Estimates of Inhalation Exposures among Land Workers during the *Deepwater Horizon* Oil Spill Clean-up Operations

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Abstract

Following the *Deepwater Horizon* oil spill disaster, thousands of workers and volunteers cleaned the shoreline across four coastal states of the Gulf of Mexico. For the GuLF STUDY, we developed quantitative estimates of oil-related chemical exposures [total petroleum hydrocarbons (THC), benzene, toluene, ethylbenzene, xylene, and *n*-hexane (BTEX-H)] from personal measurements on workers performing various spill clean-up operations on land. These operations included decontamination of vessels, equipment, booms, and personnel; handling of oily booms; hazardous waste management; beach, marsh, and jetty clean-up; aerial missions; wildlife rescue and rehabilitation; and administrative support activities. Exposure estimates were developed for unique groups of workers by (i) activity, (ii) state, and (iii) time period. Estimates of the arithmetic means (AMs) for THC ranged from 0.04 to 3.67 ppm. BTEX-H estimates were substantially lower than THC (in the parts per billion range). Both THC and BTEX-H estimates were substantially lower than their respective occupational exposure limits. The work group, ‘Fueled engines’ consistently was one of the higher exposed groups to THC and BTEX-H. Notable differences in the AM exposures were observed by activity, time and, to a lesser degree, by state. These exposure estimates were used to develop job-exposure matrices for the GuLF STUDY.

Keywords: Bayesian methods; BTEX; *Deepwater Horizon*; exposure assessment; hexane; oil spill; total hydrocarbons

Introduction

The GuLF STUDY, a prospective study investigating potential short- and long-term adverse health effects among workers and volunteers involved in the *Deepwater Horizon* (*DWH*) oil spill response and clean-up (OSRC), is the largest ever epidemiological study of an oil spill (Kwok *et al.*, 2017). The exposure assessment effort is a critical component of the GuLF STUDY. In three previous papers, we presented (i) exposure estimates of total hydrocarbons (as total petroleum hydrocarbons, THC) and benzene, toluene, ethylbenzene, xylene (combined *o*-, *m*-, and *p*-isomers), and *n*-hexane (BTEX-H) for workers on the four rig vessels responsible for stopping the spill near the wellhead and drilling relief wells (Huynh *et al.*, 2021a); (ii) exposure estimates on the large marine vessels piloting remotely operated vehicles (ROVs) and doing other support work for the rig vessels (Ramachandran *et al.*, 2021); and (iii) estimates on the thousands of smaller vessels that supported the rig vessel operations as well as conducted other clean-up activities throughout the Gulf waters (Huynh *et al.*, 2021b).

The goal of this paper is to present estimates of exposures for clean-up activities on land, specifically in Louisiana (LA), Mississippi (MS), Alabama (AL), and Florida (FL) for six oil-related components, THC and BTEX-H. The Responsible Party (RP) conducted many personal air measurements of workers and volunteers engaged in the beach clean-up in these states because these states received the largest amount of crude oil washed up on the shoreline, hence the intensity of the clean-up activities on the beaches of these states was also greatest and varied by state. Here, we describe work group activities, present exposure summary statistics, and analyze exposure trends across activities, geographical locations (by state), and over time. While the purpose of this work is to provide exposure estimates for the GuLF STUDY, the descriptive presentation of the estimates may also be useful to public health professionals engaged in disaster preparedness and response at the local, state, and federal levels to plan for these types of responses should an oil spill slick happen to reach shore.

An overview of the entire exposure assessment process from the initial data collection to the creation of the GuLF STUDY job-exposure matrices can be found in Stewart, Groth *et al.* (2021). The development of exposure groups for the epidemiologic study are described in Stenzel, Groth, Huynh *et al.* (2021). The airborne THC and the BTEX-H estimates for workers on the water (Groth, Huynh *et al.*, 2021; Groth, Banerjee *et al.*, 2021; Huynh *et al.*, 2021a,b; Ramachandran *et al.*, 2021), and of dispersants (Arnold *et al.*, 2021; Stenzel, Arnold *et al.*, 2021), particulate matter 2.5 µm in size (Pratt *et al.*, 2021) and oil mist (Stewart, Groth *et al.*, 2021) are presented elsewhere, as is the development of dermal exposures (Gorman Ng *et al.*, 2021; Stewart, Gorman Ng *et al.*, 2021).

Background

The *DWH* OSRC activities on land primarily spanned the coastline of four states (LA, AL, FL, and MS) and started within days after the *DWH* rig exploded in the Gulf of Mexico on 20 April 2010. The GuLF STUDY exposure assessment covers the period of time from the sinking of the *DWH*, which severed the pipe connecting the well to the rig and started the oil release on 22 April 2010 through 30 June 2011. In this section, we briefly describe the various OSRC activities that were performed on land. Among those activities, the greatest number of study participants reported beach and marsh clean-up.

Decontamination (decon) of vessels (e.g. removing oil and contaminants from the hull of the vessels, anchors, moor lines, etc.), equipment [e.g. scrubbers and booms (floating barriers used to contain the oil)], and personnel involved in the decon was extensive on land. At the height of the decon operations (August–October 2010), up to 17 decon sites were in operation across five Gulf states (the four GuLF STUDY states identified above and

Texas) (NOAA On Scene Coordinator Report, 2011). After having received preliminary decontamination offshore to prevent oil from being carried to shore by contaminated hulls, more extensive deconning of vessels and equipment (including booms) occurred in ports using high and low pressure washing with hot or ambient temperature water with or without cleaning agents. Brushes, rags, and sorbent pads were also used during this decon process. In addition, a final and comprehensive deconning occurred before the vessel was released from service (decommissioned from the OSRC effort). Workers cleaning beaches and their transport vehicles were deconned at stations located on the perimeter of contaminated areas using either low pressure spraying with cleaning agents or low or high pressure washing with water on the vehicles and using small, shallow inflatable swimming pools for cleaning gloves, clothing, and footwear.

Boom deployment on land occurred in shallow waters off beaches and marshes to protect these areas and prevent oil from entering inland waters. Deployment was also done just outside of ports and docks to keep incoming vessels from getting contaminated and to protect the waters during deconning. Millions of feet of various types of booms, including fire, rigid pipe, snare, and sorbent boom, were deployed during the spill containment. After having been deployed, booms were regularly inspected, moved, repaired if possible (often using solvents), or replaced, before being retrieved after no more oil was expected in the area. Boom repair facilities were located throughout the Gulf area. Contaminated booms and other materials [rags, sorbents, personal protective equipment (PPE), and other disposable equipment] were loaded by material handling vehicles (onsite drivers) to trucks that transferred the waste to designated waste disposal areas (offsite drivers).

Oil reached the LA shoreline first and then reached MS, AL, and finally FL. Shoreline Clean-up and Assessment Technique (SCAT) field teams made up of scientists from the RP, federal and state agencies, and state universities, first patrolled a particular shore segment to systematically evaluate the contamination and recommend appropriate clean-up or treatment techniques. Then, teams of workers were sent to the site to collect oil and oily sand, mousse (mixture of water and oil) and tar balls, and oiled plants and garbage with handheld equipment, depositing the waste in plastic bags. Sand cleaning operations were done with large or small mechanical beach sifters. In some cases, the sand was scraped up and loaded onto trucks, transferred to stationary sand cleaning equipment and then return to the beach once it was cleaned.

Jetties and other manmade structures were pressure sprayed or wiped with absorbent materials either from small boats or on land. For marsh clean-up, both mechanical (vessel-based platforms with long-reach hydraulic arms coupled with various cleaning devices) and manual (hand tools and power hedge trimmers) techniques were used.

Aerial operations involved hundreds of aircraft equipped with GPS (global positioning system) tracking capabilities to identify oil slicks, spray dispersants on the water, and monitor various operations conducted by vessels (e.g. *in situ* burning). Helicopters transported personnel and supplies to and from large vessels equipped with helipads, primarily located near the wellhead areas. Aerial reconnaissance missions collected information on oil formations on soil, sediment, and water, on areas with oil slicks for fishing advisories and on boom effectiveness. Other planes also searched for oily marine animals.

Hundreds of volunteers and workers collected oiled wildlife and transported them to designated facilities along the coastal states to be assessed for health issues, cleaned and cared for in a protected environment until the wildlife could be released. Lastly, other various support operations included site security, fueling of vessels and equipment (such as trucks, loaders, transport vehicles, generators, etc.), maintaining pumps/pumping, tank work (inspecting and high pressure cleaning of tank content including oil/oily water, fuels, dispersants, and other chemicals), providing industrial hygiene/safety/medical services, housekeeping and kitchen work, and office work.

Methods

Data collection and processing

Industrial hygienists contracted by the RP collected personal air measurements on workers and volunteers during the OSRC effort. Personnel wore organic vapor badges (3M 3500 or 3520, or Assay Technology 521) in the breathing zone generally for 4–18 h. The samples were analyzed for 5–11 analytes using a gas chromatograph with a high flame ionization detector (Stenzel, Groth, Banerjee *et al.*, 2021). After exclusion of samples due to the analytes not being evaluated in the GuLF STUDY, long or short measurement duration (<4 or >18 h), improper handling (e.g. the cap was left off the sample) or missing or insufficient accompanying documentation, we used a total of 21 643 (16 990 land work groups and 4653 land/water work groups) samples for this analysis.

The original dataset received from the RP contained a high proportion of measurements below the limits of detection (LODs) because the analytic laboratories developed their calibration curves to reflect occupational exposure limits rather than the sampling and analytic methods' LODs. After recalculation based on the sampling and analytical methods' true LODs, the percentages of censored data for land-based measurements were 8.7 for THC, 94.4 for benzene, 95.5 ethylbenzene, 80.3 for toluene, 61.7 for xylene, and 47.6 for *n*-hexane (Table 1). More details on the recalculation methods, the original LODs, and the percentage of censored data can be found in Stenzel, Groth, Banerjee *et al.* (2021).

Development of work groups

The study participants provided their work histories through a telephone interview (Kwok *et al.*, 2017). From the work histories, the measurement data, and the extensive documentation on the spill, we identified three exposure determinants that were likely to have affected exposures: activity, oil weathering, and time that form the basis of the work groups (Stenzel, Groth, Huynh *et al.*, 2021). In this paper and previous exposure assessment papers (Huynh *et al*, 2021a,b), the unique combination of activity/location/time was considered in this report as a work group, the members of which were expected to have similar distributions of exposures. These work groups formed the basis of the exposure groups for the epidemiologic study (Stenzel, Groth, Huynh *et al.*, 2021). Unlike the traditional similar exposure group definition that generally refers to more stable exposure groups, these work groups may contain high GSD and mixed distributions due to the dynamic nature of the spill response. A description of the work groups can be found in Table 2 and in Supplementary Table S1 (Activity Description), available at *Annals of Work Exposures and Health* online. There are work groups covered in this paper that relate only to land operations such as removing tar balls and oil from beaches and marshes, but there are other work groups included in this paper that related to combined land and water operations such as retrieving boom in shallow water. In this case, the worker may stand in the shallow water and collect the boom or stand on land collected the boom near the shoreline. The detail in the measurement documentation and work histories could not distinguish between these activities so this activity was considered a land/water work group.

Activity

Each OSRC activity described above (see Background) was used as the basis for the activity determinant. In addition, we developed tasks to reflect additional information that were collected from the study questionnaire. For deconning activity, we separately considered what was being deconned (vessels, equipment, and boom) and used 'Deconned all/land' to describe work by participants who reported more than one type of deconning effort. A group was also developed comprising workers who were in a decon area, but not actually deconning (e.g. a supervisor) ('Decon/general area'). In the same manner, we had several subsets for boom work; for jetties work; for maintaining pumps/tanks or pumping (including dis/connects); and for cleaning beaches (Supplementary Table S1, available at *Annals of Work Exposures and Health* online).

Location (state)

Another major exposure determinant was oil weathering, i.e. the process by which the composition of the crude oil is changing, due to the chemicals' solubility in water, application of dispersants, wave action, evaporation, and other natural processes (Stenzel, Groth, Huynh *et al.*, 2021). Oil weathering due to evaporation

Table 1. Number of measurements taken on land and percent censoring by work group type and analyte.

Work group[a]	*N*	THC	Benzene	Ethylbenzene	Toluene	Xylene	*n*-hexane	
		% <LOD[b]	% <LOD	% <LOD	% <LOD	% <LOD	*N*	% <LOD[c]
Combined land	16 990	9.7	95.0	96.3	82.5	61.5	14	85.7
Combined land/water	4653	5.0	92.3	92.3	72.5	62.4	217	45.2
Total	21 643	8.7	94.4	95.5	80.3	61.7	231	47.6

N, number of measurements.

[a] See text for a general description of land and land/water operations.

[b] The average LODs, based on the average sample duration of 8-h duration, for THC, benzene, toluene, ethylbenzene, and xylene were 0.0118, 0.00256, 0.00250, 0.00246, and 0.00502 ppm, respectively (see Stenzel, Groth, Huynh *et al.*, 2021 for more information).

[c] The average LOD for *n*-hexane based on the average sample duration of 10 h was 0.00279 ppm. The number of imputed hexane values from THC was16 976 for land and 4436 for combined land/water group.

Table 2. Activities description.

Work group label	Description[a]
Patrolled beaches and marshes on foot	Performed by scientists and representatives of the government and RP (also known as SCATS: Shoreline Clean-up Assessment Teams). Methodically walked and surveyed the beaches and marshes to rate the contamination using standard criteria to prioritize cleaning. May involve taking samples. However, may also include beach cleaners walking the beaches cleaning up oil and tar balls.
Cleaned marshes	Cleaned marshes: (i) manually by workers on board walks using hand tools and power hedge trimmers; and (ii) mechanically by workers on barge-based and large airboat-based platforms using long-reach hydraulic arms coupled with attachments including grapples, rakes, cutting devices, and 'squeegees' to skim thick mousse from the surface of the marsh following the removal of heavily oiled wrack and vegetation mats.
Handled booms/land or shallow water	GuLF STUDY category for participants who indicated they handled boom but provided no other boom work description. Booms included hard, spaghetti, sausage, or pompom booms and were used to prevent the oil from reaching ecologically fragile environments. Workers placed and anchored boom at the tideline to keep oil from coming ashore and moved the boom as tide and weather conditions changed.
Repaired oily booms	Repaired oily booms. May have used solvents.
Deconned with cloth/ land or water	Used absorbents to soak up oil on the water (generally near shore), on jetties and other manmade and natural structures and on beaches and marshes.
Handled/cleaned wildlife	GuLF STUDY category for participants who indicated they handled or cleaned wildlife but provided no other information. Handling may have included capturing live or dead wildlife or caring for and rehabilitating the animals in a safe environment after they were cleaned. Cleaning wildlife was done in an enclosed environment with cloth, water, and soaps. Wildlife includes mammals, reptiles, and birds.
Fueled engines	GuLF STUDY category for participants who did not indicate the type of fuel. Fueled engines of vessels, primarily, but also land equipment with either diesel fuel or, less often gasoline with ordinary 'gas pump' type equipment.
Deconned vessels/land	Decontaminated vessels (particularly the hull) of oil by pressure spraying and cloths and other absorbent materials.
Deconned other equipment/land	Cleaned equipment other than vessels. Equipment includes tools (such as rakes and shovels), skimming equipment, beach transport vessels, respirators, cleaning with brushes or absorbents, or spraying with a hand pump or pressure spraying.
Deconned booms/land	Cleaned booms using either low or (more frequently) high pressure spraying. Spray water may have been heated.
Deconned workers	Cleaned workers after having been contaminated with oil, either from working in shallow water or on land. This involved low pressure spraying of shoes in shallow pools, helping remove clothing, gloves, and shoe coverings and disposing of them in bags.
Jetties/land or water	GuLF STUDY category for participants who were part of the team that used low or high pressure spray and sorbents including cloth or scrapers to clean manmade structures (such as jetties, bridges, and bulkheads) and natural (e.g. rocks and boulders) structures on land or over water from the land or from boats. No detergents were used.
Decon/General Area/ Land	GuLF STUDY category for participants who were in a decon area but did not personally decon. These participants included foremen, supervisors, and superintendents, people walking through the area and dropping off or picking up material.
Security	Provided security onto the base by checking badges.
General environment/ land	GuLF STUDY category for participants who indicated they worked on land did not indicate any specific tasks.
Hazardous Waste/Land	Handled or moved for disposal hazardous waste. Waste could have included oil, oily water, contaminated equipment (clothing, gloves, absorbents), etc. Moving may have been done manually or mechanically (e.g. a fork lift truck).

Table 2. Continued

Work group label	Description[a]
Maintained pumps/tanks or pumped (including dis/connect) anything (inc oil)/Land	Performed maintenance on pumps and storage tanks, pumped or made connects or disconnects of piping and pumps for equipment containing chemicals on land only.
Tank work (entered + worked outside)	GuLF STUDY category to identify participants who did not specify what was contained in the tanks. Performed inspection or cleaning inside or outside tanks. May have worn an air-supplied respirator. They were professional HAZWOPERS.
Deconned all/land and water	GuLF STUDY category for participants who performed some type of deconning on land or on water. This included using low (typically 500 to <3000 psi) or high pressure spray (>3000 psi) or use of absorbents (sausage boom, pads, rolls, sweeps, and snare) to soak up the oil. Citrus-based or other detergents, particularly, D-limonene or dry ice pellets may have been used. Deconning on water generally was gross cleaning while on land it was thorough cleaning.
IH/safety = land	Industrial hygienists, safety professionals, and medics who conducted air monitoring and oversaw the safety of the workers.
Housekeeping	Cleaned offices and flotels where workers slept.
Kitchen	Cooked and cleaned up the eating areas.
Offsite driver	Drove chemicals (including oil/oily water) and equipment into and out of the base from suppliers or to authorized recycling/disposal areas.
Onsite driver	Transferred chemicals (including oil/oily water) and equipment within the base.
Ran mechanical equipment/ports and docks	Operated fork lift trucks and other equipment to transfer clean and contaminated equipment around the base.
Office work	Provided administrative support. Some workers likely got into exposed areas.
Collected oily plants and garbage	Used hand tools (garden tools, shears, and machetes) to cut oiled plants and collected garbage and put both into disposal bags.
Cleaned beaches/ non-specific tasks	GuLF STUDY category for participants who indicated that time was spent on the beach but provided no task description.
Retrieving boom in shallow water	Removed boom near shore by standing in clean or contaminated water.
Put out, moved, or inspected booms while standing in oily water	Deployed, inspected, and moved booms near shore by standing in contaminated water.
Boom deploy and pickup in shallow water	Deployed and removed booms near shore by standing in clean or contaminated water.
Deconned all/land	Deconned two or more of the following: vessels, vessel equipment, booms.
Operated mechanical equipment on beach	Operated large or small sand excavators, movers, sifters, or sand washers on the beaches.
Maintained pumps/tanks or pumped (including dis/connect) OIL/land or water	Performed maintenance on pumps and storage tanks, pumped, or made connects or disconnects of piping and pumps for equipment containing oil on either land or water (for participants who did not identify location).
Personally cleaned jetties with high pressure spray/ land or water	Personally used high pressure spray to clean manmade and natural structures on land or over water from the land or from boats.
Cleaned jetties/land (general)	Cleaned manmade and natural structures on land by pressure spraying or sorbents or cloths.
Removed tar balls and oil/beaches and marshes	GuLF STUDY category for participants who indicated they removed both oil and tar balls from the beaches.
Aerial crew/dispersant spraying	Flew planes over oil slicks to apply dispersant to break up the oil.

Table 2. Continued

Work group label	Description[a]
Maintained pumps/tanks or pumped (including dis/connect) anything (inc oil)/land and water (exc dispersant injection)	Performed maintenance on pumps and storage tanks, pumped or made connects or disconnects of piping and pumps for equipment containing chemicals (including oil and oily water) on either land or water. Does not include equipment containing dispersants on the vessel that injected dispersant below the water surface.
Beaches and marshes/ general environment	GuLF STUDY category to cover study participants who provided no specific information on what they were doing on the beach/marsh.
Removed tar balls using hand equipment	Used rakes, shovels, wheelbarrows, nets, and other hand tools on beaches and the shoreline to remove tar balls and tar patties from the ground and sand.
Removed oil using hand equipment and/or searched under sand and water	Removed oil using shovels, rakes, hand sifters, augers, and other tools. Also vacuumed up oil pools on land.
Beaches and marshes: multiple tasks	GuLF STUDY category for participants who reported performing at least two tasks on the beaches and marshes.
Used absorbents on jetties/land or water	Used sorbents or cloth to clean manmade and natural structures on land or water.
Aerial crew/ non-dispersant	Flew planes and helicopters for (i) transport of people and equipment out to the wellsite or vessels far offshore; (ii) application of dispersant; (iii) spotting for guidance to dispersant-applying planes and searching for oil slicks and to provide guidance for burning operations on the water; (iv) spotting for marine animals.
Cleaned beaches: multiple tasks	GuLF STUDY category for participants who reported performing at least two cleaning tasks.
All land	GuLF STUDY category developed for purposes of the graphs in this paper.

[a] GuLF STUDY category indicates a work group was developed to accommodate the questionnaire responses particularly to the open-ended questions of 'what else did you do?' (Kwok *et al.*, 2017).

resulted in the various volatile components of crude oil measured as THC to differentially evaporate over time resulting in both the composition of the crude oil and crude oil vapor to change over time. Because study participants would not have been able to report the degree of weathering the oil or tar had undergone with which they had had contact with, we used two proxies for weathering: location (with two subdeterminants of area on the land and state) and time period (TP).

The values for the area determinant were beaches and marshes, port and docks, and other land. The state determinant was one of the four study states (LA, MS, AL, or FL) or a broader group, 'All states', representing all measurements for an activity. If the impact of all other determinants on exposure are equal, the further the state from the wellhead, the greater the weathering the oil was likely to have undergone. Thus, FL workers were expected to have had contact with oil that had undergone greater weathering than workers in LA.

Time period

TP was used as a proxy for oil weathering (Stenzel, Groth, Huynh *et al.*, 2021) as well as a determinant in its own right, due to OSRC events changing over time, which resulted in changes in exposures. We developed TPs to reflect these changes. In TP1a (22 April–14 May 2010), oil was continuously being released as attempts to stop the flow failed. Decontamination and boom deployment started as early as late April 2010. Oil first reached the LA shore about the end of April and beach clean-up started. By TP1b (15 May–15 July 2010), oil had reached the MS, AL, and FL shorelines. The well was successfully mechanically capped on 15 July. In TP2 (16 July–10 August 2010) booms started being removed. The well was sealed at the top ('static kill') on 4 August 2010. Jetties started being cleaned. During TP3 (11 August–30 September 2010), final decontamination of vessels escalated on land and boom removal continued. The damaged well was permanently sealed at approximately 5.5 km (18 000 ft) below the Gulf water surface on 16 September 2010. Marshes started being cleaned. By the end of TP4 (1 October–31 December 2010) final decontamination of nearly all vessels was completed. During TP5 (1 January–31 March 2011) and TP6 (1 April–30 June 2011), beach and marsh clean-up continued, but the number of workers rapidly decreased during this time, so we ceased exposure assessment as of 30 June 2011. TP6 was separate from TP5 due to the higher ambient temperatures in TP6. Please refer to these papers (Stenzel, Groth, Huynh *et al.*, 2021; Stewart, Groth *et al.*, 2021) and Supplementary Materials, available at *Annals of Work Exposures and Health* online for more detailed description of the timeline.

Other considerations

Six work groups that occurred both on land and water and had limited measurement data were expected to comprise workers that likely had similar distributions of exposures in the two areas. For these activities, the measurements at both locations were combined and identified as land/water. Examples included jetty clean-up and deconned with a cloth.

We reviewed the associated documentation of every sample and assigned each sample to one or more work groups. Exposure estimates were developed for each of these unique work groups (N = 1680 or 240 activity/state × 7 time periods) when appropriate measurements were available (see Statistical analysis). Stewart, Groth *et al.*, 2021) describe the procedure used to develop estimates for unique exposure groups when appropriate measurements were not available. The same work groups were used for all six substances estimated.

Statistical analysis

Details on the statistical methodology can be found in Supplementary Materials, available at *Annals of Work Exposures and Health* online of the overview paper by Stewart, Groth *et al.* (2021) and on the priors used in the Bayesian analysis for BTEX-H in Groth, Huynh *et al.* (2021). Briefly, we used a univariate Bayesian model that accounted for data below the LOD to compute exposure descriptive statistics for THC (Huynh *et al.*, 2016). We specified the following uniform (Unif) priors for μ or [ln(geometric mean (GM)] and σ or [ln(geometric standard deviation (GSD)]: $\mu \sim \mathrm{Unif}(\ln 0.025, \ln 50)$ and $\sigma \sim \mathrm{Unif}(\ln 1.1, \ln 12)$, which provided rather vague information to the model, ensuring that the priors did not overwhelm the actual data (see justification in Huynh *et al.*, 2021a,b). To predict BTEX-H exposures, we used a bivariate left-censored Bayesian model that used informative prior relationships developed from the correlations between THC (predictor) and each of the BTEX-H chemicals (response variable) (Groth *et al.*, 2017, 2018; Groth, Huynh *et al.*, 2021). For the samples (N = 21 643 covered in this paper), about 99% of missing *n*-hexane measurements were imputed using the bivariate Bayesian regression model outlined in Groth, Huynh *et al.* (2021). We computed posterior medians for the arithmetic means (AMs), GMs, GSDs, and 95th percentiles and their 95% credible intervals (CIs) for each work group and each chemical. Only work groups with ≥5 measurements and censoring level ≤80% are included in this report because these criteria have been found to produce acceptable relative bias (<15%) and imprecision (<65%) based on our simulation study (Huynh *et al.*, 2016). Statistically credible differences between groups were identified if two groups were independent (non-overlapping groups) and did not have overlapping 95% CI. All of the analyses were conducted in JAGS (Just Another Gibbs Sampler) (Plummer, 2003) and R (R Development Core Team, 2015).

Results

Supplementary Tables S2–S7, available at *Annals of Work Exposures and Health* online provide the posterior median estimates for the AMs, GMs, GSDs, and 95th percentiles and their 95% CIs for the THC and BTEX-H chemicals by work group. THC is shown in parts per million (ppm); the BTEX-H chemicals are shown in parts per billion (ppb).

THC estimates

The AM posterior medians for THC levels ranged from 0.04 ppm [95% CI 0.03, 0.21 ppm, All states, TP2, work group 'Jetties/land or water' and 'Cleaned jetties/land (general)' (which used the same data as 'Jetties/land or water', the two groups were developed to differentiate between study participants who only worked on land from participants for whom it was unclear where they worked)] and 0.04 ppm (95% CI 0.04, 0.07 ppm, AL, TP2, 'Operated mechanical equipment on beach') to 3.67 ppm [95% CI 1.67, 11.1 ppm, LA, TP3, 'Tank work (entered + worked outside)'].

We observed notable differences among some activities. For example in TP1b, the AM for 'Fueled engines' (AM = 1.59 ppm, 95% CI 0.78, 3.97 ppm, All states) was greater than that for 'Repaired oily booms' (AM = 0.53 ppm, 95% CI 0.40, 0.72 ppm, All states), and both AMs were notably greater than those for 'Deconned booms/land' (AM = 0.21 ppm, 95% CI 0.15, 0.29 ppm, All states), 'General environment/land'

(AM = 0.20 ppm, 95% CI 0.13, 0.34 ppm, All states), 'Collected oily plants and garbage' (AM = 0.18 ppm, 95% CI 0.14, 0.24 ppm, All states), and 'Removed tar balls and oil/beaches & marshes' (AM = 0.11 ppm, 95% CI 0.10, 0.12 ppm, All states). Other striking differences may be found in Supplementary Table S2, available at *Annals of Work Exposures and Health* online.

Within each TP, exposures for workers in some states were more elevated than others. For example, the AM in TP1b for 'Removed tar balls and oil/beaches & marshes' was 0.22 ppm in LA (95% CI 0.17, 0.30 ppm), 0.20 ppm in FL (95% CI 0.15, 0.27 ppm), 0.15 ppm in MS (95% CI 0.13, 0.18 ppm) versus 0.06 ppm in AL (95% CI 0.06, 0.07 ppm).

There were also marked differences over time. 'All land operations' had lower AMs in TP1a (AM = 0.18 ppm, 95% CI 0.15, 0.23 ppm), in TP1b (AM = 0.18 ppm, 95% CI 0.17, 0.19 ppm), and in TP2 (AM = 0.19 ppm, 95% CI 0.18, 0.21 ppm) than in TP3 (AM = 0.43 ppm, 95% CI 0.40, 0.47 ppm), TP4 (AM = 0.27 ppm, 95% CI 0.25, 0.29 ppm), TP5 (AM = 0.25 ppm, 95% CI 0.23, 0.27 ppm), and TP6 (AM = 0.40 ppm, 95% CI 0.37, 0.45 ppm). TP3's AM was greater than TP4 and TP5's AM; and TP6's AM was greater than TP4 and TP5's AM for this same work group. Specific activities also showed credible differences over time (Supplementary Table S2, available at *Annals of Work Exposures and Health* online). Generally, however, time trends were inconsistent (Fig. 1).

BTEX-H estimates

The AM estimates for benzene ranged from 1.29 ppb (95% CI 0.08, 13.66 ppb, *N* = 5, TP1a, 'Cleaned beaches/non-specific tasks', LA) to 62.52 ppb (95% CI 24.50, 198.42 ppb, *N* = 18, TP3, 'Fueled engines', MS); toluene 1.10 ppb (95% CI 0.09, 9.64 ppb, *N* = 5, TP3, 'Removed oil using hand equipment and/or searched under sand & water', MS) to 144.49 ppb (95% CI 78.62, 276.19 ppb, *N* = 108, TP2, 'Repaired oily booms', LA); ethylbenzene 1.81 ppb (95% CI 0.10, 20.87 ppb, *N* = 5, TP6, 'General environment/land', MS) to 31.21 ppb [95% CI 14.45, 80.23 ppb, *N* = 47, TP2, 'Maintained pumps/tanks or pumped (including dis/connect) anything (inc oil)/land and water (exc dispersant injection)', All states]; xylene 4.09 ppb (95% CI 1.02, 17.72 ppb, *N* = 10, TP4, 'Beaches marshes/general environment', All states) to 112.56 ppb [95% CI 58.23, 278.4 ppb, *N* = 47, TP2, 'Maintained pumps/tanks or pumped (including dis/connect) anything (inc oil)/land and water (exc dispersant injection', All states]; and *n*-hexane 2.67 ppb (95% CI 0.59, 12.5 ppb, *N* = 11, TP5, 'Deconned vessels/land', MS) to 152.8 ppb (95% CI 76.26, 353.5 ppb, *N* = 17, TP2, 'Fueled engines', LA). Inconsistent patterns for trends across activities and geographical location and over time were observed for the BTEX-H chemicals for many land operations (Fig. 2 for toluene and xylene, Fig. 3 for benzene and ethylbenzene, and Fig. 4 for hexane).

Variability of the measurements was high for some of the chemicals. The percentages of GSD posterior medians >6 (and >9) for THC were 7.3 (1.1)% (GSD range 1.2–9.2); for benzene, 61.4 (30)% (2.9–10.6); for toluene 53.0 (15.6)% (2.1–11.0); for ethylbenzene, 51.6 (31.1)% (4.1–9.6); for xylene, 3.9 (0.7)% (1.5–9.4); and for *n*-hexane, 50 (6.3)% (3–9.9).

Discussion

This paper presents our exposure estimates for work groups that covered a wide range of OSRC activities on land and in a few cases land and water, including oil decontamination of vessels and equipment; handling of booms and hazardous wastes; beach, marsh, and jetty clean-up; wildlife searches, rescue, and rehabilitation; air operations; and general support. Important factors that appeared to have affected workers' exposures to the oil-related chemicals while performing this work included oil weathering patterns, work activities, state, and TP. As expected, the exposure estimates for land activities were generally lower than exposures levels on the four rig vessels (Huynh *et al.*, 2021a); on the ROV and other marine vessels (Ramachandran *et al.*, 2021); and on the other, generally smaller, support vessels (Huynh *et al.*, 2021b). By the time the oil slick reached the shoreline, the oil had undergone considerable transformation due to weathering processes including evaporation, photo-oxidation, emulsification, adsorption, dispersion, dissolution, and biodegradation, resulting in many of the volatile components being eliminated or at least reduced in concentration. Thus, even when land workers came into direct contact with the oil (e.g. beach workers), exposures were much lower.

Two work groups that tended to have the highest exposures were 'Fuelers' and 'Tank work (entered + worked outside)'. The former was exposed to gasoline and diesel fuel. If the fuel was gasoline, those vapors likely overwhelmed the vapors in the ambient air from the oil because the BTEX concentration in gasoline is about 10 times that found in the fresh crude oil. The *n*-hexane concentration is about four times that found in crude oil. If the fuel was diesel, the diesel vapors may not have contributed substantially to exposures, as the

BTEX-H concentration is about one tenth that found in fresh crude oil. For tank work, the tank contents would likely have overwhelmed ambient oil exposures because tank work likely involved the worker being in very close proximity to either liquid layers of chemicals in the tanks or at least large contaminated surface areas. This is true of both workers entering tanks and those working immediately outside tanks because mechanical ventilation of the tank was likely required to promote safe work on the tank.

Decontamination of vessels, equipment, and personnel occurred both on land and on vessels offshore. Gross decontamination was done offshore to remove much of the oil on the outside of the vessels so the vessel would not produce an oil sheen as it moved to shore (Huynh *et al.*, 2021b). Decon work groups responsible for other interim or final decontamination on land in some cases had lower exposures but in other cases, higher exposures, likely due to differing degrees of weathered oil, cleaning techniques, chemicals used, and decon station setups, the latter which may have resulted in further or closer contact to the contaminated equipment. Beach work was another major activity and included several tasks: cleaning the sand of oil or oily sand; cleaning the sand of tar mousse, balls, or patties; and collecting oily plants and garbage. During our site visits, we observed that the outer surface of tar materials often was crusted over, which likely reduced or eliminated the release of volatiles. However, once this surface was broken or compromised as could have occurred during the clean-up process, the inner core of the material may have provided a source of volatiles that could be released, in many cases near the workers' breathing zones. Several other work groups in support roles had minimal contact with the oil (e.g. kitchen workers, housekeepers, security staff, and office workers, etc.).

Notable differences in the AMs of the measurements were observed by state, but there were fewer differences than for the water activities. Nonetheless, often LA was the state with the highest AM for some work groups. The LA shoreline was closest to the wellhead so the oil was probably less weathered. The LA shoreline was also most impacted, having approximately 847 miles (1363 km) of oiled shoreline compared with 158 mi (254 km) for MS, 95 mi (153 km) for AL, and 178 mi (286 km) for FL (Wilson *et al.*, 2017). In addition, LA also collected the largest amount of oiled waste prior to June 2011 [about 76 million lbs (34 million kg) collected in LA, 3.9 million lbs (1.8 million kg) in MS, 2.5 million lbs (1.1 million kg) in AL, no data were available for FL]. As a result, exposures from beach clean-up work for some groups were generally higher in LA than other states that were further away.

In contrast to the work groups on the support vessels, there were many measurements (approximately 1800 samples) collected from land workers in TPs 5 and 6 (1 January–30 June 2011). These data reflect the ongoing clean-up activities on land long after the four rig vessels had completed their mission of sealing the well in TP3 (11 August–30 September 2010) and after the other vessels had completed their clean-up activities and been decommissioned from service (by 31 December 2010). Beach and marsh clean-up, however, continued even beyond the close of the GuLF STUDY exposure assessment period on 30 June 2011. Exposure patterns over time for work groups on land were less clear compared with those of the rig vessels (Huynh *et al.*, 2021a), ROV and marine vessels (Ramachandran *et al.*, 2021), and other supporting vessels (Huynh *et al.*, 2021b).

The RP worked with OSHA to develop PPE matrices that included many work groups identified here. Enforcement of PPE, however, was the responsibility of the industrial hygienists/safety professionals on site, and no consistent documentation of PPE worn was made. Thus, our estimates do not reflect PPE use.

NIOSH conducted health hazard evaluations for some of these work groups at two locations onshore in LA related to decontamination. Eight measurements were collected on 10 August 2010 on the jobs identified as pressure washer (n = 2), hose holder (n =2), and brusher and decontamination (n = 3) with an observed THC concentration range of 0.01–0.15 ppm calculated as n-hexane (MW = 86.2). The BTEX measurements from NIOSH were all below the detection limits (King *et al.*, 2010; NIOSH, 2010). In our data, the samples were collected on 20 different days in TP2 and at 8 different decon locations in LA. The closest work group for which we have measurements is in LA, 'Deconned all/land' (AM = 0.34, 95% CI 0.25, 0.53 ppm, N = 79).

Our estimates are below existing occupational exposure limits. Perhaps the closest equivalent exposure limit to THC is petroleum distillates, which has a NIOSH Recommended Exposure Limit (REL) of 86 ppm (or 350 mg m^{-3}) (NIOSH, 2007). In Supplementary Table S1, available at *Annals of Work Exposures and Health* online, the highest 95th percentile (the typical compliance metric used to assess compliance with occupational exposure limits) observed was 20.43 ppm in TP3 for 'Tank work (entered + worked outside)' in AL. This group likely had exposures from other solvents such as gasoline, diesel fuel, or oil/oily water while cleaning the tanks, but the workers were probably wearing

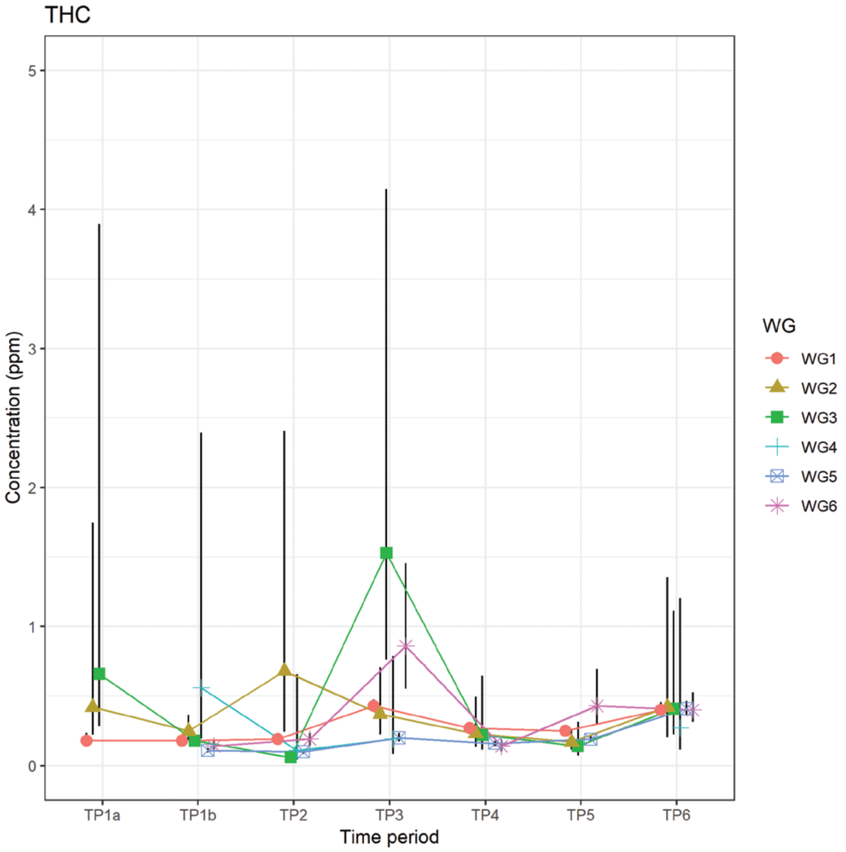

Figure 1. Exposure trends over time of selected work groups for all states for THC: WG1 = 'All land', WG2 = 'IH/safety = land', WG3 = 'Clean beaches/non-specific tasks', WG4 = 'Boom deploy & pickup in shallow water', WG5 = 'Removed tar balls and oil/beaches & marshes', WG6 = 'Removed oil using hand equipment and/or searched under sand & water'. Lack of a symbol for a particular TP means either that no samples were taken or the measurements did not meet the *N* > 5 and censoring <80% criteria.

supplied-air respirators at least for those situations that required a confined space entry, resulting in the actual exposure levels being much lower than the predicted air concentrations. Our BTEX-H estimates, however, were substantially below the current exposure limits. The respective ACGIH Threshold Limit Values™ for benzene, toluene, ethylbenzene, xylene, and hexane are 0.5, 20, 100, 100, and 50 ppm, respectively (ACGIH, 2018). The highest 95th percentiles observed for work groups reported here were 0.28 ppm (note the change in the measurement units from the rest of this report) for benzene (TP3, 'Fueled engines', MS), 0.56 ppm for toluene (TP2, 'Repaired oily booms', LA), 0.13 ppm for ethylbenzene [TP2, 'Maintained pumps/tanks or pumped (including dis/connect) anything (inc oil)/Land', All states], 0.47 ppm for xylene [TP2, 'Maintained pumps/tanks or pumped (including dis/connect) anything (inc oil)/Land', All states] and 0.57 ppm for hexane (TP3, 'Fueled engines', LA) (Supplementary Tables S2–S7, available at *Annals of Work Exposures and Health* online). In spite of these low levels, it is important to develop quantitative estimates so that researchers can investigate the exposure–disease relationships for these activities.

The sampling strategy for near shore and on land measurements was to collect sufficient samples to assess representative exposures by sampling at least 10% of the workforce for each similar exposure group (BP Gulf Science Data, 2016). This contrasts with the industrial hygiene approach on water that focused on obtaining measurements for the workers with the highest potential exposure (so that measures could be taken as needed to minimize exposures). In reviewing the water measurement data and the scope of activities monitored, the industrial hygienists did not limit monitoring to workers with the highest potential exposure, but rather it appeared that the industrial hygienists could use their professional judgment to determine if they thought an

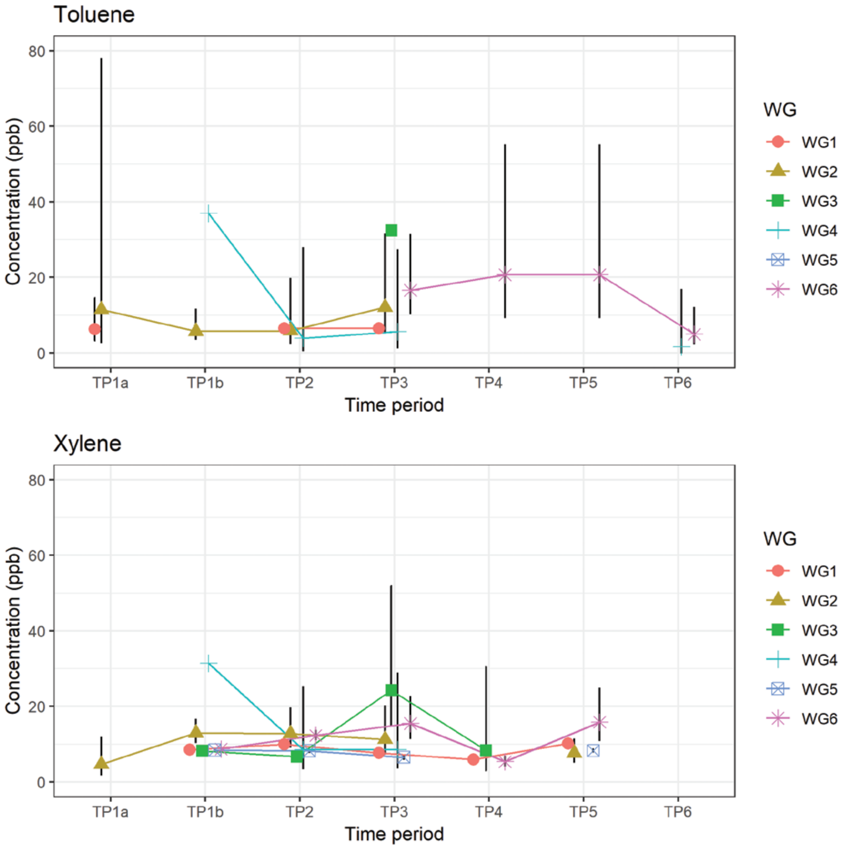

Figure 2. Exposure trends over time of selected work groups for all states for toluene and xylene. WG1 = 'All land', WG2 = 'IH/safety = land', WG3 = 'Clean beaches/non-specific tasks', WG4 = 'Boom deploy & pickup in shallow water', WG5 = 'Removed tar balls and oil/beaches & marshes', WG6 = 'Removed oil using hand equipment and/or searched under sand & water'. Lack of a symbol for a particular TP means either that no samples were taken or the measurements did not meet the *N* > 5 and censoring <80% criteria.

activity would result minimal exposure and there was no need to monitor those activities.

This paper shares the same methodological limitations as those of the rig vessels (Huynh *et al.*, 2021a) and the supporting vessels on water (Huynh *et al.*, 2021b). One was high variability in the GSD estimates likely due to the dynamic, non-routine, and outdoor working conditions. Some of the variability, however, may be due to the work groups having actually been made up of multiple exposure distributions. The simulation work of Huynh *et al.* (2016) demonstrated that Bayesian methods can achieve our relative bias and imprecision criteria in situations where there are multiple exposure distributions. We considered state and TP, but exposure conditions may have varied further within the Gulf states or within TPs. For example, decon operations used a variety of chemicals. Some cleaning chemicals, such as D-limonene, appeared to have contributed exposures to THC but not the individual BTEX-H chemicals, but we had no consistent information on cleaning chemicals. Where samples were analyzed for both D-limonene and THC, in most cases the observed THC concentration appeared to be reflecting most of the actual D-limonene concentration (analysis not shown). Further grouping was limited by the available sampling information and the level of detail of the study participants' work histories. Additionally, there was no useful information on repeated measurements within subjects, and there was no assurance that a repeat measurement on the same subject represented the same exposure group, therefore a repeated measurements analysis was not considered in this paper (Stewart, Groth *et al.*, 2021). Other statistical assumptions included the use of overarching priors of broad groups to represent smaller groups, independence of observations, and linear regression assumptions including lognormality. The

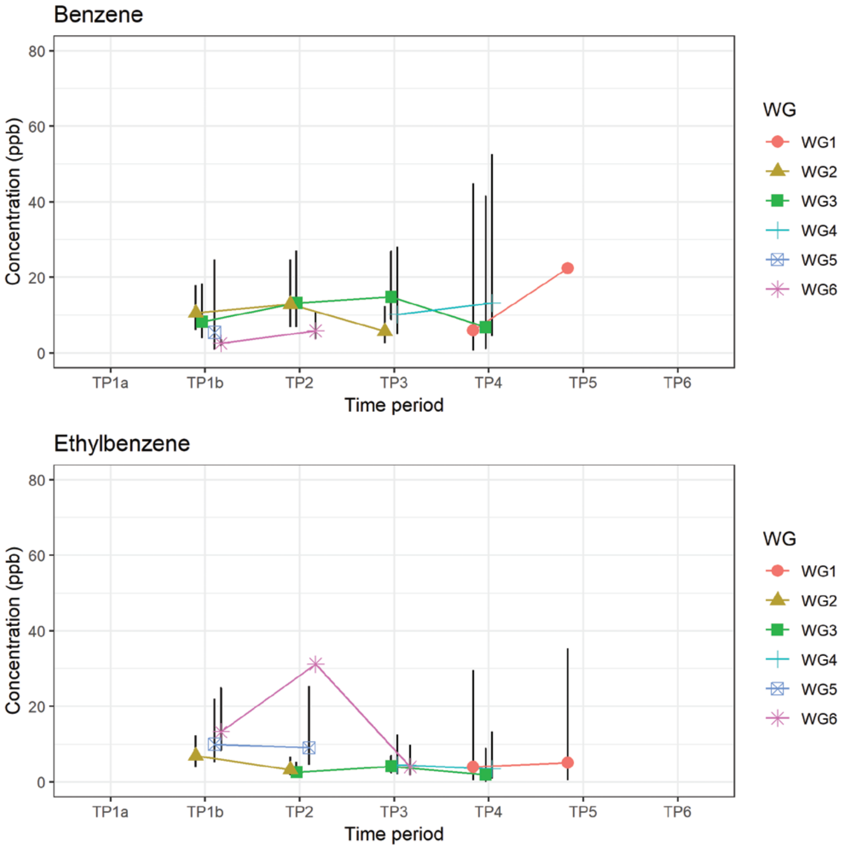

Figure 3. Exposure trends over time of selected work groups for all states for benzene and ethylbenzene. WG1 = 'All land', WG2 = 'Repaired oily booms' (LA), WG3 = 'Fueled engines', WG4 = 'Cleaned beaches/non-specific tasks', WG5 = 'Boom deploy & pickup in shallow water', WG6 = 'Maintained pumps/tanks or pumped (including dis/connect) anything (inc oil)/land or water (exc dispersant injection)'. Lack of a symbol for a particular TP means either that no samples were taken or the measurements did not meet the $N > 5$ and censoring <80% criteria.

lognormality assumption also extends to measurements below the LOD. Future work could relax this assumption and consider nonparametric modeling of exposures below the LOD. If there were sufficient measurements for a particular work group, the broad priors should not have influenced the results substantially. *n*-Hexane had relatively few observations and required imputations that likely increased the uncertainty in the estimates (Groth, Huynh *et al*, 2021).

Recognizing these limitations, this analysis has several strengths. This is the first study on oil spill workers to develop quantitative exposure estimates for investigating exposure–response relationships in an epidemiologic study. Other strengths are the large number of measurements (21 643 over a 14-month period, substantially larger than the number collected on the water) and the development of an extensive set of work groups with quantitative measurements to capture the OSRC activities on land. There was consistency in our approach to developing work groups. The work groups were developed by assigning the same exposure determinants we used for water activities (e.g. activities, states, and TPs), which were found to result in credible differences among various AMs across our exposure studies (Huynh *et al*, 2021a,b; Ramachandran *et al.*, 2021). The use of Bayesian methods to account for censored data allowed us to maximize the use of the available quantitative data and documentation to minimize bias and imprecision (Huynh *et al.*, 2016; Groth *et al.*, 2017; Quick *et al.*, 2017).

While the main purpose of this manuscript was to estimate exposures to crude oil during the clean-up operations on land for the GuLF STUDY, our extensive description of the various activities may also be of interest to public health organizations and private entities involved in emergency preparedness and response for oil

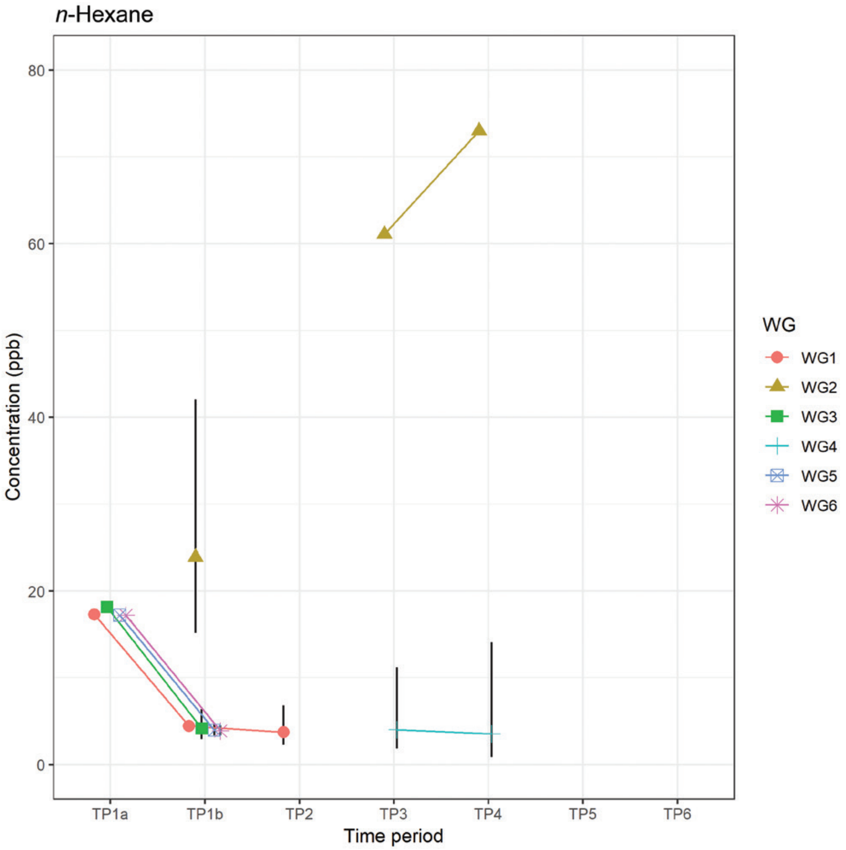

Figure 4. Exposure trends over time of selected work groups for all states for hexane. WG1 = 'All land (LA)', WG2 = 'Repaired oily booms' (LA), WG3 = 'Decon/General Area/Land' (LA), WG4 = 'Tank work (entered + worked outside)', WG5 = 'Cleaned beaches/non-specific tasks', WG6 = 'Beaches & marshes: multiple tasks'. Lack of a symbol for a particular TP means either that no samples were taken or the measurements did not meet the *N* > 5 and censoring <80% criteria.

spills. For instance, the reported exposure estimates can be used to prioritize PPE for potentially high exposure tasks. In addition, if the exposure estimates for certain tasks appeared high as compared with published occupational exposure limits, this information could inform response teams to innovate and modify land cleaning techniques for oil-contaminated equipment, wildlife, and the environment. Another potential utility of this information is in the area of risk assessment. Corporations engaged in offshore drilling should find this information useful in their risk assessment and prioritize mitigation strategies should the oil spill happen to reach shore. Lastly, the exposure estimates are relatively low compared with the existing occupational exposure limits but if detrimental health hazards were to be found associated with these low chemical levels, our work would contribute new evidence to lower exposure limits in the future.

Conclusions

This paper describes exposure estimates for a wide variety of work groups that performed OSRC activities on land, including decontamination of vessels and equipment, handling of booms, beach, marsh, and jetty clean-up, wildlife rehabilitation, and waste management. We developed exposure estimates from over 20 000 personal full-shift measurements for each of the six substances. The 'Fueled engines' and 'Tank work' groups were associated with some of the highest THC air concentrations on land, likely due to the presence of additional hydrocarbon solvents or the higher concentration of BTEX-H in gasoline as compared with crude oil. Generally, exposures were lower than those on rig and the supporting vessels. The estimates from these work groups have been used to develop the job-exposure matrices for the GuLF STUDY.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Conflict of interest

The authors declare that there is no conflict of interest.

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