Published in final edited form as:

Environ Pollut. 2022 March 01; 296: 118717. doi:10.1016/j.envpol.2021.118717.

Heavy Metal Pollution of Soils and Risk Assessment in Houston, Texas following Hurricane Harvey

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Abstract

In August 2017, after Hurricane Harvey made landfall, almost 52 inches of rain fell during a three-day period along the Gulf Coast Region of Texas, including Harris County, where Houston is located. Harris County was heavily impacted with over 177,000 homes and buildings (approximately 12 percent of all buildings in the county) experiencing flooding. The objective of this study was to measure 13 heavy metals in soil in residential areas and to assess cancer and non-cancer risk for children and adults after floodwaters receded. Between September and November 2017, we collected 174 surface soil samples in 10 communities, which were classified as “High Environmental Impact” or “Low Environmental Impact” communities, based on a composite metric of six environmental parameters. A second campaign was conducted between May 2019 and July 2019 when additional 204 soil samples were collected. Concentrations of

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Author Statement

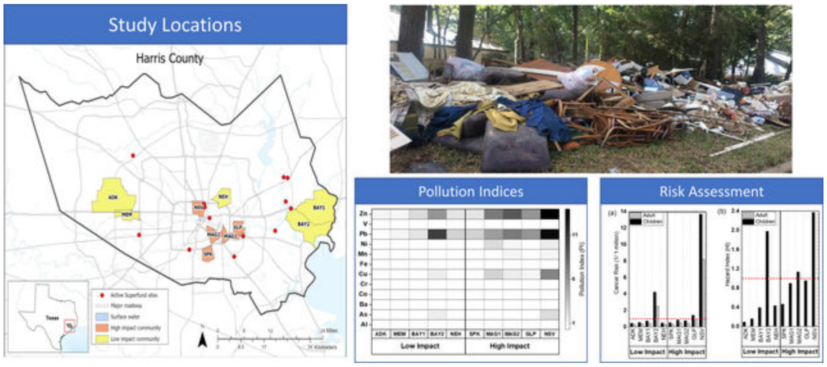
The authors’ responsibilities were as follows – IH: designed the study, conducted research and sample collection, maintained study oversight, performed data analysis, and wrote the paper; ES: designed the study, maintained study oversight, and wrote the paper; KW contributed to study design, and wrote the paper; HAH: designed the study, assisted in sample collection, and edited the paper; BC, MA, AR, and TO: assisted in sample collection and analysis and edited the paper. All authors read and approved the final manuscript. The authors declare that they have no conflicts of interest with the publication of this work.

Declaration of interests

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.

metals at both sampling campaigns were higher in High Environmental Impact communities than in Low Environmental Impact communities and there was little change in metal levels between the two sampling periods. The Pollution Indices of lead (Pb), zinc, copper, nickel, and manganese in High Environmental Impact communities were significantly higher than those in Low Environmental Impact communities. Further, cancer risk estimates in three communities for arsenic through soil ingestion were greater than 1 in 1,000,000. Although average soil Pb was lower than the benchmark of the United States Environmental Protection Agency, the hazard indices for non-cancer outcomes in three communities, mostly attributed to Pb, were greater than 1. Health risk estimates for children living in these communities were greater than those for adults.

Graphical Abstract



Keywords

Hurricane; flooding; heavy metal; soil exposure; children; risk assessment

1. Introduction

In August 2017, Harris County, the most populous county in Texas (TX) which includes the city of Houston, was heavily impacted by Hurricane Harvey with more than 50 inches of rain falling over a three-day period. With this torrential rainfall, 177,000 homes and buildings (approximately 12 percent of all buildings in the county) flooded and more than 37,000 people were displaced (Harris County Flood Control District, 2019). Days after Hurricane Harvey made landfall on the TX Coastal Bend, controlled releases of two reservoirs on the west side of Houston caused additional severe flooding in several residential communities.

Heavy metals such as Pb, zinc (Zn), copper (Cu), and arsenic (As) in soils in urban area can be elevated due to, in part, industrial activities (Davis et al. 2014) and high volumes of traffic (Goldhaber et al. 2009; Solt et al. 2015). Toxic heavy metals emitted from these point and mobile sources can be transported to surrounding residential areas and eventually deposited on urban soils. Further, Harris County is home to one of the world's largest petrochemical complexes. According to the United States Environmental Protection Agency (U.S. EPA) Facility Registry Service (FRS), there are also almost 1,000 metal manufacturing and handling facilities registered in Houston, TX (US EPA, 2020). Further, there are 13 currently active Superfund sites in Harris County, TX, contaminated with organic compounds and heavy metals, among other chemicals (US EPA, 2021a). Of particular concern was the potential for migration of toxic chemicals carried by flood water from these facilities or sites into communities following Hurricane Harvey.

Other issues regarding potential exposure to toxic chemicals are demolition and rebuilding activities. After floodwaters recede, demolition and rebuilding activities can lead to the release of toxic chemicals, which involved the removal of painted drywalls, carpets and flooring, insulation, and other building materials. These restorative actions potentially exacerbated environmental quality issues, especially in regard to the soil, due to the massive scale removal of building materials and damaged appliances or electronics that may have contained metals, all of which remained curbside near residential homes for many weeks to several months.

Following Hurricane Harvey, early studies reported elevated levels of pathogens such as E-coli in flood waters inside and outside homes, as well as in the complex system of bayous (Kapoor et al., 2018; Yu et al., 2018) that crisscross the city and along which communities and industries lie. Another study examined concentrations of 16 polycyclic aromatic hydrocarbons (PAHs) in post-Harvey soil samples collected in the front yards of 24 homes in a residential community in southeast Houston (Manchester) near petrochemical facilities (Horney et al., 2018). The results suggested that primary sources of PAHs in post-hurricane soil samples were from combustion such as petrochemical facilities, major freeway, and railyards. However, a comparison to PAHs in soils pre-Harvey was not possible due to the lack of baseline measurements. While previous studies found that Pb and As in soil were elevated in residential areas and school yards in New Orleans after Hurricanes Katrina and Rita (2005) (Abel et al., 2010; Presley et al., 2010), contamination of multiple heavy metals in soil post-Harvey has not been fully explored.

Due to no formal zoning in Houston, some residential areas are in close proximity to industrial facilities and/or hazardous waste sites and residents have potentially high risks of exposure to heavy metals and other environmental contaminants (Han et al., 2020; Kwon et al., 2016; Raun et al., 2013). Ingestion of contaminated soil, especially for children, is one of the important exposure pathways of metal exposure. According to the U.S. EPA Exposure Handbook, young children (< 6 years old) have higher ingestion rates than other age groups because they tend to play on the ground and to lick dirt or their hands after playing in or touching soil (US EPA 2017). Given their toxicity, there are increased risks from exposure to heavy metals for numerous health effects including cancer, developmental neurological disorders, and cardiovascular disease (ATSDR 2016).

The purpose of this study was to investigate post-Harvey spatiotemporal differences of metals in soil at multiple locations within 10 residential communities in Houston, TX, USA. Metal concentrations in the soil were measured at two time points – within 3 months after Hurricane Harvey (T1) and approximately 21 to 23 months (T2) following the first sampling campaign. We also conducted cancer and noncancer risk assessments for adults and children using the measured metal concentrations in soil.

2. Materials and Methods

2.1. Sampling locations

As part of a coordinated effort in response to Hurricane Harvey (Symanski et al., 2021), we selected four communities that were part of on an ongoing community-engaged study focused on evaluating and mitigating risks associated with metal aerosols from nearby metal recycling plants (Han et al., 2020; Symanski et al., 2020); namely, Magnolia Park 1 (MAG1), Magnolia Park 2 (MAG2), Northside Village/Fifth Ward (NSV), and South Park (SPK). Based on our existing community-academic partnership and referral by community organizations and residents, six other communities in Houston that experienced serious flooding were also selected for sampling: Addicks (ADK), Baytown 1 (BAY1), Baytown 2 (BAY2), Galena Park (GLP), Memorial (MEM), and Northeast Houston (NEH) (Figure 1). The faculty, staff, and students at The University of Texas Health Science Center at Houston (UTHealth) as well as our partners in government and non-governmental organizations served as volunteers during the two sampling campaigns. US EPA EJScreen data were obtained for the polygon areas that included all soil sampling locations within each of the 10 communities. Demographic characteristics of 10 communities are summarized in Supplementary Material Table S1.

2.2. Environmental impact score

We categorized the 10 communities into two groups using a composite metric of six environmental parameters related to potential mobile and stationary emission sources of metals from the U.S. EPA EJScreen: (1) ambient particulate matter, (2) daily traffic counts, (3) percent of households built before 1960 (as a proxy for potential exposure to lead-based paint), (4) number of Superfund sites, (5) number of Risk Management Facilities, and (6) number of Hazardous Waste Facilities (Table 1). Percentiles for environmental parameters represent each community's ranking compared to Texas as a whole. By community, we first assigned a value of one (1) if the reported percentile for an individual parameter was greater than or equal to the 95th percentile for Texas; otherwise, a value of zero (0) was assigned. We summed the six individual impact scores to obtain a single composite metric. For the purpose of data analysis and interpretation, we categorized communities according to median score such that half of the 10 neighborhoods were classified as “Low Environmental Impact” communities (hereafter: “Low Impact”) and the other five neighborhoods were classified as “High Environmental Impact” communities (hereafter: “High Impact”). It should be noted that the term ‘Low Impact’ is a relative comparison of an EJ index score less than the 95th percentile for Texas and should not be interpreted to imply that these communities are in pristine areas or are at low risk from anthropogenic metals pollution.

2.3. Soil sample collection and analysis

A total of 378 soil samples were collected in the 10 communities in 2017 and 2019. Of the 378 soil samples, 174 and 204 samples were collected at T1 (September to November 2017, after Hurricane Harvey made landfall on August 25, 2017) and at T2 (May to July 2019), respectively. Within each community, we collected a single composite soil sample using a grid sampling method, approximately 500 m × 500 m. We identified an open area at each sampling location where there were no downed trees or flooding debris from inside homes and removed grass, gravel, or other materials on the surface. We used 30 cm LaMotte soil sampling tubes with a 2.5 cm core diameter (LaMotte, Chestertown, MD) to collect topsoil (0–30 cm) samples. At each sampling location, we collected soil from two different areas approximately 1–2 meters apart and then combined them into one composite soil sample. Field investigators recorded the coordinates of the location and description of the sampling site. Soil samples were transported to the laboratory within two hours after collection and stored at 4 °C until analysis for metals. All sampling locations were visited again during the T2 sampling campaign and the same field procedures were followed. Although the planned number of soil samples was originally 204 for both T1 and T2, 30 sampling sites for T1 were not accessible due to the debris of demolition materials and roadway closures. During T2, we collected the soil samples from those 30 inaccessible sites at T1 as the debris was removed and the roadways were open.

All samples were analyzed within 3 months of collection. Soil samples were dried at room temperature and then 0.5 g of homogenized dry soil samples were placed into 55 mL acid digestion vessels. We added 50 ppb internal standard mix (AG-INTSTD-ASL-1, AccuStandard, New Haven, CT) to each weighed sample for quality control (QC). Following the US EPA SW-846 3050B method (US EPA, 1996), we digested soil samples with concentrated nitric acid using a Mars6 Express microwave oven (CEM, Matthews, NC). After digestion, the aliquots were centrifuged at 4000 rotations per minute (RPM) for 15 minutes and further diluted (20:1) with ultra-pure deionized water followed by filtration. The filtered final aliquots were analyzed by Inductively Coupled Plasma Mass Spectrometry (ICP/MS) 7500 (Agilent Technology, Palo Alto, CA). We analyzed 13 elements: Aluminum (Al), arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), vanadium (V), and zinc (Zn). We tuned the ICP/MS before sample analysis and constructed standard calibration curves. The standard solutions for Al and Fe ranged from 0 to 200 ppm while the standard solutions for all other metals were between 0 and 2 ppm. The calibration curve coefficients of determination (R^2) ranged from 0.9997 to 1. We calculated instrument detection limits (IDL) for each metal by using 1 ppb of analyte solution (n=10) and calculated the IDL for each metal by multiplying 2.821 by the standard deviation of each metal (t value=2.821, degrees of freedom= 9 and α= 0.01). For QC, we analyzed standard reference material (SRM) 2711a (National Institute of Standard and Technology, Gaithersburg, MD). The recovery rates of metals ranged from 78 to 114 % for all metals except As (138%) and Cr (68%) (See Supplementary Table S2). For every 15 samples, we conducted analyses on duplicate and spiked samples. The relative standard deviation (RSD) of duplicate samples was less than 20% of the mean for all paired measurements. The recovery rates were also less than 20% of the mean for all spiked samples (See Supplementary Table S3).

2.4. Data analysis

2.4.1. Statistical analysis—We calculated the mean, geometric mean (GM), and selected percentiles of soil metal concentrations by neighborhood and time period (T1 and T2). We performed the Wilcoxon Signed Rank test to examine differences of metals concentrations using log transformed data between T1 and T2 within each neighborhood, and Analysis of Variance (ANOVA) to compare GM concentrations of metals across the

10 neighborhoods. Further, simple linear regression was performed to examine associations between metal concentrations and overall environmental impact score. We used SAS 9.4 (SAS Institute, Cary, NC) for data analysis and results were evaluated at a significance level of 0.05.

We calculated Pollution Indices (PI) (Kowalska et al., 2018; Weissmannova and Pavlovsky, 2017) to assess the relative severity of soil contamination of heavy metals by anthropogenic sources using equation (1):

$$PI\frac{c_i}{c_B} \tag{1}$$

where C_i is the concentration of the ith metal in soil and C_B is background soil concentrations as reported by the Texas Commission on Environmental Quality (TCEQ, 2018). PI values greater than 1 account for soil metal concentrations that can be attributed to anthropogenic activities with a classification as follows: (1) no contamination ($PI \leq 1$); (2) low contamination ($1 < PI \leq 2$); (3) moderate contamination ($2 < PI \leq 3$); (4) strong contamination ($3 < PI \leq 5$); and (5) very strong contamination ($PI > 5$) (Kowalska et al., 2018).

2.4.2. Health Risk Assessment—We estimated health risks associated with soil ingestion for both adults and children (ages between 1 and 5) in each community using U.S. EPA methodology (US EPA, 2011, 2019a). A cancer risk assessment was performed for As and non-cancer hazard assessments for As, Ba, Cd, Co, Cr, Cu, Mn, Ni, and Pb. In all assessments, the average daily dose (ADD) (mg/kg-day) was calculated as follows (3):

$$ADD = \frac{C \times IR \times EF \times ED}{BW \times AT} \tag{3}$$

where C (mg/kg) is the 95th upper confidence limit (UCL) of the mean metal concentration in each community. IR is the ingestion rate of soil (mg/day). EF represents exposure frequency (day/year) and ED is exposure duration (year). BW (kg) is body weight and AT represents averaging time for exposure (days). The 95th UCL of mean metal concentrations was determined using U.S. EPA ProUCL 5.1. (Washington, DC). U.S. EPA exposure parameters used in equation (3) are presented in Supplementary Table S4.

For the cancer risk assessment, the ADD for As was multiplied by a slope factor of 1.5 (mg/kg-day)$^{-1}$ (US EPA, 2019b). Using guidance from the U.S. EPA, if cancer risks were greater than one in a million, then results were interpreted as having more than minimal risk (US EPA, 2019b). For the non-cancer risk assessment, we calculated Hazard Quotient (HQ) values for each metal by dividing the reference dose (RfD) from the calculated ADD (See Supplementary Table S4) (US EPA, 2019b). Additionally, the total Hazard Index (HI) was calculated summing HQ values. In general, HQ and HI values greater than 1 suggest that there is a potential noncancer health risk associated with metal exposure over periods of 60 and 5 years, respectively, for adults and children (US EPA, 2011, 2019a).

3. Results and Discussion

3.1 Community composite metric

Table S1 describes the demographics of each community, along with selected environmental parameters from the EJ Screen (US EPA, 2021b). After summing the individual impact scores, we obtained the following values for the composite metric: 0 for ADK and MEM; 1 for BAY1, BAY2, and NEH; 2 for MAG1 and SPK; 3 for GLP and MAG2; 4 for NSV (Table 1). Thus, five of the communities (ADK, MEM, BAY1, BAY2, and NEH) were classified as Low Impact and five communities were considered High Impact communities.

3.2. Metal concentrations between post-flooding and recovery periods

There were no significant differences in average metal concentrations between T1 (September-November 2017, post-Harvey) and T2 (May-July 2019) within each community (Supplementary Figures S1–S2). In contrast to our findings of no temporal changes, concentrations of Pb, As, and Cu in a residential area of Bridge Township, New Jersey (NJ) were the highest one month after Hurricane Sandy (October 2012), gradually decreasing over time and nearing background levels after a period of one year (Personna et al., 2015). Another study in New Orleans, Louisiana (LA) reported that As concentrations rapidly decreased to background concentrations within 18 months following flooding due to Hurricane Katrina in 2005 (Rotkin-Ellman et al., 2010).

Characteristics of flood water and soil composition, along with surface chemical reactions between metals and soil particles, affect the fate and transport of metals in soil (Dermont et al., 2008). The discrepancy between our study and other investigations may be related to differences in environmental conditions that affected the distribution of metals in the soil. Residential areas in NJ and LA were inundated by seawater (high salinity) and rain by Hurricanes Sandy and Katrina, respectively. Both hurricanes deposited sediments from seashores containing high levels of metals to soils of residential areas inland. However, there was no similar transport during Hurricane Harvey of coast-line sediment to communities in Houston. Additionally, the different recovery and reconstruction processes after flooding between Houston and New Orleans may affect different temporal patterns. While contaminated soils and sediments in New Orleans after Hurricane Katrina were removed during rebuilding activities (Abel et al., 2010; Abel et al., 2007; Presley et al., 2010), there was no removal of soil in the communities during the recovery period following Hurricane Harvey. Also, more than 177,000 homes were repaired or rebuilt and waste materials (painted walls, sheetrock, appliances, or electronic devices) were often piled in the front of homes in Houston for periods of weeks to months after the storm. Because the adsorption and binding capacity of metals in soil depend on soil particle size and other organic and inorganic composition (Huang et al., 2014; Wang et al., 2015), the samples in this study may include the heavy metals that had leached from materials removed from homes and may have persisted in soils due to their strong binding capacity.

3.3. Community differences in soil metal concentrations

Table 2 shows overall mean soil metal concentrations by community across all sampling periods (See Supplementary Figure S3). Among the metals, Al, Fe, Ba, Mn, and Zn had the highest concentrations in each community. When comparisons were made between communities, the GM concentrations of 12 metals were significantly higher in the High Impact communities than in the Low Impact communities ($p<0.001$). The one exception was Al; although the GMs of Al tended to be lower in the Low Impact communities, BAY1 had relatively high Al GM concentration for this metal. However, there was no statistically significant difference between GM Al concentrations between High and Low Impact communities.

Figure 2 shows the mean PI values for individual metals in each community. Mean PI values for Pb were higher than 1 for 8 communities (NSV=13.1, BAY1=1.7, BAY2=10.5, MAG1=5.6, MAG2=7.1, GLP=6.1, NEH=2.7, and SPK=2.8) and lower than 1 for ADK (mean = 0.6) and MEM (mean = 0.9). Similarly, mean PI values for Zn were greater than 1 for all communities except ADK (mean = 0.9). The mean PI values for Cu were also higher than 1 for NSV (mean = 6.7), BAY2 (mean = 1.5), MAG1 (mean = 2.7), and MAG2 (mean = 1.3) and lower than 1 for the other communities. The mean PI values for Ni were greater than 1 for NSV (mean = 1.4), MAG1 (mean = 2.4), and MAG2 (mean = 1.1) and less than 1 for the other communities. Only the mean PI values for As for NSV (mean = 2.4) and BAY2 (mean = 1.4) were greater than 1. We did not find a difference in mean PI values between T1 and T2 within communities (Supplementary Figure S4). These metals in soils were elevated near industrial facilities such as copper smelter and metal fabrication facilities (Fry et al., 2020; Kang et al., 2019; Wu et al., 2020). Further, levels of metals including Pb, Zn, Cu, Ni, and As in soils adjacent to highways were higher than those in soil farther away from highways (Kibblewhite, 2018; Solt et al., 2015). The results suggest that soil contamination of Pb, Zn, Cu, Ni, and As is attributed to multiple anthropogenic sources (e.g., industrial activities, hazardous waste disposal sites, traffic sources, housing characteristics). Among the 13 metals, the results showed that three of the High Impact communities (NSV, MAG1, and MAG2) were primarily contaminated with Pb, Zn, Cu, and Ni (Figure 2). Compared to soil Pb concentrations from 46 U.S. studies reviewed by Frank et al (2019), mean concentrations of Pb for NSV (mean= 195.7 mg/kg) and BAY2 (mean=158.2 mg/kg) were greater than soil samples collected near roadways (mean=115 mg/kg, n=1,048) or in schoolyards and playgrounds (mean=87 mg/kg, n=182), but lower in locations nearby Superfund sites that had undergone remediation (mean=358 mg/kg, n=6,055). Mean concentrations of soil Pb at all communities did not exceed the U.S. EPA soil screening level for Pb (i.e., 400 mg/kg) (US EPA, 2021c). However, mean Pb concentrations at NSV and BAY2 were above the California EPA residential soil Pb screening level (80 mg/kg) (Department of Toxic Substance Control, 2021). Like Pb, mean concentrations of Cu and Zn in the High Impact communities (NSV, GLP, MAG1, and MAG2) were approximately two to four times greater than those in previous studies (Pouyat et al., 2015; Solt et al., 2015).

Further, we explored associations between metal concentrations in soil and overall environmental impact scores by community. We found that all metals except Al were highly or moderately correlated with the overall environmental impact scores (Figure 3) (R^2 : 0.495 – 0.838), suggesting that close proximity to anthropogenic sources such as industrial facilities, hazardous waste sites, or traffic are important contributors for these 12 metals. While the EJ indices cannot quantify specific metal contamination, the results of this study suggest that their use may discriminate areas that are burdened by relative heavy metal contamination in soils and this tool could be applied to at risk geographies in other cities. Previous studies have reported that concentrations of these metals such as Mn, Fe, Pb, Cu, and Zn were elevated in soils near industrial facilities in comparison to background locations (Kang et al., 2019; Lee et al., 2020; Pelfrêne et al., 2015; Wu et al., 2020). Our own previous investigation found that airborne concentrations of Pb were higher at the fence line of metal manufacturing and scrap metal recycling facilities whereas airborne Pb was lower at sampling locations farther away from these facilities (Han et al., 2020). Further, Cu and Zn are also emitted from brake and tire wear (Harrison et al., 2012) and can be deposited in soils near major roadways. This suggests that metals emitted from industrial facilities or road ways are mostly deposited in areas in relatively close proximity to these sources.

3.3. Health risk estimates

Figure 4 shows the estimated cancer and non-cancer risks by community for children and adults. The estimated cancer risks for As were the highest in NSV (children= 13.7E-06 and adults= 8.2E-06) followed by BAY2 (children= 4.3E-06 and adults= 2.6E-06) and GLP (children=1.4E-06 and adults= 0.9E-06). The almost two-fold increase in cancer risk in children is related to higher soil ingestion rates because of greater duration of time spent outdoors (Landrigan et al., 2018; Moya and Phillips, 2014) and smaller body weights in comparison to adults (US EPA, 2011, 2019a, b). In other communities, the cancer risks were below 1.0E-06 for both children and adults (Figure 4a).

Noncancer risks (HI) for As, Ba, Cd, Co, Cr, Cu, Mn, Ni, and Pb were greater than 1 in NSV (HI=2.4), BAY2 (HI=1.9), and MAG2 (HI=1.1) for children and less than 1 for adults in all communities (Figure 4b). The relatively high noncancer risks for children living in High Impact communities represent a potential public health concern given their susceptibility to adverse neurodevelopmental disorders and other health outcomes (US EPA, 2019a, b). To understand their relative contribution on noncancer risk, we examined the hazard quotient (HQ) values for individual metals. While the contribution of Pb in the soil concentration of all metals combined was ≤ 24 % (ranging from 4% in ADK to 24% in NSV), most (96 to 98%) of the noncancer risk was attributable to Pb. The results indicate that the abatement of soil Pb is a key to lower noncancer risks for children living near industrial facilities although soil Pb concentrations did not exceed the U.S. EPA soil guideline for Pb.

4. Conclusions

After Hurricane Harvey, we collected 378 soil samples across 10 communities in Harris County, TX during two sampling campaigns in 2017 (T1) and 2019 (T2). There was no change in metal soil concentrations between sampling periods. Although the true impact of flooding on metal concentrations in this study is unknown due to the lack of baseline measurements pre-Harvey, metal concentrations at the sampling sites remained the same after 2 years, suggesting metals were immobile and persistent in soils. Environmental Impact Score using the EJ index can be a useful tool to assess potential metal contamination in soil in U.S. cities. We observed that heavy metal concentrations in High Environmental Impact communities were greater than Low Environmental Impact communities and that two communities (ADK and MEM) exhibited no contamination. Correspondingly, risk estimates for heavy metal exposure through soil ingestion were higher at High Impact communities compared to Low Impact communities, and for children as compared to adults. Cancer and non-cancer health risks associated with metal exposures can be reduced by minimizing contact with soil, especially in communities with a high environmental impact. In addition, abatement of As and Pb in soil is a key to reduce cancer and noncancer risks for children. Future studies should examine all routes of exposures to metals, especially for communities located near industrial facilities.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

The authors would like to thank all of the volunteers who assisted with field sampling.

Funding:

This research was funded the National Institute of Environmental Health Sciences (NIEHS) (Award #R01ES023563S1 and #P30ES030285), the Centers for Disease Control and Prevention/National Institute of Occupational Safety and Health (CDD/NIOSH) (Award #T42OH008421), and with Occupational Medicine contracts through the Southwest Center for Occupational and Environmental Health (SWCOEH). The content is solely the responsibility of the authors and does not necessarily represent the official views of NIEHS or CDC/ NIOSH.

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Highlights

- 13 heavy metals in soil changed little in 2 years after Hurricane Harvey
- The Composite impact score can identify geographies at risk for metals pollution
- Pb, Zn, Cu, Ni, and As were higher in High Impact communities
- Health risks for children in three communities exceeded benchmark levels

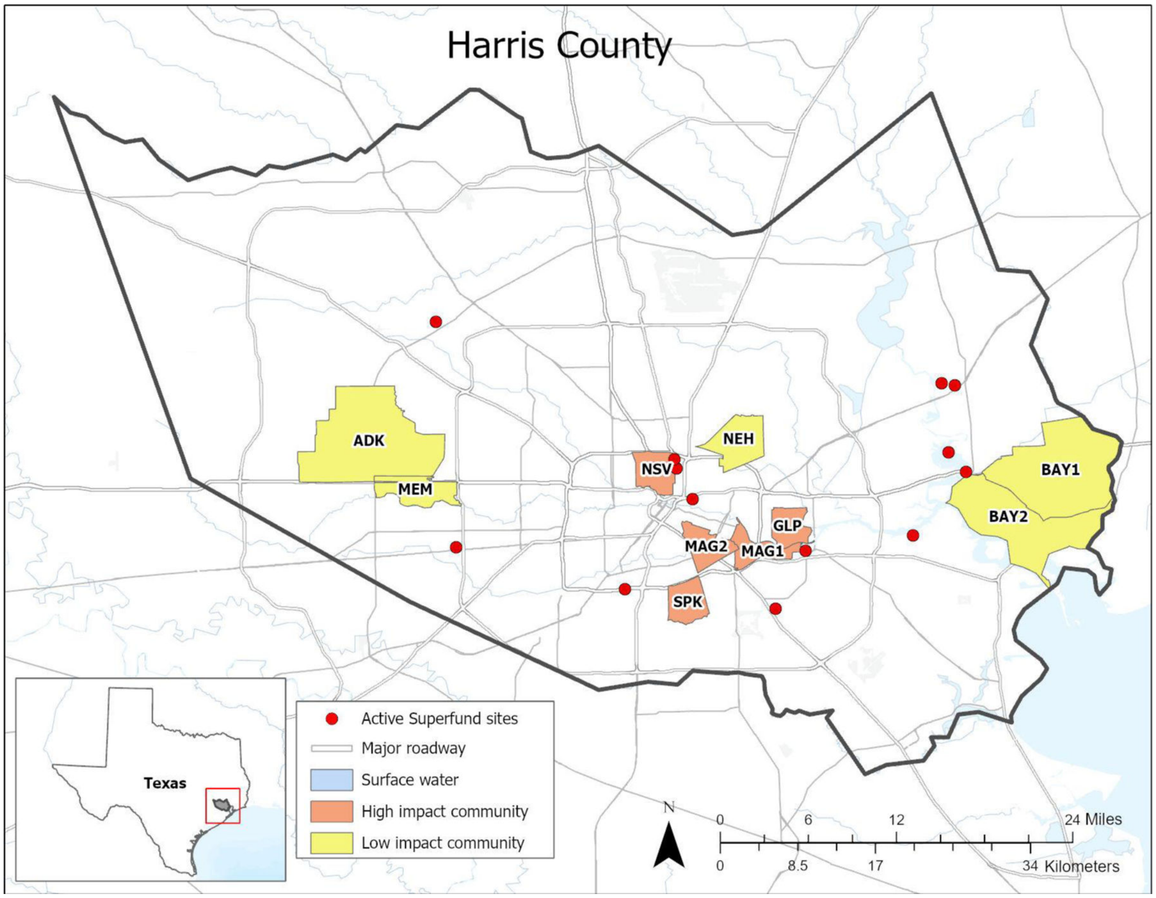

Figure 1.

Soil sampling was conducted in 10 communities in Harris County, TX during post-Harvey T1 (30 – 90 days after the hurricane) and T2 (21–23 months later).

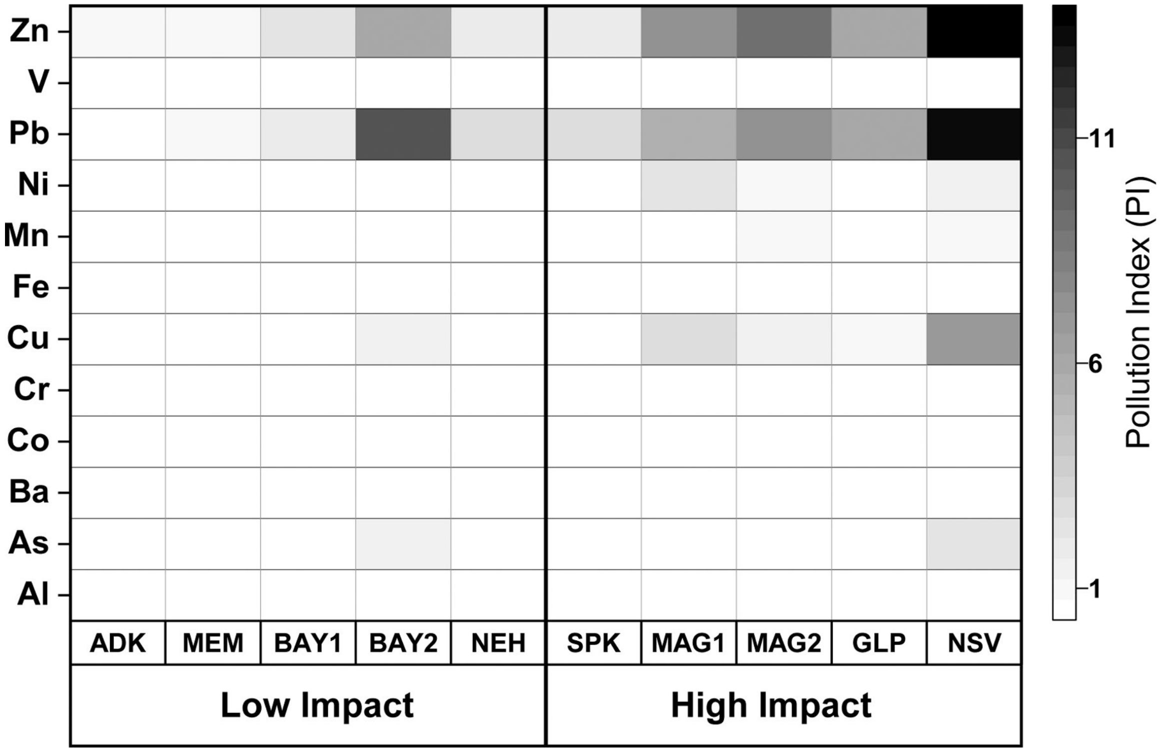

Figure 2.

Heat map of mean Pollution Index (PI) for each metal over 10 communities. The PI ≤ 1 shows white color whereas the PI > 1 shows gray or black colors.

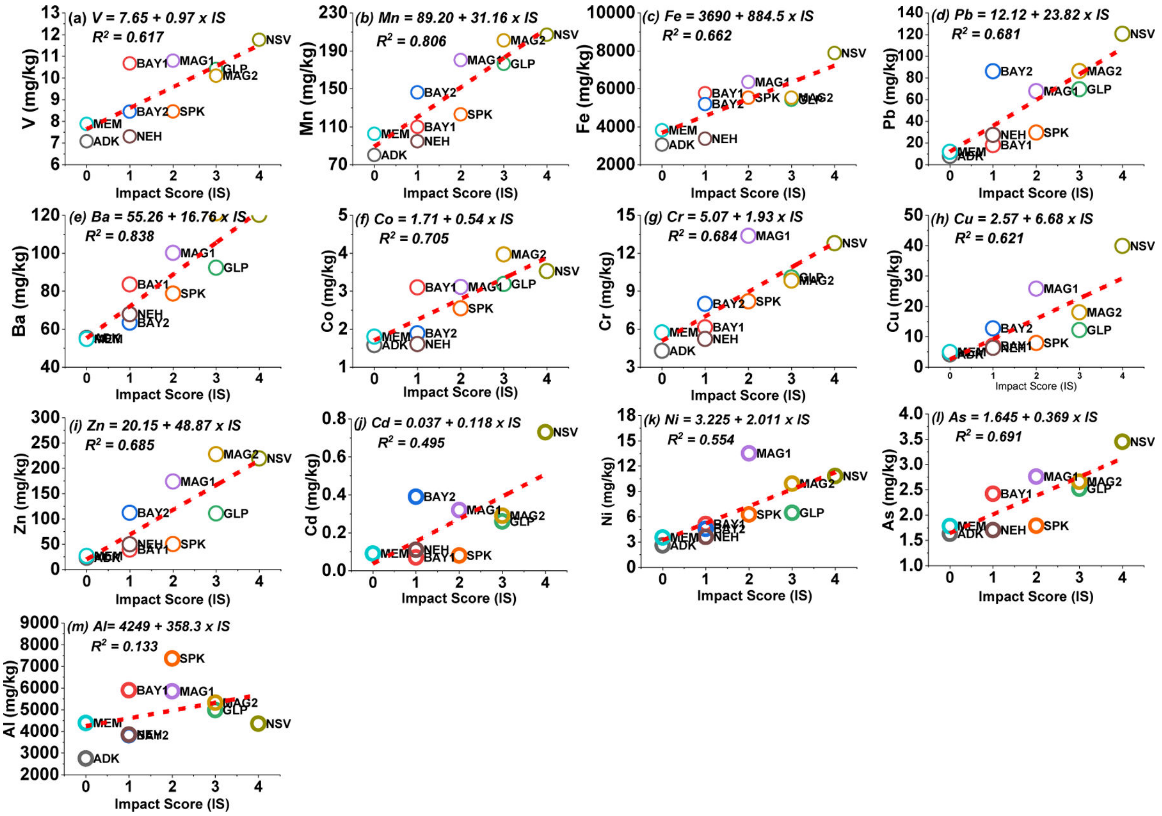

Figure 3.

Plots of average concentrations of 13 metals regressed on overall environmental impact score computed by neighborhood in Houston, TX. The abbreviations of communities are: ADK (Addicks); BAY1 (Baytown 1); BAY2 (Baytown 2); GLP (Galena Park); MAG1 (Magnolia Park 1); MAG2 (Magnolia Park 2); MEM (Memorial); NEH (Northeast Houston); NSV (Northside Village); and SPK (South Park).

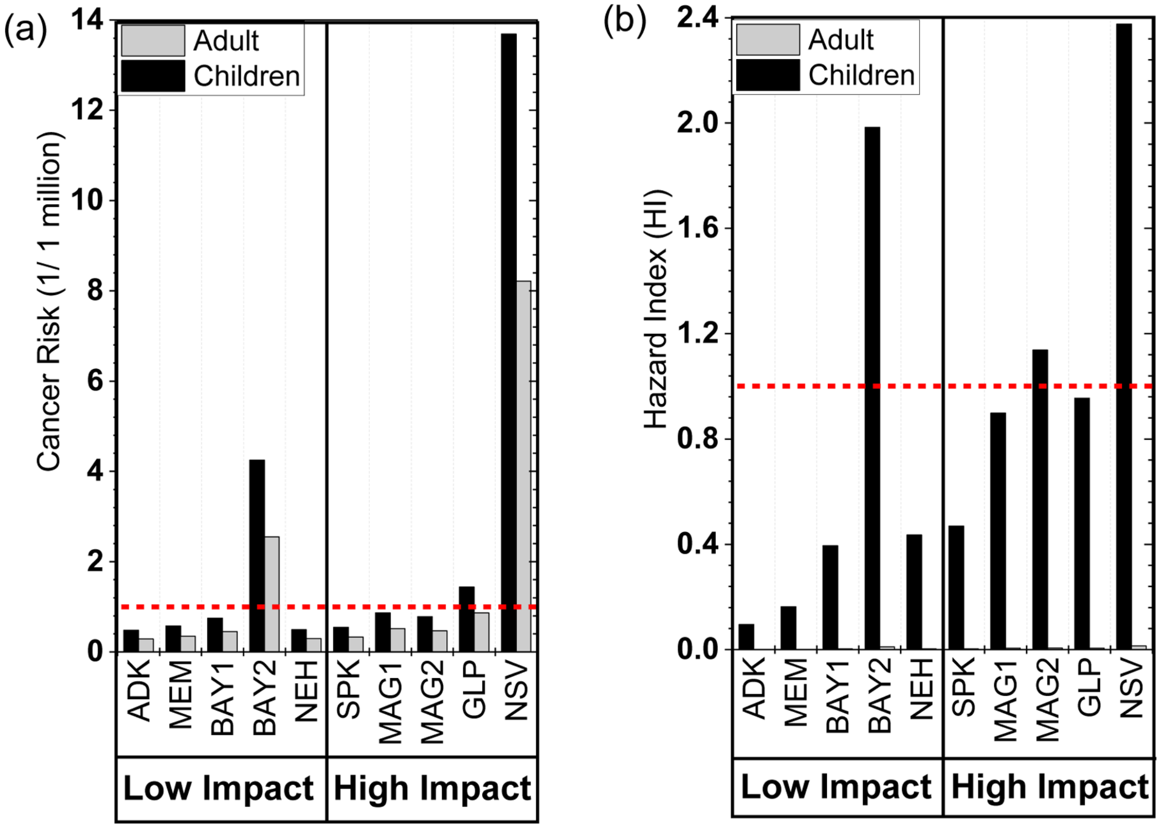

Figure 4.

Calculated cancer (a) and noncancer (b) risks for adults and children by neighborhood in Houston, TX from ingestion of heavy metals in soil. Dotted lines represent thresholds of 1 in 1 million for cancer risk and 1 for hazard index (HI) for noncancer hazard.

Table 1.

Composite Score and Classification of 10 Houston communities in Texas using U.S. EPA Environmental Justice Parameters

Classification	**Neighborhood**[a]		**PM**[b]	**Traffic**[c]	**% Lead Paint**[d]	**Superfund**[e]	**RMP**[f]	**HWP**[g]	**Composite Score**
Low Impact	ADK	Score (Percentile)	0 (64)	0 (71)	0 (65)	0 (76)	0 (60)	0 (56)	**0**
	MEM	Score (Percentile)	0 (2)	0 (7)	0 (51)	0 (0)	0 (3)	0 (19)	**0**
	BAY1	Score (Percentile)	0 (81)	0 (92)	0 (81)	1 (95)	0 (93)	0 (81)	**1**
	BAY2	Score (Percentile)	0 (64)	0 (59)	0 (92)	0 (73)	0 (82)	1 (95)	**1**
	NEH	Score (Percentile)	0 (83)	0 (56)	1 (95)	0 (87)	0 (74)	0 (85)	**1**
High Impact	SPK	Score (Percentile)	0 (89)	0 (87)	1 (99)	0 (92)	0 (60)	1 (97)	**2**
	MAG1	Score (Percentile)	0 (85)	0 (66)	1 (98)	0 (87)	0 (93)	1 (98)	**2**
	MAG2	Score (Percentile)	0 (81)	0 (66)	1 (98)	1 (96)	0 (79)	1 (97)	**3**
	GLP	Score (Percentile)	0 (73)	0 (64)	0 (94)	1 (95)	1 (98)	1 (98)	**3**
	NSV	Score (Percentile)	0 (78)	1 (95)	1 (96)	1 (99)	0 (93)	1 (96)	**4**

[a] Neighborhood- ADK: Addicks, BAY1: Baytown 1; BAY2: Baytown 2, GLP: Galena Park, MAG1: Magnolia Park 1, MAG: Magnolia Park 2, MEM: Memorial, NEH: Northeast Houston, NSV: Northside Village, SPK: South Park

[b] Percentile ranking of airborne particulate matter compared to Texas state.

[c] Percentile ranking of average daily traffic count of vehicles at major roads within 500 meters compared to Texas state.

[d] Percentile ranking of percent of housing units built pre-1960, as an indicator of potential lead paint exposure, compared to Texas state.

[e] Percentile ranking of number of Superfund sites within 5 kilometers (km) (or nearest one beyond 5 km), compared to Texas state.

[f] Percentile ranking of count of risk management plan (potential chemical accident management plan) facilities within 5 km (or nearest one beyond 5 km), compared to Texas state.

[g] Count of hazardous waste facilities within 5 km (or nearest beyond 5 km), compared to Texas state.

Table 2.

Summary of descriptive statistics for 13 metals in 10 Houston communities in Texas, USA from 2017 to 2019

Element		Low Impact					High Impact				
		ADK (N=39)	MEM (N=42)	BAY1 (N=35)	BAY2 (N=27)	NEH (N=40)	SPK (N=35)	MAG1 (N=40)	MAG2 (N=38)	GLP (N=40)	NSV (N=42)
Al	GM	2746	4385	5896	3824	3851	7361	5849	5324	4979	4363
	Mean±SD	3057 ± 1594	4742 ± 1898	6776 ± 2882	4073 ± 1626	4499 ± 2507	8358 ± 3832	6365 ± 2795	5640 ± 1935	5447 ± 2485	4776 ± 1927
Fe	GM	3053	3812	5768	5203	3371	5536	6355	5530	5426	7887
	Mean±SD	3447 ± 1746	4092 ± 1544	6684 ± 3389	5699 ± 2795	3814 ± 2061	6025 ± 2314	6783 ± 2534	5724 ± 1634	5856 ± 2335	10727 ± 11914
Ba	GM	55.37	54.87	83.51	63.37	67.83	78.81	100.2	121.0	92.39	120.2
	Mean±SD	62.42 ± 35.28	61.06 ± 28.69	98.97 ± 49.74	70.66 ± 36.58	84.78 ± 29.39	84.78 ± 29.39	112.2 ± 62.23	126.6 ± 41.96	99.56 ± 37.29	160.4 ± 240.8
Mn	GM	80.30	102.6	109.8	146.3	94.70	123.0	180.4	201.1	176.4	207.1
	Mean±SD	102.9 ± 84.10	119.1 ± 71.80	161.8 ± 188.7	173.8 ± 109.7	115.2 ± 66.40	137.7 ± 73.30	210.8 ± 120.4	237.1 ± 210.1	200.6 ± 101.7	248.7 ± 166.5
Zn	GM	23.03	26.63	39.29	111.9	49.60	50.20	173.8	227.7	110.8	219.4
	Mean±SD	25.74 ± 13.39	31.34 ± 18.35	65.54 ± 133.1	186.2 ± 219.3	31.34 ± 18.35	62.61 ± 44.21	219.7 ± 146.5	270.1 ± 169.0	185.3 ± 411.1	418.4 ± 907.5
Pb	GM	8.06	11.95	18.17	86.14	27.47	29.70	67.78	86.40	69.69	120.7
	Mean±SD	8.77 ± 3.70	14.76 ± 9.69	25.36 ± 25.44	158.2 ± 170.8	39.74 ± 34.47	41.96 ± 34.82	84.06 ± 76.09	107.1 ± 72.35	91.19 ± 68.16	195.7 ± 273.5
Cu	GM	4.17	4.94	7.04	12.76	6.35	7.94	25.84	18.03	12.22	39.92
	Mean±SD	4.64 ± 2.28	6.70 ± 8.53	10.70 ± 19.50	22.41 ± 30.84	7.91 ± 5.46	9.01 ± 5.13	40.80 ± 60.70	20.08 ± 9.32	13.84 ± 7.21	100.9 ± 277.6
Cr	GM	4.28	5.74	6.15	8.00	5.23	8.19	13.38	9.84	10.09	12.79
	Mean±SD	4.63 ± 1.80	6.45 ± 3.38	7.09 ± 3.35	9.68 ± 7.00	5.85 ± 2.74	9.07 ± 4.45	17.87 ± 16.40	10.47 ± 4.12	11.34 ± 6.20	18.36 ± 26.11
As	GM	1.63	1.78	2.42	4.92	1.70	1.79	2.76	2.66	2.52	3.45
	Mean±SD	1.79 ± 0.82	2.09 ± 1.51	2.71 ± 1.26	8.06 ± 11.73	1.86 ± 0.81	1.99 ± 1.14	3.13 ± 1.94	2.87 ± 1.36	3.19 ± 4.17	13.98 ± 63.37
Ni	GM	2.60	3.53	5.14	4.56	3.62	6.27	13.52	9.93	6.46	10.82
	Mean±SD	3.04 ± 1.99	4.09 ± 3.38	5.62 ± 2.03	5.21 ± 2.99	4.23 ± 2.56	6.64 ± 2.08	24.10 ± 35.71	10.45 ± 3.78	7.01 ± 2.76	13.56 ± 11.11
V	GM	7.08	7.88	10.67	8.45	7.08	8.46	10.80	10.10	10.42	11.76
	Mean±SD	8.03 ± 4.40	8.45 ± 3.03	12.14 ± 5.60	8.80 ± 2.58	7.75 ± 3.33	8.99 ± 3.31	11.21 ± 3.03	10.45 ± 2.84	10.97 ± 3.52	12.33 ± 3.62
Cd	GM	N/A	0.09	0.07	0.39	0.11	0.08	0.32	0.29	0.26	0.73
	Mean±SD	N/A	0.11 ± 0.05	0.12 ± 0.11	0.98 ± 1.40	0.16 ± 0.12	0.13 ± 0.16	0.61 ± 0.62	0.40 ± 0.29	0.35 ± 0.25	1.12 ± 1.35
Co	GM	1.58	1.80	3.10	1.89	1.61	2.55	3.11	3.97	3.19	3.53
	Mean±SD	1.83 ± 1.13	2.02 ± 1.01	4.58 ± 6.20	2.09 ± 1.09	1.84 ± 0.95	2.75 ± 1.09	3.37 ± 1.43	4.47 ± 3.28	3.62 ± 1.74	3.86 ± 1.87

Unit: mg/kg or ppm

ADK: Addicks; MEM: Memorial; BAY1: Baytown1; BAY2: Baytown2; NEH: North East Houston; SPK: South Park; MAG1: Magnolia Park1; MAG2: Magnolia Park2; GLP: Galena Park; and NSV: Northside Village