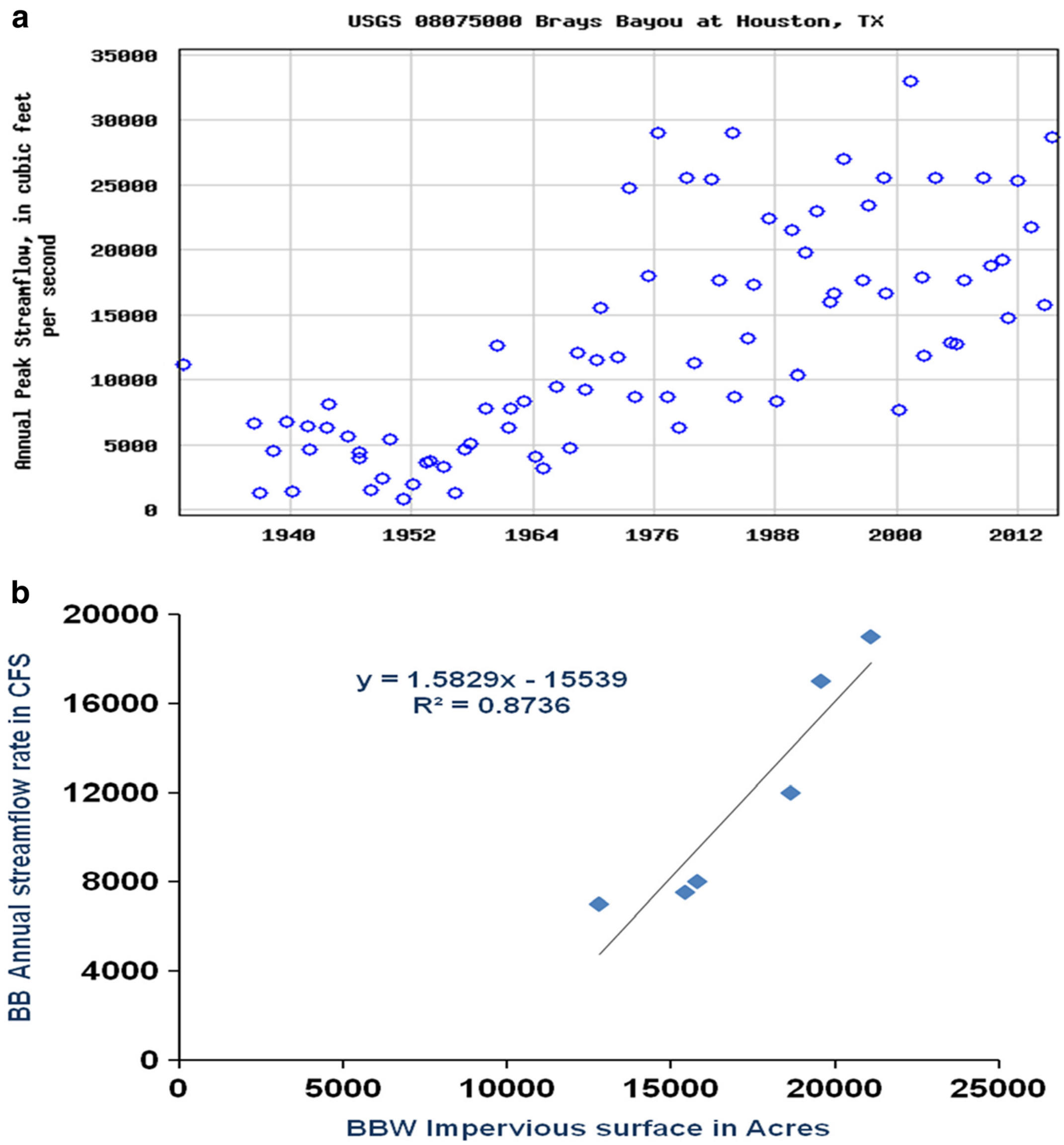

Fig. 6 Annual stream flow discharge of Brays Bayou (**a**). Correlation between annual streamflow of Brays Bayou and the total impervious surface area calculated from the Landsat images for the six selected years within Brays Bayou watershed (**b**)

nutrients increased from upstream to downstream in the bayou.

3.5 Microbial Analysis

Our microbial analysis confirmed the presence of *E. coli* in the water samples of Brays Bayou. The bacterial data from point sampling locations was spatially interpolated and mapped at the watershed scale. The spatial distribution map of *E. coli* in Brays Bayou (Fig. 9) shows the trends of bacterial contamination from the upstream to downstream in the Brays Bayou. Spatial interpolation helps to identify the areas of increased bacterial contamination. Numbers of *E. coli* colonies were found below 220/100 ml of water in Brays Bayou samples (Fig. 9), and the highest numbers of *E. coli* colonies were found in the fourth sampling location towards the lower end of UBB (Fig. 9). The higher concentration of *E. coli* in UBBW is associated to waste water treatment plant overflows, non-compliance, discharges from septic tanks, and improper pet waste disposal. Also, several waste water treatment

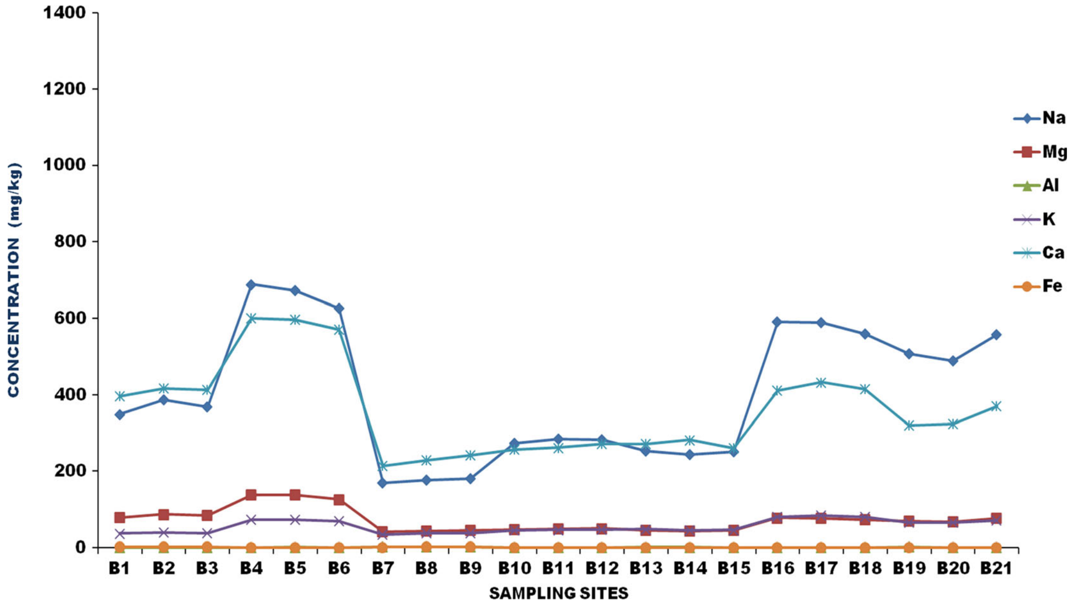

Fig. 7 Heavy metal and nutrient elemental concentration in water samples collected from Brays Bayou. B1 to B21 represents sampling sites from upstream to downstream of the Brays

plants are located within the UBBW region. According to the TCEQ-mandated guidelines, the concentrations of *E. coli* as a geometric mean and for individual samples should be below 126 maximum probable numbers (MPN)/100 ml and 394 MPN/100 ml, respectively (TCEQ 2013a and 2013b). None of our water samples from Brays Bayou exceeded the guideline value. However, TCEQ had documented that 70% of the samples from Brays Bayou exceeded the guideline value (TCEQ 2008) historically.

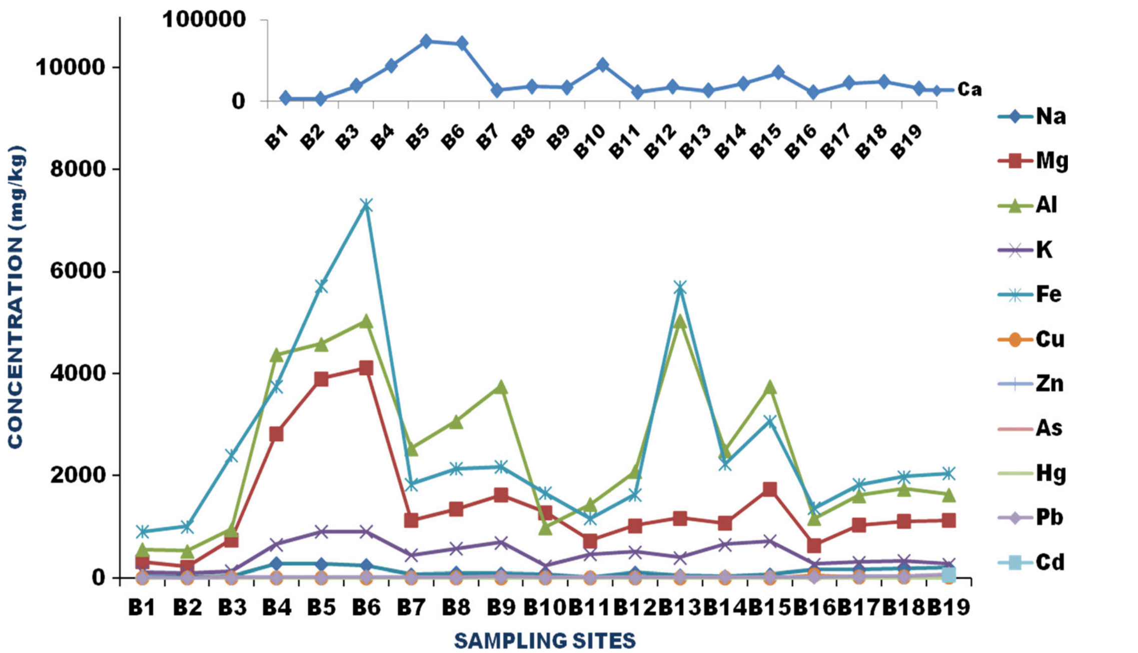

Fig. 8 Heavy metal and nutrient elemental concentration in sediment samples collected from Brays Bayou. B1 to B21 represents sampling sites from upstream to downstream of the Brays Bayou. Inserted image shows the concentration of calcium in the sediment samples

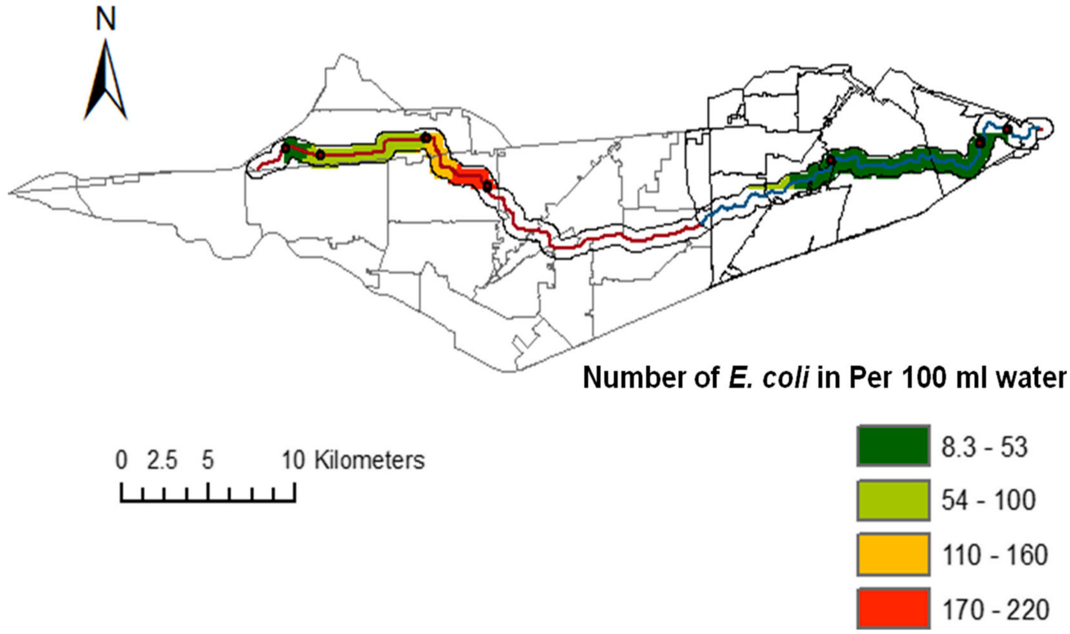

Fig. 9 Geospatial distribution of *E. coli* concentrations in Brays Bayou water. The legend describes the number of *E. coli* colonies observed at the sampling locations

4 Discussion

The Brays Bayou watershed showed a significant decrease in vegetation and a significant increase in the impervious surface during the time period of 1984 to 2010. The loss in vegetation shown in Fig. 3 can be attributed to increase in urbanization in Fort Bend County and Harris County. The population of Fort Bend County has increased from approximately 182,145 in 1980s to 585,375 in 2010 (U.S. Census Bureau 2016). Additionally, the population of Harris County where the UBBW was located increased from 2.75 million in 1984 to 4.1 million in 2010 (U.S. Census Bureau 2016). Subsequent population increases warrant infrastructure growth and a demand for housing to support the population. This increased urbanization has created more impervious surfaces in order to meet the needs of the growing population. Additionally, the construction of new buildings on vegetated lands has contributed to the vegetation reduction. The spread of the impervious surface area from east to west of upper Brays Bayou can be visualized as most of the vegetation in the western part of the UBBW (Fig. 3a) starts to disappear by 2010 (Fig. 3b). The proximity of BBW to many growing cities within Houston metropolitan area could explain the continual vegetation loss (Fig. 3) in both UBBW and LBBW. The LBBW in 2010 (Fig. 3d) showed a significant increase in the impervious surface compared to the 1984 (Fig. 3c). The increase in impervious surface can be contributed to construction of highways, more roads, parking lots, and other urban construction as the LBBW is in close proximity to the city of Houston and is significantly influenced by the urban sprawl of the city. Some areas sustained almost total vegetation loss over the observation period. The increases in impervious area in both UBBW (Fig. 5a) and LBBW (Fig. 5b) were 3402 acres and 2224 acres, respectively. UBBW had more increase in impervious surface area than LBBW. This confirms the increase in urbanization in BBW and documents the possible environmental and socio-economical hazards from catastrophes like urban flood, urban heat storm, and urban sprawl.

When comparing UBBW and LBBW, it is evident that UBBW have undergone a greater loss of vegetation. The reason for significant increase in imperviousness in the watershed is due to increase in roads and increase in construction due to urban sprawl (Fig. 4d). Also, increase in impervious surface along the banks of the bayou can increase the surface runoff and thus increasing the stream water flow rate and flooding. Construction of more concrete (cemented and paved) areas around the bayous that accompanies urbanization has reduced the permeability of the soil. It can be speculated that intense rainfall events can trigger larger flood events in Brays Bayou. This is clearly evident from the fact that the impervious surface area in BB (combining UBB and LBB) increased by 1376 acres (about 120%) during the period of 1984 to 2010 (Fig. 5c, d). The Tax Day (Mulligan 2016) flood of 2016 is a good indication of the vulnerability of the Brays Bayou to future flood events. Historical water flow data in Brays Bayou (Fig. 6) indicates that the increase in impervious surface promotes higher stream flow rate and thus impacts the bayou ecosystem.

The reason for lower concentrations of metals especially Cu, Zn, As, Hg, and Pb (Fig. 8) in sediment samples in the upper to middle part of the Brays Bayou may be due to the fact that the region was completely paved and the bayou has a lower volume of water. The higher concentration of these metals at the lower parts of the bayou may be due to increase in flow volume resulting in bank and channel erosion (Fig. 8). The heavy metal and nutrient distribution in the sediment of Brays Bayou depends on several factors such as discharges from domestic and industrial discharges, waste water treatment plant discharges, septic overflows, elemental build up and discharges of pipelines, pressure tank and water heater discharges from industrial point sources, particle deposition and resuspension due to a dredging process, and fertilizer and pesticide runoff from urbanized properties such as landscaped areas, residential lawns, and sport fields (HCFCD 2016; TCEQ 2008, 2009; TCEQ 2013a, 2013b).

Mixtures of these chemicals may have devastating effects on ecological and human health. These heavy metals found in the sediment normally enter into the flora and fauna and bioaccumulates through food chain (Yi et al. 2011). Aluminum is found commonly in the environment and aquatic ecosystem. Aluminum can cause the hyperglycemia and respiratory stress in fish (Laitinenen and Valtonen 1995). Arsenic causes acute and chronic toxicity. Chronic exposure to As can lead carcinogenicity by causing the oxidative stress (Ventura-Limaa et al. 2011). Fish can get exposed to As through ingestion of gills (Ahmed et al. 2008). Various manufacturers, smelters, and power plants can increase the As concentration in an aquatic ecosystem (Authman et al. 2015). Sources of Cd also include atmospheric deposition, runoff from point and non-point sources, and discharge of waste from industrial products like batteries, plastic stabilizers, and pigment into water bodies (Järup 2003; Wright and Welbourn 1994). It is noted that the Pb concentration increases with increase in use of smelters, ovens, and scrap yards of discarded vehicles (Al-Khashman 2004). Lead is one example of a toxic trace metal that has been found to contribute to neurological disorders and cancers. Excess amount of Na can lead to blood pressure which is associated with hypertension strokes, muscle spasms, and fatigue. No matter the circumstances under which these pollutants are released, the environmental impact is the same, since these pollutants affect the aquatic organisms that humans depend upon for nutrition and survival. The pollutants can be converted to toxic compounds in the body of the aquatic organisms or they can be stored in the adipose tissue and muscles of the organism. Human consumption of aquatic organisms allows for transfer and accumulation of these harmful products. Inside the human body, these toxic chemicals can initiate health problems. Zn originates from wear and tear of vulcanized vehicle tires and corrosion of galvanized automobile parts (Al-Khashman 2004; Wahab et al. 2012). Iron is one of the commonly used metal, so aquatic water can often receive Fe as industrial effluents. Atmospheric deposition is one of the major source of Cu discharge in aquatic environment. Since Cu is a stress causing agent, it can increase infections and death rates among fish (Woody 2007). The presence of As, Cu, Hg, and Pb in sediment samples of Brays Bayou results in bioaccumulation of these metals in fish which upon further consumption can result in acute to chronic health effects on human beings (Kumar and Mukherjee 2011; Imar and Carlose 2011). Risk assessment on humans is normally characterized by cancer and non-cancer risk. Cancer risk can be calculated by using established risk assessment models for humans by USEPA (Liu et al. 2013). The spatial interpolated *E. coli* concentration map (Fig. 9) of BBW shows that there is no significant bacterial contamination in bayou during our sampling period.

5 Conclusion

Based on the remote sensing result, 28.35% of the vegetative lands were disappeared from BBW. These percentages were consistent with the increase in urbanization. Loss in vegetation of 5589 acres in UBBW and 3874 acres in LBBW was recorded. This result warranted the shift of urbanization from the east to west side (towards Katy and Fort Bend County) of the UBBW. Impervious area increase within the buffer region was increased by 249 acres in UBB and 1127 acres in the LBB.

Concentrations of Cu, Zn, As, Hg, and Pb in sediment samples were higher towards the downstream than the upstream of Brays Bayou. The Pb was found at the highest concentration (70 mg/kg) in certain Brays Bayou sampling locations. Good correlation was found between Pb and Zn (0.895) in Brays Bayous sediment samples. Though concentration of Cu, Zn, As, Hg, and Pb were much lower than Na, K, Mg, and Ca, attention is required because mixture of these chemicals may show additive or synergistic effects for detrimental human health impacts. One reason to see low *E. coli* presence in Brays Bayou is perhaps we confined our sampling to only surface water samples and the concentrations may get higher by doing a comprehensive longitudinal profile sampling of Brays Bayou.

Integration of remote sensing and GIS along with the chemical and biological analysis helps to understand the land use and land cover changes and their impact on the bayou water quality characteristics. The spatial and temporal landscape changes along with the historical water flow showed a strong positive correlation (0.87) between increase in water flow and increase in impervious surface area in BBW. These results provide valuable information and extend our knowledge about the land use and land cover changes and its impact on the urban watershed. This knowledge will allow and advance current methods of planning for combating flooding and pollution and promoting sustainable landscape changes in the urban regions.

Funding This research work was supported by the National Science Foundation (NSF) HBCU-UP Research Initiation Award (HRD-1400962) and the NSF HBCU-UP Targeted Infusion (HRD-1622993) Award. We also acknowledge the support of Title III graduate fellowship funds available at Texas Southern University.

References

Ahmed, K., Akhand, A., Hasan, M., Islam, M., & Hasan, A. (2008). Toxicity of arsenic (sodium arsenite) to fresh water spotted snakehead *Channa punctatus* (Bloch) on cellular death and DNA content. *American Eurasian Journal of Agricultural and Environmental Sciences, 4*, 18–22.

Al-Khashman, O. A. (2004). Heavy metal distribution in dust, street dust and soils from the work place in Karak Industrial Estate, Jordan. *Atmospheric Environment, 38*, 6803–6812.

Alsaaideh, B., Al-Hanbali, A., & Tateishi, R. (2011). Assessment of land use/cover change and urban expansion of the central part of Jordan using remote sensing and GIS. *Asian Journal of Geoinformatics, 11*(3), 1–9.

Arnold, C. L., & Gibbons, C. J. (1996). Impervious surface coverage: the emergence of a key environmental indicator. *Journal of the American Planning Association, 62*(2), 243–258.

Authman, M., Zaki, M., Khallaf, E., & Abbas, H. (2015). Use of fish as bio-indicator of the effects of heavy metals pollution. *Journal of Aquatic Resources Development, 6*, 1–13.

Bedient, P. B., Holder, A., & Vieux, B. E. (2002). A radar-based flood alert system (FAS) designed for Houston, Texas. *9th International Conference on Urban Drainage - Global Solutions for Urban Drainage*, 1–33.

Belanger, K., Beckett, W., Triche, E., Bracken, M. B., Holford, T., Ren, P., Mcsharry, J. E., Gold, D. R., Platts-Mills, T. A., & Leaderer, B. P. (2003). Symptoms of wheeze and persistent cough in the first year of life: associations with indoor allergens, air contaminants, and maternal history of asthma. *American Journal of Epidemiology, 158*(3), 195–202.

Brezonik, P. L., & Stadelmann, T. H. (2002). Analysis and predictive models of stormwater runoff volumes, loads, and pollutant concentrations from watersheds in the twin cities metropolitan area, Minnesota, USA. *Water Resources, 36*(7), 1743–1757.

Brody, S. D., Zahran, S., Highfield, W. E., Grover, H., & Vedlitz, A. (2008). Identifying the impact of the built environment on flood damage in Texas. *Disasters, 32*(1), 1–18.

Eisakhani, M., Pauzi, A., Karim, O., Malakahamad, A., Kutty, M. S. R., & Isa, M. H. (2009). GIS-based non-point sources of pollution simulation in Cameron Highlands, Malaysia. *World Academy of Science, Engineering and Technology, 3*(3), 1–5.

Emerson, J. B., Keady, P. B., Brewer, T. E., Clements, N., Morgan, E. E., Awerbuch, J., Muller, S. L., & Fierer, N. (2015). Impacts of flood damage on airborne bacteria and fungi in homes after the 2013 Colorado Front Range Flood. *Environmental Science and Technology, 49*, 2675–2684.

FBCTRA (Ford BEND County Toll Road Authority). (2016). http://www.fbctra.com/roads/. Accessed 05 Sept 2016.

Fernandez, A., Black, J., Jones, M., Wilson, L., Salvador-Carulla, L., Astell-Burt, T., & Black, D. (2015). Flooding and mental health: a systematic mapping review. *PloS One, 10*(4), 1–20.

Fu, J., Zhao, C., Luo, C., Kyazas, G., Zhao, D., An, S., & Zhu, H. (2010). Heavy metals in surface sediments of the Jialu River, China: their relations to environmental factors. *Journal of Hazardous Materials, 270*, 102–109.

Hamilton, J. (2015). Rememberig Houston's Memorial Day floods. *Houston Chronicle*. http://www.chron.com/houston/article/Remembering-Houston-s-Memorial-Day-floods-7944644.php. Accessed 05 May 2016.

HCFCD (Harris County Flood Control District). (2016). Bayous and watersheds: Brays Bayou, Project Brays. https://www.hcfcd.org/projects-studies/brays-bayou-projects-studies/project-brays/. Accessed 05 July 2016.

Hoppe, K. A., Metwali, N., Perry, S. S., Hart, T., Kostle, P. A., & Thorne, P. S. (2012). Assessment of airborne exposures and health in flooded homes undergoing renovation. *Indoor Air, 22*(6), 446–456.

Imar, M. R., & Carlose, J. R. S. (2011). Metal level in fish captured in Puerto Rico and estimation of risk from fish consumption.

Archives of Environmental Contamination and Toxicology, 60, 132–144.
IOM. (2011). Climate change, the indoor environment, and health. Institue of Medicine. Washington: The National Academies Press.
Järup, L. (2003). Hazards of heavy metal contamination. *British Medical Bulletin, 68*, 167–182.
Kim, K.-W., Myung, J.-H., Ahn, J. S., & Chon, H.-T. (1998). Heavy metal contamination in dusts and stream sediment in the Taejon area, Korea. *Journal of Geochemical Exploration, 64*, 409–419.
Kumar, B., & Mukherjee, D. P. (2011). Assessment of human health risk for arsenic, copper, nickel, mercury and zinc in fish collected from tropical wetlands in India. *Advances in Life Science and Technology, 2*, 1–13.
Laitinenen, M., & Valtonen, T. (1995). Cardiovascular, ventilatory and haematological responses of brown trout (Salmo trutta L.), to the combined effects of acidity and aluminium in humic water at winter temperatures. *Aquatic Toxicology, 31*(2), 99–112.
Lester, J., & Gonzalez, L. (2005). Briefing paper on Houston Area Bayous III: Brays Bayou, Sims Bayou, Houston Ship Channel and Upper Galveston Bay. *Galveston Bay Status and Trends Project*, 1–10.
Liu, X., Song, Q., Tang, Y., Wanlu, L., Xu, J., Wu, J., Wang, F., & Brookes, P. C. (2013). Human health risk assessment of heavy metals in soil-vegetable system: A multi-medium analysis. *Science of the Total Environement, 463-464*, 530–540.
Menne, B., & Murray, V. (2013). Floods in the WHO European region health effects and their prevention. *World Health Organization*. http://www.euro.who.int/__data/assets/pdf_file/0020/189020/e96853.pdf. Accessed 12 May 2017.
Mulligan, M. (2016). Photos tell story of Houston's historic Tax Day floods. *Houston Chronicle*. http://www.chron.com/news/houston-texas/houston/article/Houston-s-historic-Tax-Day-Floods-photos-7303001.php. Accessed 10 July 2016.
Niemi, G. J., Kelly, J. R., & Danz, N. L. (2007). Environmental indicators for the coastal region of the North American Great Lakes: introduction and prospectus. *Journal of Great Lakes Research, 33*(Special Issue 3), 1–12.
Niu, L., Yang, F., Xu, C., Yang, H., & Liu, W. (2013). Status of metal accumulation in farmland soils across China: from distribution to risk assessment. *Environmental Pollution, 176*, 55–62.
Portnoy, J., Kwak, K., Dowling, P., VanOsdol, T., & Barnes, C. (2001). Health effects of indoor fungi. *Annals of Allergy Clinical Immunology, 108*, 157–166.
Rao, C., Riggs, M., Chew, G., Muilenberg, M., T., P. S., Van Sickle, D., Dunn, K., & Brown, C. (2007). Characterization of airborne molds, endotoxins, and glucans in homes in New Orleans after Hurricanes Katrina and Rita. *Applied and Environmental Microbiology., 73*, 1630–1634.
Rouse, J.W., Haas, R.H., Schelle, J.A., Deering, D.W., & Harlan, J.C. (1974). Monitoring the vernal advancement and retrogradation (green wave effect) of natural vegetation. Type III Final Report, NASA Goddard Space Flight Center, Green belt, Maryland.
Solomon, G. M., Hjelmroos-Koski, M., Rotkin-Ellman, M., & Hammond, S. K. (2006). Airborne mold and endotoxin concentrations in New Orleans, Louisiana, after flooding, October through November 2005. *Environmental Health Perspectives, 114*(9), 1381–1386.
Song, Y., Choi, M., Lee, J., & Jang, D. (2014). Regional background concentrations of heavy metals (Cr, Co, Ni, Cu, Zn, Pb) in coastal sediments of the South Sea of Korea. *Science of the Total Environment, 482*, 80–91.
Sridhar, B. B. M., Vincent, R. K., Witter, J. D., & Spongberg, A. L. (2009). Mapping the total phosphorus concentration of biosolid amended surface soils using LANDSAT TM data. *Science of Total Environment, 407*, 2894–2899.
Sridhar, B. B. M., Vincent, R. K., Roberts, S. J., & Czajkowski, K. (2011). Remote sensing of soybean stress as an indicator of chemical concentration of biosolid amended surface soils. *International Journal of Applied Earth Observation, 13*, 676–681.
TCEQ (2008). Bacteria TMDLs for TMDLs for Brays Bayou. Technical Support Document: Texas Commision on Environmental Quality, 1–98. https://www.h-gac.com/community/water/tmdl/Houston-Metro/documents/houston-metro_11-11-08_presentation.pdf. Accessed 08 May 2016.
TCEQ (2009). Indicator bacteria total maximum daily loads for the Brays Bayou watershed. Technical Support Document: Texas Commision on Environmental Quality, 1–59. https://www.tceq.texas.gov/assets/public/waterquality/tmdl/72houmetbact/72-braysbayou-tsd.pdf. Accessed 08 May 2016.
TCEQ (Texas Commision on Environmental Quality). (2013a). Brays Bayou above tidal and tributaries. Bacteria in waters used for contact recreation. Brays Bayou Addendum one. https://www.tceq.texas.gov/assets/public/waterquality/tmdl/72houmetbact/72-brays-TMDLaddendum.pdf. Accessed 18 July 2016.
TCEQ (Texas Commision on Environmental Quality). (2013b). Sims Bayou above tridal and tributary: bacteria in waters used for contact recreation. 1–21. https://www.tceq.texas.gov/assets/public/waterquality/tmdl/72houmetbact/72-sims-TMDLaddendum.pdf.
U.S. Census Bureau. (2016). State and county facts. https://www.census.gov/quickfacts/table/PST045215/00. Accessed 08 June 2016.
United Nations. (2017). World population prospects: the 2017 revision (Department of Economic and Social Affairs, Population Division, New York). *ESA/P/WP/248*, 1–53.
USGS. (2006). Flood hazards—a national threat. U.S. Geological Survery (USGS). http://pubs.usgs.gov/fs/2006/3026/. Accessed 16 July 2016.
Uygun, S. B., & Aldek, M. (2015). Determination effects of impervious areas on urban watershed. *Environmental Science Pollution Research International, 22*, 2272–2286.
Ventura-Limaa, J., Bogoc, M., & Monserrata, J. (2011). Arsenic toxicity in mammals and aquatic animals: a comparative biochemical approach. *Ecotoxicology and Environmental Safety, 74*(3), 211–218.
Vincent, R. K., Qin, X., McKay, R. M. L., Miner, J., Czajkowski, K., Savino, J., & Bridgeman, T. (2004). Phycocyanin detection from LANDSAT TM data for mapping cyanobacterial blooms in Lake Erie. *Remote Sensing of Environment, 89*, 381–392.
Wahab, N., F., D., Isa, N., Sumari, S., & Hanafi, N. (2012). Heavy metal concentration of settled surface dust in residential

building. *The Malaysian journal of Analytical Sciences, 16*(1), 18–23.

Wissmar, R. C., Timm, R. K., & Logsdon, M. G. (2004). Effects of changing forest and impervious land covers on discharge characteristics of watersheds. *Journal of Environmental Management, 34*(1), 91–98.

Woody, C. A. (2007). Copper: effects on freshwater food chains and salmon—a literature review : Draft Cu effects on fish. *Fisheries Research and Consulting*, 1–18.

Wright, D., & Welbourn, P. (1994). Cadmium in the aquatic environment: a review of ecological, physiological, and toxicological effects on biota. *Environmental Reviews, 2*(2), 187–214.

Xiao, R. B., Ouyang, Z. Y., Zheng, H., Li, W. F., Schienke, E. W., & Wang, X. K. (2007). Spatial pattern of impervious surfaces and their impacts on land surface temperature in Beijing, China. *Journal of Environmental Sciences, 19*(2), 250–256.

Yi, Y., Yang, Z., & Zhang, S. (2011). Ecological risk assessment of heavy metals in sediment and human health risk assessment of heavy metals in fishes in the middle and lower reaches of the Yangtze River basin. *Envrionmental Pollution, 159*(2), 575–2585.

Zhang, L., Shi, Z. Jiang, Z., Wang, F., Huang, X & Zhang J. (2015). Distribution and bioaccumulation of heavy metals in marine organisms in east and west Guangdong coastal regions. *Marine Pollution Bulletin, 101*(930–937).