Development of a data visualization platform that uses evidence-based recommendations of short-term guidelines for ambient air levels of benzene during disaster response

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Abstract

Background

Industrial disasters have led to hazardous air pollution and public health impacts. Response officials have limited exposure guidelines to consult during the event; often, guidelines are outdated and may not represent relevant elevated-exposure periods. During the 2019 Intercontinental Terminals Company (ITC) fire in Houston, large-scale releases of benzene—a hazardous chemical and known carcinogen—presented a public health threat. This incident, among others, highlight the need for effective response and nimble, rapid public health communication.

Method

We developed a data-driven visualization tool to store, display, and interpret ambient benzene concentration information to assist health officials during environmental emergencies. Guidance values to interpret risk from acute exposure to benzene were updated using recent literature and regulatory guidance, which additionally consider exposure periodicity. The visualization platform can process data from several types of sampling instruments and air monitors automatically and publicly display information in real-time, along with the associated risk information, and action recommendations. The protocol was validated by retrospectively applying it to the ITC event.

Results

The new guidance values are 6- to 30-times lower than those derived by the Texas regulatory agency. Fixed-site monitoring data assessed using the protocol and revised thresholds, indicated an additional 8 shelter-in-place and 17 air quality alerts would have occurred. At least one of these shelter-in-place alerts corresponded to prolonged, elevated benzene concentrations (~ 1000 ppb).

Conclusion

This new tool addresses essential gaps in timely communication of air pollution measurements, provides context to understand potential health risks from exposure to benzene, and provides a clear protocol for local officials in responding to industrial air releases of benzene. This type of protocol has been identified as a critical need by several community groups in the Houston region who have expressed concerns about disparities in air quality attributable, in part, to industry air emission exceedances.

1. Introduction

Fence-line communities are often impacted by unplanned industrial emission events, in addition to chronic low-level exposures. There is growing evidence that communities living near petrochemical industry have a greater risk of cancer [1, 2] and higher prevalence of other harmful health-impacts, including increased asthma and adverse effects on reproductive outcomes [3]. Of the numerous air pollutants commonly associated with the petrochemical industry, benzene is of particular concern given its toxicity and ubiquity. During 2020, approximately 36% of the more than 2.6 million pounds of benzene air emissions in the United States were a result of "fugitive" emissions [4]. Regional health inequalities arise from uneven benzene exposure—overall and due to excusion events—as found in a pan-European analysis of the petrochemical industry [1].

The Houston Texas metropolitan area houses 42% of the petrochemical industry capacity of the United States (US) [5] and is the fourth largest city in the country. Due to the lack of zoning within the area, industrial facilities adjacent to residential communities are commonplace. According to an investigation by the Houston Chronical, a chemical fire or explosion occurred in the area once every six weeks, on average, between late 2014 to mid-2016 [6]. On March 17, 2019, the Intercontinental Terminals Company (ITC) reported a fire at their largest tank farm, a 7.5-acre facility with 227 tanks and a storage capacity of nearly 12 million barrels of volatile compounds [7, 8]. Facility personnel were evacuated, shelter-in-place orders were issued by the city of Deer Park [9, 10], and local School Districts were closed on the following day [11]. While initial health concerns were related to particulate matter from the blaze and flare-ups, which continued for five days, the exposure profile became dominated by extreme ambient concentrations of benzene that volatilized from over a dozen breached tanks [7]. A second shelter-in-place was issued on March 21st for Deer Park because benzene concentrations greater than 1,000 ppb were measured (1 ppb = 3.195 μg/m^3; in what follows we will use the common regulatory standard of ppb) [10]. Elevated concentrations of benzene were detected in the area through April and May [12]. A timeline of the event is shown in Fig. 1.

Benzene is a well-studied, widely used aromatic hydrocarbon [13], whose production ranks in the top twenty chemicals by volume in the United States [14] and is listed as a high production volume chemical by the Organisation for Economic Co-operation and Development with global benzene production at approximately 43 million metric tons in 2012 [13]. Inhalation is the primary route of exposure to benzene; in petrochemical regions, a large portion of ambient benzene can be attributed to industrial activity [1]. Toxic effects from inhalation of benzene, including aplastic anemia and pancytopenia, have been studied since the 19th century [15]; chronic exposure causes acute myeloid leukemia and has been associated with other types of hematologic cancers [13]. Changes in hematopoiesis and hematotoxic effects, including altered blood cell counts and lymphocyte counts and immunotoxicity, are consistent indicators of benzene exposure [15–17] and can be measured even after brief exposure periods [18]. Of additional concern is hematotoxicity from short-term benzene exposure is associated with future risk of hematological cancers [13, 17]. While the exact form of the exposure-response curve for benzene has been debated [16, 19–22], the US Environmental Protection Agency (USEPA) cited studies showing supralinear exposure-response benzene at concentrations less than 1 ppm and used these data as primary evidence to lower benzene concentrations in gasoline formulations [19]. However, previous risk assessments do not account for increased toxicity at lower benzene exposure concentrations and may have underestimated risk [19, 23].

There is no regulatory benzene ambient air threshold at the federal level in the United States. Rather, there are several outdated regulatory and advisory numbers that have been developed for high-concentration occupational exposures or singular once-in-a-lifetime events [24]. The ITC fire and resulting elevated ambient benzene concentrations were not resolved quickly. In such situations, officials need more guidance to inform decision making. Which guidelines or combination of guidelines should be used in such incidents is unclear because they may not apply to prolonged, elevated-exposure periods that do not fit neatly into "chronic" or "acute" scenarios. Directions whether to shelter-in-place, evacuate, what circumstances should be considered, and how alerts for action levels are managed are not obvious when relying on exposure guidelines alone. As a result, public health officials lack adequate decision-support tools to evaluate large-scale exposures, particularly amidst emergency events. Moreover, there is a demonstrated lack of emergency notification systems in cities to alert residents of anthropogenic disasters [25].

To assist Houston Health Department officials assessing risk during disaster events and to inform protective action, guidelines relevant for extended, acute exposure to benzene were developed, including recommendations on when to shelter-in-place or evacuate. A visualization tool was created to share air toxics data with the public to inform personal decision-making. Updated health thresholds for benzene were developed for this tool because recent toxicity studies supported a need to re-evaluate health-based benzene thresholds. Finally, the ITC fire is used as a case study to illustrate and validate the platform.

2. Methods

2.1. Data Assimilation and Visualization

The Houston-metro region currently includes twelve fixed-site air monitoring stations that continuously measure ambient concentrations of multiple volatile organic compounds, including benzene, using automated gas chromatographs. Data are automatically obtained and uploaded from the Texas Commission on Environmental Quality (TCEQ) fixed-site monitors to the platform, which is hosted on Amazon Web Services with Leaflet for dynamic mapping [26]. The platform can compile ambient air quality measurements of benzene in real-time from various sources to include mobile monitoring data during an excursion event and to display measured levels both spatially and temporally. Measurements obtained from mobile monitoring equipment and entered via the Survey123 form are loaded into the data visualization platform [27]. The data assimilation process was designed to provide a simple but comprehensive set of tools to visualize all ambient benzene measurements available for the current situation. The system allows for easy access of static information to ArcGIS users, providing all available information to Houston City officials for policy and planning. The assimilated benzene measurements are published to the Kinder Institute’s public data repository, the Urban Data Platform (UDP) [28]. Historical data from all measurement devices is available to future researchers and the Houston Health Department.

Key components of the dynamic mapping and visualization tool include 1) dynamic ellipses; 2) color to illustrate the level of concern; 3) transparency to incorporate the age of the mobile-monitoring measurements; 4) hourly and daily timelines; 5) ease of exploring the visualization, and 6) recommendations for action based on exposure guidelines.

The dynamic ellipses illustrate the direction of the wind associated with each measurement. A triangle is placed at the location of the monitor and oriented to point in the direction of the wind. The extent of the ellipses is not directly associated with the ambient plume for the pollutant but rather to provide information on direction of the wind at the time of the measurement. When wind information is not available, a circle is used to depict the measurement. Mobile measurements are depicted with a square.

Information is colored in accordance with the newly developed action recommendations (described in the Results Section) based on observed levels of benzene. However, the tool is flexible enough to be used in different contexts; information presented can be modified based on type of pollutant(s) and available toxicity data. Hourly data that are missing or lost are indicated in gray on the map and shown as missing in the daily timeline. For fixed-site monitors, or any continuously measured data, lower confidence bounds (95% and 99%) for the 24-hour moving average are found using log-transformed hourly data. The limits of the confidence interval are back-transformed to give the limits in a confidence interval for the 24-hour moving average. As time lapses, the color intensity of the mobile measurements becomes more transparent. A handheld or Mobile Ambient Air Monitoring Laboratory (MAAML) measurement older than four hours will remain in the visualization but will be less prominent due to the transparency. The fixed-site monitor measurements are shown with no transparency as their values are updated hourly.

The visualization tool is designed to allow the user to explore the region. Users can select a monitor for information available displayed as either an hourly view within a day or a daily view across a week. Color-coded hourly timelines for each monitoring location are provided at the daily level and let the user visualize the recent changes in benzene concentrations.

2.2. Data collected during the ITC fire

The locations and data for all fixed-site monitors in the greater Houston area were obtained using the Texas Air Monitoring Information System database [29]. The available benzene data from fixed-site monitors between March 16 to May 15, 2019 were downloaded and analyzed. There were 8–16% missing hourly data (total recorded measurements, not including the daily standard check and blank sample). Distance of these monitors to the ITC fire was estimated using Google Earth [30].

We reviewed the ITC Story Board, which was created by USEPA and TCEQ and launched on March 31, 2019 as an interactive resource to keep the community informed on the response activities for the fire [31]. The Story Board includes mobile air monitoring data collected by the USEPA's Trace Atmospheric Gas Analyzer (TAGA) unit. The user can scroll through the data, which is available by day but not time. The legend indicates if the readings were above the TCEQ Air Monitoring Comparison Value (AMCV) for the measured compounds (benzene, toluene, and xylenes). As the user must click on the individual measurement locations to see the data, it is difficult to understand the magnitude or duration of exposure during the event. For greater clarity, these data were requested through a Freedom of Information Act request (FOIA Request EPA-R6-2021-005977). The raw data received under that request have been published at the Kinder Institute's UDP [12]. An extensive analysis of these data in the context of the response is beyond the scope of this project. Therefore, a targeted review was conducted to understand and validate the protocol for days the fixed-site monitors indicated a potential exposure scenario and where the Story Map showed concurrent mobile monitoring data. Data were filtered and sorted using RStudio (R version 4.2.0).

2.3. Evaluation and update of Acute Inhalation Reference Values for Benzene

An exploration into existing state and federal agency guidance values for benzene found limited acute reference concentrations, which varied greatly between federal and states levels and for applicable exposure-periods. Key and supporting studies used by state and federal regulatory agencies to define acute health threshold values for benzene exposure, as well as the support documents describing threshold development, were reviewed to understand and identify differences in procedure and how they were applied in each case [15, 32–36]. These support documents include literature reviews on the toxic effects of benzene [15, 16, 33, 35]; the most recent of these includes literature through 2014. The studies used by state and federal regulatory agencies to define health threshold values for acute benzene exposure are all more than 20 years old.

To identify more recent studies published within the last decade that evaluate benzene toxicity and exposure-response relationships, we conducted a literature review using systematic review methodologies. Search logic was developed to identify relevant studies that measured short-term effects of benzene exposure through inhalation. Search terms are presented in Supplementary Material (Table S2).

The updated literature review identified newer studies, which we then used to determine points of departure (POD) to describe acute benzene exposure effects. The POD for each endpoint was derived as a function of benzene concentration and the continuous models in the USEPA Benchmark Dose Software (BMDS v 3.2) [37]. This software was developed by the USEPA in collaboration with National Institute for Occupational Safety and Health. The software utilizes multiple mathematical models to estimate quantitative relationships between chemical dose and subject response, including frequentist continuous models, dichotomous models, nested models, and Bayesian models [37]. One standard deviation from the control mean was used as a benchmark response value, as suggested by 2012 USEPA Benchmark Dose Technical Guidance [38]. To derive health-based exposure limits, dosimetric adjustments and uncertainty factors were applied to the benchmark dose, lower confidence limit (BMDL) derived from the key and supporting studies using Texas Commission on Environmental Quality (TCEQ) guidelines. Importantly, these state guidelines are closely aligned with federal guidelines developed by USEPA as well as the World Health Organization, which will increase the likelihood of these updated, more protective short-term guidelines for benzene exposure to be adopted by regulatory authorities.

The literature review and the development of short-term guidelines for benzene in ambient air are fully described in the Supplementary Material. Included in the Supplementary Material is a full examination of acute health effects of inhalation exposure to benzene, the protocols used for the systematic review, a review of available regulatory evaluations, detailed calculations for new guidelines based upon recent literature, and a full comparison of the new guidelines with existing guidelines.

3. Results

The literature review identified 1111 studies. Using the selection criteria described in the Supplementary Material, 20 were considered for inclusion. While most of these were occupational cohort studies, two included mouse models. These animal studies identified hematological effects under subacute conditions at 1 ppm of benzene exposure, a significantly lower concentration than previously cited [39, 40].

In a subacute study of mice treated with benzene as low as 1 ppm, researchers found benzene exposure led to increased platelet counts and decreased red blood cells correlated with the downregulation of target microRNA [39]. Following this new evidence, Chen et al. (2019) identified a protein phosphatase complex involved in the transcription of cytochrome P4502E1, a key enzyme in the benzene metabolic pathway [40]. They demonstrated that wild-type mice showed significant reduction of reticulocytes, lymphocytes, and white blood cell counts at benzene exposures of 1 ppm compared to mice with the deletion of the Ppp2r1a gene, suggesting its role in benzene metabolism.

The studies on acute benzene exposure effects to the hematological systems in humans are limited. Kirkeleit et al. measured peripheral blood lymphocyte levels and serum levels of immunoglobulins in ten benzene-exposed workers, after three 12-hour shifts with an average benzene exposure of 0.15 ppm [18]. They found that the benzene-exposed workers had reduced levels of immunoglobulins (IgM and IgA) and decreased blood CD4 T cells compared to non-benzene exposed workers. However, the sample size in this study was inadequate for an accurate risk estimation.

Benchmark dose models were fit to the data from the two mouse models [39, 40]. The Chen et al. analysis demonstrated greater uncertainty in the BMDL model than did the models based on Liang et al.; however, the estimated reference exposure levels were similar (see Table S7). The derivation of the reference exposure levels from the analysis using the platelet count data of Liang et al. are shown in Table 1 and Table S7.

Table 1
Derivation of the Acute 1-hr Reference Value (ReV) and 24-hr ReV based on the platelet count data from Liang et al (2018) using the restricted exponential model (see Table S5) [39].

Parameter	**Summary (1hr)**	**Summary (24-hr)**
Study	Liang et al. 2018 [39]	
Study population	C57BL/6J mice (male), 4 animals per group, 8 groups	
Exposure Methods	6 h per day for 6 days/wk for 2 wks via inhalation from 0 to 25 ppm	
Critical Effects	Increased platelet count	
LOAEL	1 ppm (average analytical concentration)	
NOAEL	Not Found	
$BMDL_{1SD}$	0.44 ppm (exponential model, v.3.2)	
Exposure Duration	6 h	
Extrapolation to 1-h/24-hr	TCEQ (2015b) default procedures (n = 3) 0.799 ppm = $((0.44\ ppm)^3 \times (6/1))^{1/3}$	TCEQ (2015b) default procedures 0.094 ppm = (0.44 ppm x 6/24 x 6/7)
POD_{ADJ}	0.80 ppm	0.094 ppm
POD_{HEC}	0.80 ppm (RGDR = 1)	0.094 ppm (RGDR = 1)
Total Uncertainty Factors (UFs)	30	
Interspecies UFA	*3*	
Intraspecies UFH	*10*	
LOAEL UFL	*1 (BMDL)*	
Incomplete Database UFD	*1 (database quality = high)*	
Acute ReV	26.7 ppb (85 ug/m^3)	3.1 ppb (10 ug/m^3)

LOAEL - lowest observed adverse effect level; NOAEL - no observed adverse effect level; BDML - benchmark dose level lower 95% confidence limit (BMDL); PODADJ - point of departure, adjusted for dosimetry; PODHEC - point of departure, human equivalent; RGDR - regional gas dose ratio

Acute toxicity guidance values are health-based exposure concentrations used in assessing health risks of short-term chemical exposures and assume that such exposures are rare or intermittent. Acute toxicity values are typically derived from studies using animals that are "naive," meaning they have never been exposed to a chemical, thus making it difficult to predict the aggregate effects from intermittent acute exposures, or in the context of chronic exposures. TCEQ defines its 24-h acute reference values (ReVs) as an "*estimate of an inhalation exposure concentration that is likely to be without an appreciable risk of adverse effects to the human population (including susceptible subgroups) for a* single *24-h exposure*" [36]. However, the period within which a single exposure may occur is not defined. As noted by USEPA, many chemicals lack enough information to determine accurate periodicity of exposures [34]. To address potential additional risk from excess intermittent exposure, California Office of Environmental Health Hazard Assessment (OEHHA) recommends that exposure at acute reference values occur no more frequently than every two weeks in a year [34]. This interval is based on acute toxicology experiments where animals are observed for two weeks past exposure.

The literature on benzene toxicity indicates that aggregate exposure to benzene can lead to myelodysplastic syndrome and hepatotoxicity from benzene exposure is associated with future risk of hematological cancers [13]. The clearance of benzene metabolites from the target organ (bone marrow) is difficult to predict, but research suggests that benzene metabolites are retained in bone marrow for at least one to two days in mouse models [16, 35]. Because of this retention, the aggregate effects from intermittent acute exposure to benzene should be considered when developing short-term exposure thresholds and associated actions or interventions. Therefore, we applied the OEHHA definition of periodicity that acute benzene exposure should not occur more than once in two weeks.

Table 2 presents the Benzene Action Guidance Plan (BAGP), which is a summary of action and communication guidelines developed using the updated inhalation acute ReVs (Table 1) and a periodicity of two weeks. These actions additionally consider the efficacy of shelter-in-place over time.

Table 2
Proposed Benzene Action Guidance Plan, including communication guidelines for excursion events. Event visualization colors additionally include the following messages: Extreme (red): be prepared to evacuate if advised by Emergency Response Personnel; Warn (orange): be prepared to shelter-in-place if advised by Emergency Response Personnel; Watch (yellow): expect air quality alerts to be issued by Health Department; Investigate (green): Monitor (blue): minor exceedances are being monitored.

Real-Time Exposure Condition Visualization Algorithm for Mapping			**Guidelines for Expert Decision-Making (Including Forecasting)**			
Map Color	**Exposure Condition for Mapping**	**Lowering color/visualization**	**Action**	**Guidelines for expert decision-making**	**Rationale**	**Deescalate condition**
Extreme Event **(RED)**	99% LCB* for 24MA† is greater than or equal to 3 ppb	99% LCB for 24MA is **less** than 3 ppb	Evacuate	The event will not be resolved within 24 hours	Continuing event, with large release or extended warning conditions	Event has been resolved, contained, mitigated**
Warn **(ORANGE)**	95% LCB for 24MA is greater than or equal to 3 ppb **OR** Two out of three consecutive hourly measurements are greater than or equal to 27 ppb	95% LCB for 24MA is less than 3 ppb **AND** No hourly measurements are greater than 27 ppb within 24 hours	Shelter-in-place	Benzene levels are expected to be below 3 ppb within 24 hours (to be confirmed by two consecutive hourly measurements)	Short-term event that expected to be resolved within 24 hours	Event has been resolved, contained, mitigated**
Watch **(YELLOW)**	24MA is greater than or equal to 3 ppb for 6 consecutive hours **OR** Two hourly measurements are greater than 27 ppb within 48 hours	24MA is less than 3 ppb for 3 consecutive hours **AND** No hourly measurements are greater than 27 ppb within 24 hours	Communicate	Benzene levels have been confirmed, and location of the event is known. Continue monitoring and communicate to public. Issue AQ alert	Exceedance event is occurring, and the population affected is known	24MA is less than 3 ppb for 6 consecutive hours

**LCB – lower confidence bound; †24MA – 24-hour moving average calculated using all available measurements in the affected area; §RABITS - Rapid Alert Benzene Information: Time Sensitive; Other triggering events may include NRC Spill Report to TCEQ, TCEQ contacts City of Houston; odor complaint from Resident; **As determined by Emergency Response Incident Commander*

Real-Time Exposure Condition Visualization Algorithm for Mapping			Guidelines for Expert Decision-Making (Including Forecasting)			
Map Color	**Exposure Condition for Mapping**	**Lowering color/visualization**	**Action**	**Guidelines for expert decision-making**	**Rationale**	**Deescalate condition**
Investigate (GREEN)	24MA is greater than or equal to 3 ppb **OR** Hourly measurements are greater than or equal to 27 ppb, twice in two weeks **OR** There have been 3 RABIT[§] alerts or other triggering event	Criteria is not met	Investigate	Deploy monitors, contact/investigate likely source. Continue to monitor	Benzene concentrations have exceeded the 1-hr threshold guidance value, or the concentrations have, or are expected to exceed, the 24-hr threshold guidance value	Benzene levels are not confirmed.
Monitor (BLUE)	24MA is less than 3ppb	N/A	Monitor	Stationary monitoring, obtained hourly	Near simultaneous monitoring of hourly benzene levels is adequate	

[*]LCB – lower confidence bound; [†]24MA – 24-hour moving average calculated using all available measurements in the affected area; [§]RABITS - Rapid Alert Benzene Information: Time Sensitive; Other triggering events may include NRC Spill Report to TCEQ, TCEQ contacts City of Houston; odor complaint from Resident; [**]As determined by Emergency Response Incident Commander

[Table 2 **SHOULD APPEAR HERE IN THE TEXT. CURRENTLY, IT CAN BE FOUND ON PP 31–32**]

Shelter-in-place is an effective measure to reduce exposure to elevated ambient levels of hazardous air pollutants during short-term emergency events [41, 42] and can reduce indoor exposures relative to outdoor by as much as an order of magnitude. However, its effectiveness drops off rapidly as exposure durations extend. Longer release durations (greater than 12 to 24 hours) causes indoor concentrations to equilibrate with outdoor levels [41, 42].

The BAGP consists of a series of increasingly aggressive intervention actions and communication guidelines, based on the severity of the excursion event. During normal operations, the platform will continue to record and report benzene readings from fixed-site monitors. If there is a triggering event, or if monitoring data shows that the 24-moving average of benzene is greater than or equal to 3 ppb (i.e., an exposure greater than the 24-hr ReV) or hourly measurements are greater than or equal to 27 ppb twice in two weeks (i.e., more than one exposure greater than the 1-hr ReV in a two-week period), the action plan activates, and the visualization color will change. The first recommended action for emergency response personnel is to "investigate" by deploying monitors, contacting, or otherwise investigating likely sources, while continuing to monitor.

Each successive step in the BAGP is triggered by a combination of increased exposure concentrations over shorter lengths of time and assumes that decision-makers have—where necessary—deployed mobile monitoring, identified and confirmed an excursion event is occurring, are aware of its severity, and understand the anticipated time to its resolution. Each step in the action plan describes what benzene exposure conditions are needed to escalate or de-escalate the recommended actions and the rationale for recommended actions to be made by emergency response personnel (Table 2). Given the limited efficacy of shelter-in-place, the recommended action in the BAGP for longer release durations, at high concentrations, may be to evacuate. Such considerations must be made given on-the-ground information gathered during the event.

To illustrate the value of the BAGP and visualization platform, they were applied to the 2019 ITC fire. The exposure condition visualization algorithm presented in Table 2 was applied retroactively to benzene concentration data collected by fixed-site monitors during the fire. In total, the BAGP indicates there would have been an additional 8 shelter-in-place alerts and 17 air quality alerts, based on fixed-site monitoring alone. Table 3 provides a summary of these recommended actions.

Table 3
Actions taken during the ITC fire versus proposed actions by retroactively applying the Benzene Action Guidance Plan with updated guidance reference values for acute benzene exposure.

Location	**Action**	**Dates (beginning on)**
City of Deer Park	2x Shelter-in-Place	3/17/2019, 3/21/2019
Industrial Park	Area Closure	3/23/2019
La Porte Industrial Area	Shelter-in-Place	3/30/2019

Fixed-site Monitor (Distance to ITC Fire)	**Proposed Action**	**Dates (beginning on)**
Lynchburg Ferry (2 mi NNE)	4x Shelter-in-Place	3/20/2019, 3/25/2019, 4/4/2019, 4/15/2019
	7x AQ Alert	3/22/2019, 3/26/2019, 3/30/2019, 4/5/2019, 4/10/2019, 4/16/2019, 4/21/2019
Deer Park (4.8 mi SSW)	2x Shelter-in-Place	3/20/2019, 3/31/2019
	2x AQ Alert	3/22/2019, 4/2/2019
Channelview (5.3 mi NNW)	2x Shelter-in-Place	3/19/2019, 3/29/2019
	3x AQ Alert	3/20/2019, 3/23/2019, 3/30/2019
Haden Rd (5.6 mi WNW)	AQ Alert	3/24/2019
Galena Park (8.8 mi W)	3x AQ Alert	3/20/2019, 5/6/2019, 5/8/2019
Cesar Chavez (10.3 mi WSW)	AQ Alert	3/21/2019

In Fig. 2, we show daily ambient benzene concentrations during the ITC fire at the Deer Park Monitor as well as the action recommendations for this area. The fixed-site monitor in Deer Park was nearly five miles from the ITC fire. However, this monitor showed elevated benzene concentrations at the outset of the fire through the beginning of April 2019 (Fig. 2). These data indicate that two shelter-in-place and two air quality alerts should have been issued: one beginning on March 20th and a second on March 31, 2019. The first date corresponds to a shelter-in-place order that was issued by Deer Park (Fig. 1). An analysis of the USEPA TAGA data for March 31 (Fig. 3) shows that elevated levels of benzene were measured throughout the Deer Park neighborhood, supporting the recommended actions of the BAGP, which included a third shelter-in-place for the area. During this time, there were multiple measurements of high benzene concentrations, including some as high as 1032 ppb between 9 am and 4 pm. No samples were collected by the TAGA team after 5pm or before 8am on March 31 through April 1, 2019.

Figure 4 provides a snapshot of the visualization platform for two different time points in March of 2019. On March 19th, the fixed-site monitor information is augmented with 3 MAAML measurements and 27 measurements from handheld devices (Fig. 4A). Mobile monitoring data provide insight to benzene concentrations for the region beyond the constraint of the fixed-site monitors locations. On March 31st there is an increase in benzene concentrations for the Deer Park location and the subsequent increase at other locations downwind (Fig. 4B). The second time point includes a close-up of the Deer Park fixed-site monitor (Fig. 4C). The severity of the event is illustrated through a designation of orange and a recommendation of shelter-in-place action. An animation of the visualization for the design event is available at apps.kinderudp.org/benzene [43].

4. Limitations

The BAGP has some important limitations. Primarily, it is difficult to validate the efficacy of this tool outside of an emergency scenario with concurrent mobile monitoring. The retroactive case study explored here was assisted by mobile monitoring data collected by the USEPA TAGA unit. The methodology of data collection of this monitoring effort (i.e. timing or location protocol, resampling guidelines, or whether or not data validation was completed with summa cannisters) was not provided with the FOIA response. Therefore, it is difficult to understand if the areas sampled by the TAGA unit, given on-the-ground metrological data, were appropriate or would have provided adequate coverage to assess the efficacy of the BAGP. An in-depth retrospective, including predictive exposure modeling, was out of scope for this project but is the logical next step in a future analysis.

Another important limitation of this work is the inability to validate or assess the protectiveness of using two weeks for acute benzene exposure periodicity to limit the cumulative effects of multiple acute exposures. Ideally, periodicity would be determined through comprehensive toxicokinetic studies to establish a robust model for human metabolism of benzene. While the approximate retention-time of the parent compound in the body is understood, benzene's toxicity comes from its metabolic products that can accumulate in the bone marrow [15]. One study on benzene inhalation to measure benzene metabolites in the marrow found a significant proportion were retained for at least 24-hours [35]. As this study was conducted using massive benzene concentrations; it is unclear how metabolite formation occurs at lower doses, but extrapolation likely underestimates toxicity at relevant exposures [15]. When considering repeat or extended sub-chronic benzene exposures, the accumulation of toxic benzene metabolites within bone marrow supports using a more conservative approach in deriving acute values, as adverse effects are likely to worsen with repeat exposure.

5. Discussion

The 2019 ITC fire provides a critical example of how existing acute exposure guidelines are limited in providing guidance during a disaster. There are no national ambient air quality standards for benzene; some state reference values are merely guidelines that are unaccompanied by regulatory action [32, 35]. Recent literature indicates adverse health effects in animal studies at acute benzene exposure concentrations that are an order of magnitude lower than studies referenced in existing guidance documents [32, 35]. This could lead to an underestimation of true risk from benzene exposure, particularly as understanding of toxicological modes of actions evolve [20–22]. Protective values are imperative in informing guidance during extreme excursion events and should be reviewed periodically in the context of scientific advancements.

This study includes the necessary task of updating acute reference values for benzene, which represent more up-to-date and protective thresholds for acute exposure. The BAGP also includes exposure periodicity. This combination is a novel approach and a powerful tool with the potential to better protect populations across the globe, particularly those living near industry who experience chronic exposures to benzene, as well as high or intermediate exposures because of upset emission events. Heretofore, there has not been a decision-support tool available to public health professionals adequate in determining how to translate ambient air quality data into actual human health risk in the context of an industrial emergency.

This information is critical in developing communication guidelines related to public health threats that may result from repeated or prolonged exposures to benzene in industrial areas. Recent studies have shown that petrochemical activity is connected to disparities in regional mortality rates [1]. Within Houston, a recent identification of a cancer cluster, including acute myeloid leukemia—known to be caused by chronic benzene exposure—occurred in the population at rates that were statistically significantly greater than expected [44]. Smith (2010) notes that there is likely no practical threshold for benzene and exposure effects are probably additive [19]. Using the approach as described in the BAGP that both reduces overall exposure to a known human carcinogen by using a lowered acute reference value, coupled with a consideration of periodicity, provides stronger protective action.

The fixed-site continuous monitor south of the Deer Park community measured elevated levels of benzene for approximately 24 hours between March 31 and April 1, 2019. There were five measurements between 28.7 ppb and 43.2 ppm, above the 1-hr acute ReV of 27 ppb derived in this study. While the Deer Park fixed-site monitor was able to capture some of the benzene plume, when compared with the limited mobile monitor sample data taken within the community, it did not reflect the potential exposure to benzene in residential areas and illustrates the need for flexible, targeted, and on-going monitoring during these excursion events with timely communication to the affected communities. Had the BAGP and visualization platform been in place during the ITC fire, Deer Park residents would have been issued an air quality alert and shelter-in-place alert, if additional mobile monitoring had warranted such a measure. City officials would have known to deploy monitors and map the extent of benzene exposure in real-time and provide communication to the public on recommended actions.

One policy outcome resulting from this evaluation has been the adoption of the BAGP by the city of Houston. The measure, developed in partnership with public health stakeholders and evaluated by the City of Houston Medical Director, ensures that local public health officials have a sound scientific basis for assessing health threats resulting from large scale industrial disasters.

While this paper and the tool focuses on Houston as a study test case, the relevance of this methodology and its application extends beyond Houston. In its current form, this tool is immediately applicable to acute releases of benzene in any urban corridor with adequate monitoring—including the 579 air quality stations associated with the European Environmental Agency that measure benzene [1]. Jephcote and Mah (2019) found the petrochemical industry in all European Union regions were compliant with the annual average benzene limit of 1.6 ppb (5 μg/m^3), but many monitors measured hourly concentrations of benzene in excess of 30 ppb (100 μg/m^3) [1]. The BAGP would provide these areas with a means of rapid communication to impacted areas, and if necessary, recommended guidance for excursion events.

6. Conclusions

In this study, we address the gap that exists between the development of health-based threshold values and their practical implementation in real-world scenarios, including the health implications of acute exposures to hazardous air pollutants during unplanned emission upsets. This analysis and the resulting BAGP go beyond what is currently available to decision-makers in situations where there are rapidly changing, elevated levels of air contaminants, and no available single exposure threshold values that can inform action guidance (e.g., evacuation or shelter-in-place). During the ITC fire, this guidance plan would likely have led to more protective actions for Deer Park residents.

This work provides a framework for the management of any acutely toxic air pollutant using sound scientific principles. Specifically, the methodology includes updating any relevant health-based toxicity threshold values; developing applicable actions based on exposure limits and periodicity; and provides a means of communication during acute releases of hazardous air emissions. This work fills an urgent need to secure more comprehensive air quality management plans with a public health and communication focus.

Abbreviations

ITC: Intercontinental Terminals Company

US: United States

USEPA: United States Environmental Protection Agency

TCEQ: Texas Commission on Environmental Quality

UDP: Urban Data Platform

MAAML: Mobile Ambient Air Monitoring Laboratory

TAGA: Trace Atmospheric Gas Analyzer

AMCV: Air Monitoring Comparison Value

FOIA: Freedom of Information Act

POD: points of departure

BMDS: Benchmark dose software

BMDL: benchmark dose, lower confidence limit

ReVs: reference values

OEHHA: California Office of Environmental Health Hazard Assessment

BAGP: Benzene Action Guidance Plan

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated during and/or analyzed during the current study are available in the Rice University-Kinder Institute repository, https://apps.kinderudp.org/benzene/ [43] and https://doi.org/10.25612/837.4D1QM20GBVA4 [12].

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

CD: Methodology, Writing, Formal analysis, Visualization, Data Curation. CP: Conceptualization, Methodology, Writing, Formal Analysis. KE: Conceptualization, Methodology, Formal Analysis, Writing. LH: Conceptualization, Writing. BE: Software, Formal Analysis, Visualization, Writing. KM: Data Curation, Investigation, Writing. AQ: Data Curation, Investigation, Writing. EC: Conceptualization, Methodology, Writing. All authors read and approved the final manuscript.

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Supplementary Material

SUPPLEMENTARY MATERIAL

Additional file 1 details the development of short-term guidelines for benzene, including a full examination of acute health effects of inhalation exposure to benzene, the protocols used for the systematic review, a review of recent regulatory evaluations, detailed calculations for new short-term guidelines for benzene based upon recent literature, adjustments for extrapolating from animal exposures to human exposures, the application of uncertainty factors and a full comparison of the new guidelines with existing guidelines.

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Figures

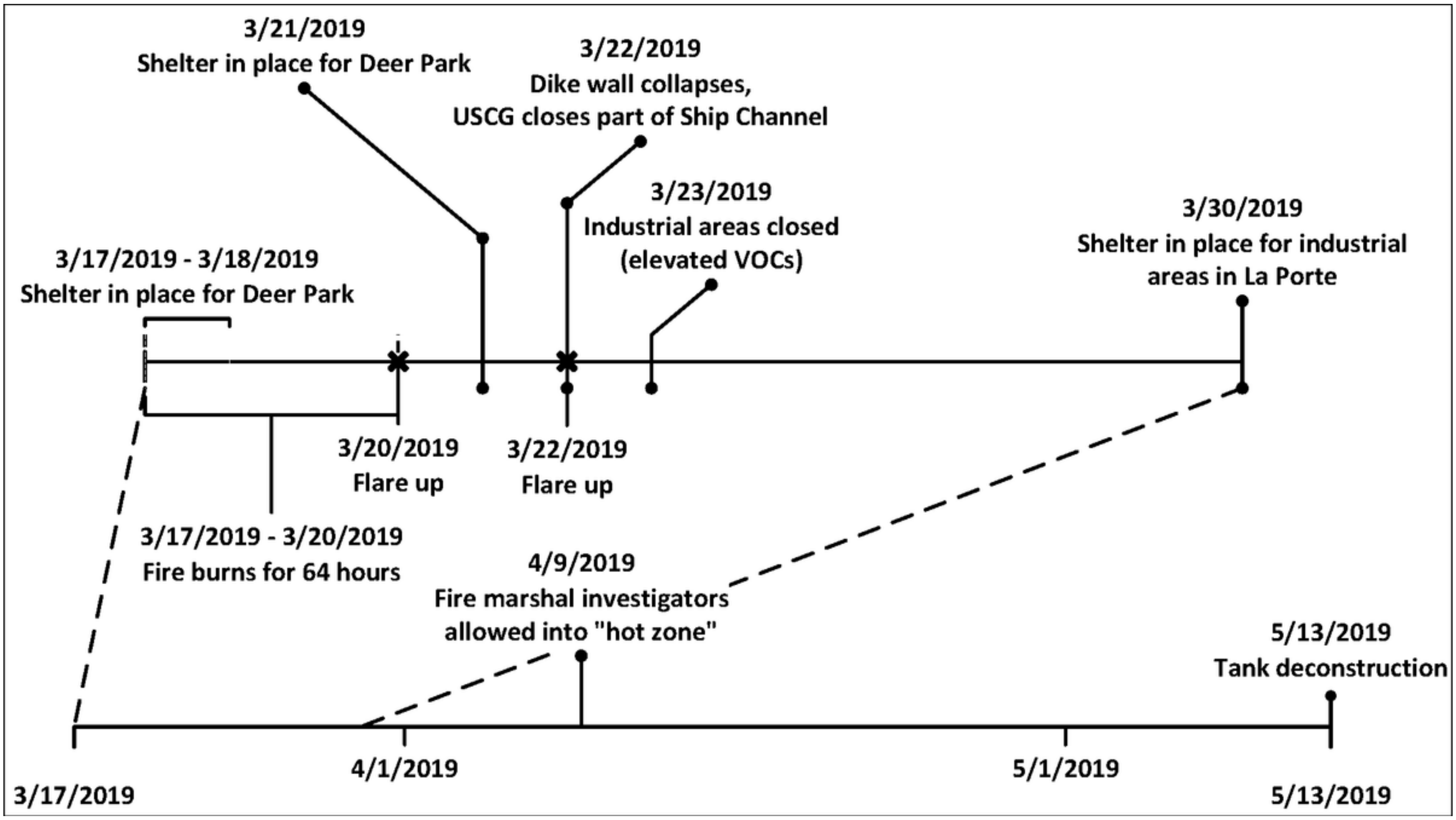

Figure 1

Timeline for the release of benzene from the Houston ITC fire and the related actions that were put in place to protect public health.

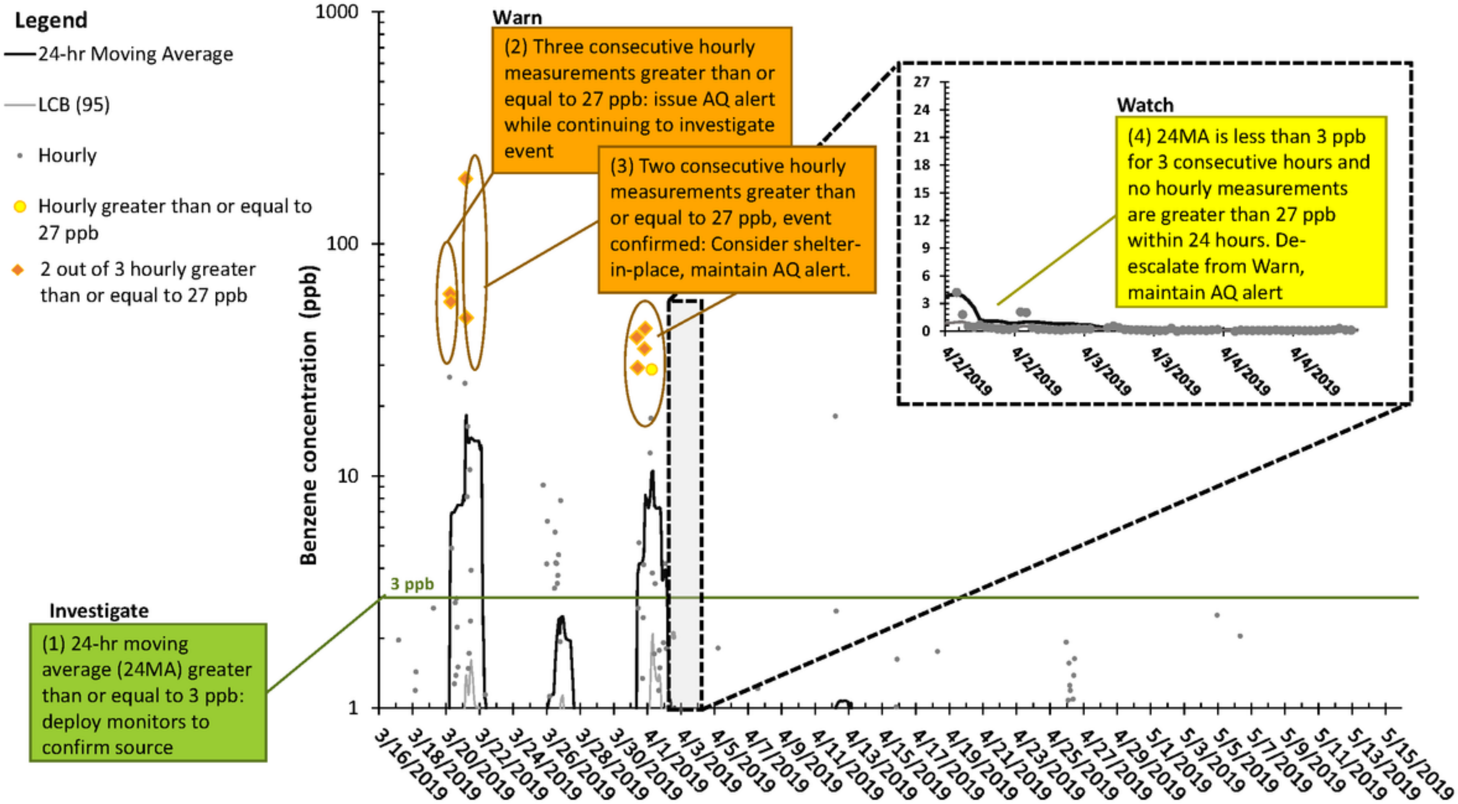

Figure 2

Deer Park monitor readings of ambient benzene concentrations and example action alerts from Table 2 that would have been applied during the ITC event, between March 16 and May 15, 2019. (1) the 24-hour moving average (24MA) rises above 3 ppb, triggering mobile monitor deployment and communication with the source; (2) three consecutive measurements above 27 ppb indicates a "warn" condition, and triggering an air quality (AQ) alert; (3) additional elevated hourly measurements, including two consecutive hourly measurements above 27 ppb supporting shelter-in-place; (4) 24MA drops below 3 ppb for 3 consecutive hours and there are no hourly measurements greater than 27 ppb within previous 24 hours indicates a de-escalation from "warn" to "watch" and maintain AQ alert. Not depicted for Deer Park are an additional watch condition and ongoing "investigate" status.

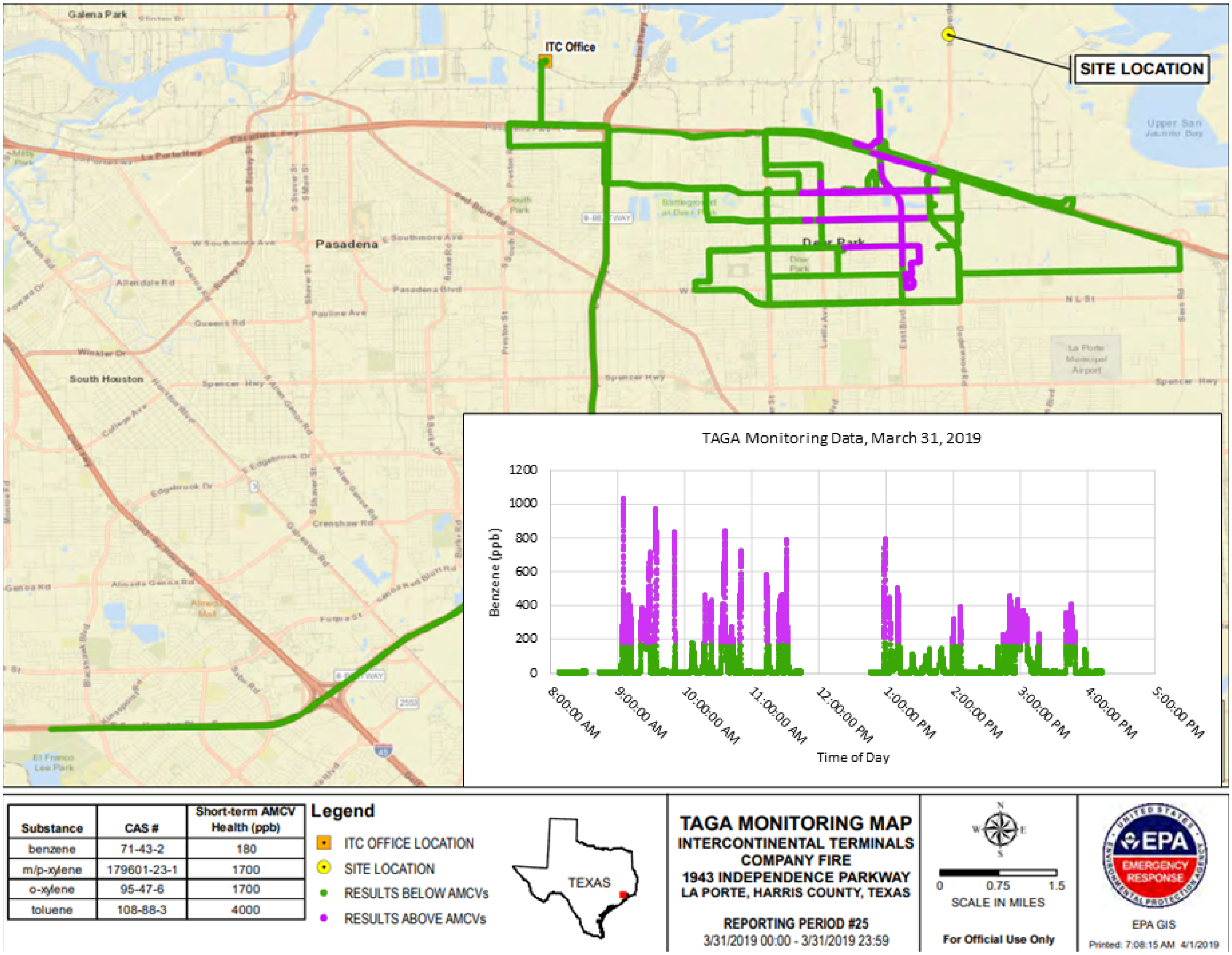

Figure 3

Base map of Trace Atmospheric Gas Analyzer (TAGA) data collected by USEPA on March 31, 2019 in the Deer Park residential area, updated to include scatter plot of the same data to illustrate magnitude and duration of exposure. Purple markers show sample data above Texas Commission on Environmental Quality (TCEQ) 1-hr Air Monitoring Comparison Values (AMCVs). This study indicates that a more protective value for the 1-hr acute ReV should be 27 ppb. The original map can be found at: https://response.epa.gov/sites/14150/files/ITC%20TAGA%20MAP%203-31-19.pdf

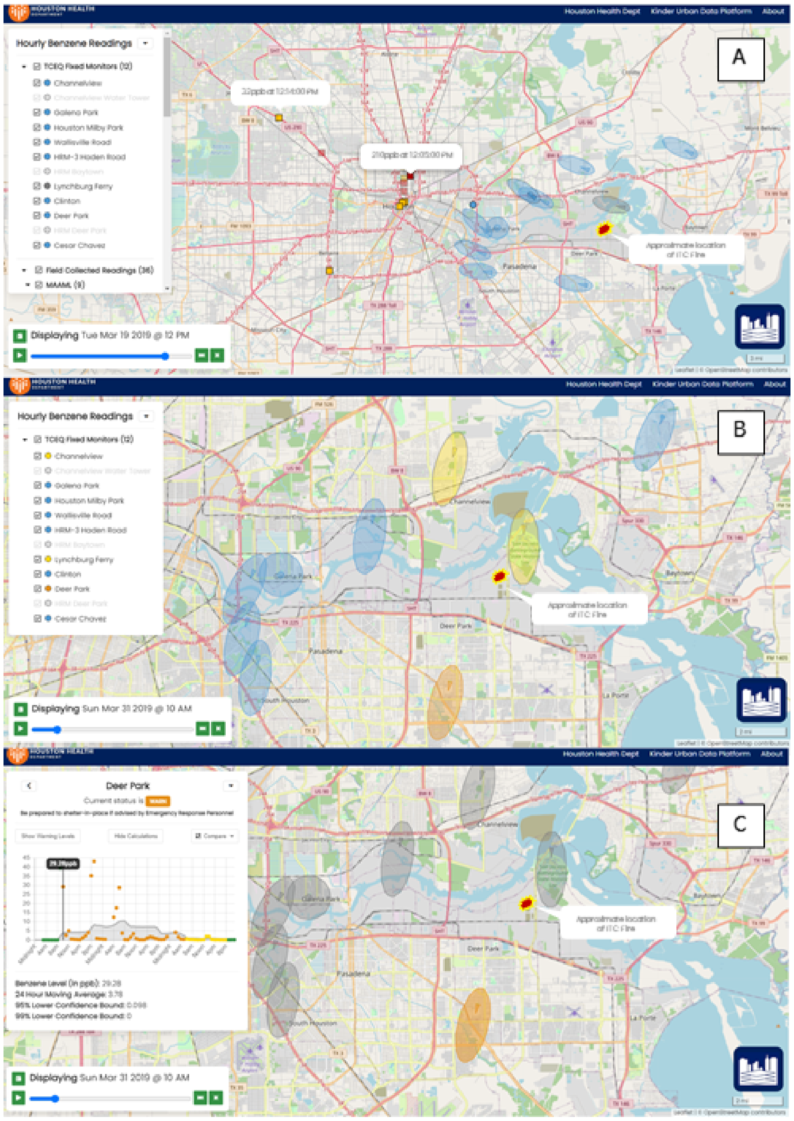

Figure 4

Visualization platform screenshots for two different time points, as well as an individual monitor for one time point: A) March 19, 2019 at 12 pm; and B) March 31, 2019 at 10 am. C) Screenshot of the Deer Park Monitor on March 31, 2019 at 10 am, with site data and calculations shown. On March 19th, 2019, the fixed site monitor information is augmented with 9 MAAML measurements and 27 measurements from handheld devices. An animation of the visualization for the design event is available at https://apps.kinderudp.org/benzene [43].

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Draftv1.0SupportingMaterialDanforth.pdf