Journal of Water & Health

Journal of Water and Health Vol 21 No 7, 956 doi: 10.2166/wh.2023.109

Community health impacts after a jet fuel leak contaminated a drinking water system: Oahu, Hawaii, November 2021

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ABSTRACT

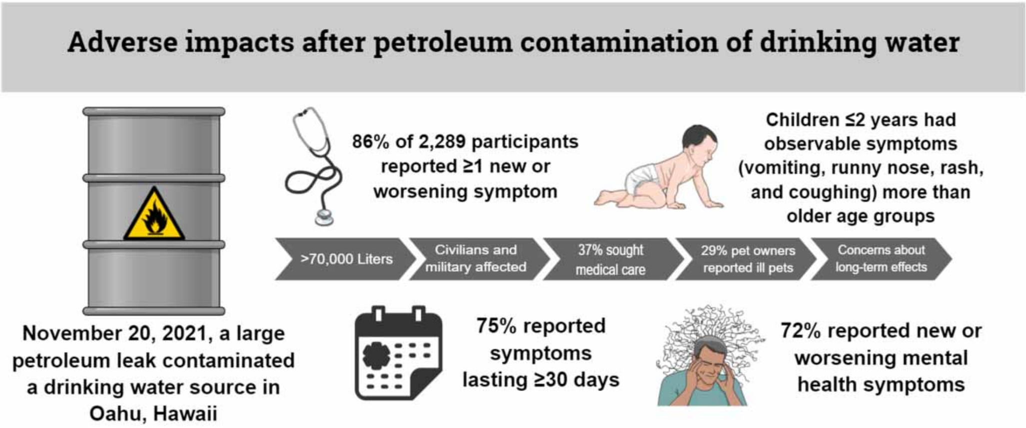
Background: In 2021, a large petroleum leak contaminated a water source that supplied drinking water to military and civilians in Oahu, Hawaii. *Methods*: We conducted an Assessment of Chemical Exposures (ACE) survey and supplemented that information with complementary data sources: (1) poison center caller records; (2) emergency department visit data; and (3) a key informant questionnaire. *Results*: Among 2,289 survey participants, 86% reported $\geq$1 new or worsening symptom, 75% of which lasted $\geq$30 days, and 37% sought medical care. Most ($n = 1{,}653$, 72%) reported new mental health symptoms. Among equally observable symptoms across age groups, proportions of children $\leq$2 years experiencing vomiting, runny nose, skin rashes, and coughing (33, 46, 56, and 35%, respectively) were higher than other age groups. Poison center calls increased the first 2 weeks after the contamination, while emergency department visits increased in early December 2021. Key informant interviews revealed themes of lack of support, mental health symptoms, and long-term health impact concerns. *Discussion*: This event led to widespread exposure to petroleum products and negatively affected thousands of people. Follow-up health surveys or interventions should give special consideration to longer-term physical and mental health, especially children due to their unique sensitivity to environmental exposures.

Key words: drinking water contamination, environmental exposure, petroleum spill

HIGHLIGHTS

- Report of early physical and psychosocial health issues related to petroleum contaminated water event.
- Certain health symptoms are proportionally high for young children compared to older groups.
- New or worsening mental health symptoms reported in all age groups.
- Establishing community trust through transparency, open communication, and sector-specific guidance should be a priority in emergency events.
- Monitoring strategies need to be implemented for long-term health follow-up.

GRAPHICAL ABSTRACT



INTRODUCTION

Beginning 28 November 2021, the Hawaii Department of Health (HDOH) received complaints of illness and a fuel-like odor coming from the tap water of people served by the Joint Base Pearl Harbor-Hickam (JBPHH) water distribution system (Figure 1; HDOH 2021d). Preliminary water testing at Red Hill Elementary School on 29 November 2021 revealed petroleum hydrocarbons in water samples (HDOH 2021g). The U.S. Department of the Navy-collected water samples were sent to a California laboratory for contaminant-specific results. While the Navy water samples were undergoing analysis, on 29 November 2021, HDOH issued a health advisory recommending all JBPHH water system users avoid using the water for drinking, cooking, and oral hygiene (Figure 1). Users who noted a fuel-like odor in their water were also advised to refrain from using water for bathing, dishwashing, and laundry (HDOH 2021b). Further water samples taken by HDOH on 5 December 2021 from the Navy's Red Hill Shaft showed contamination with total petroleum hydrocarbons in the diesel range (TPH-d) at more than 350 times the action level (Figure 1) (Hawaii Department of Health 2021c). Water samples from the Navy's Aiea Halawa Shaft that day found TPH-d levels more than double the HDOH action level for drinking water (HDOH 2021f).

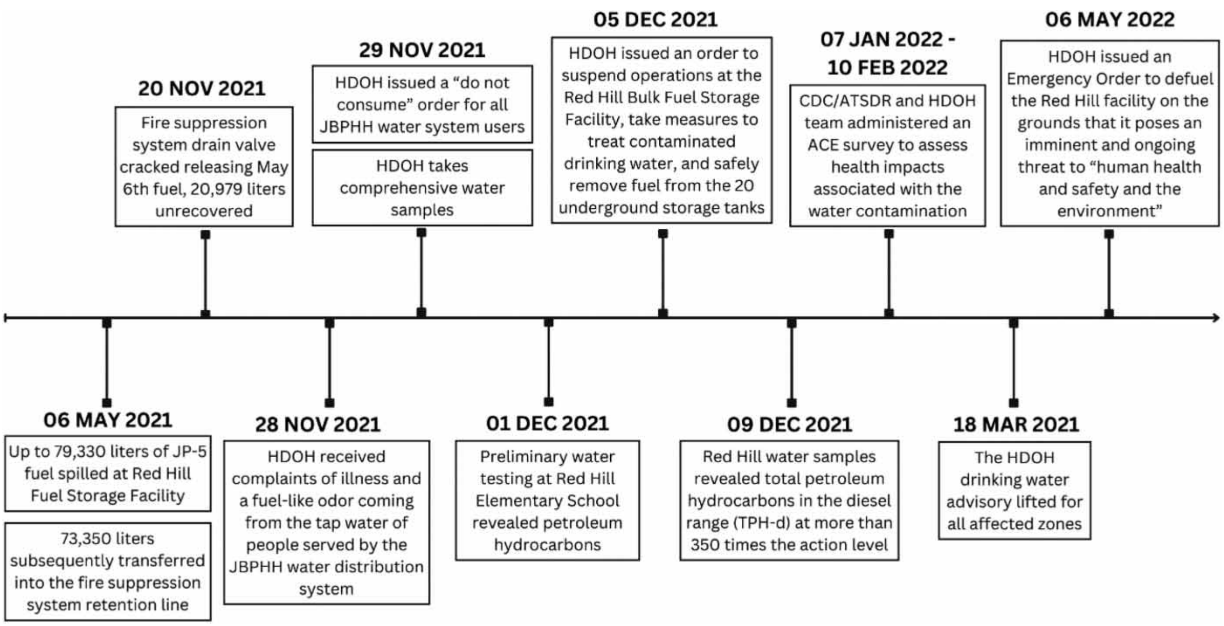


Figure 1 | Timeline of events related to the water contamination on 20 November 2021 – Oahu, Hawaii.

During this time, the Navy reported that the samples their team collected from the drinking water distribution system (DWDS) showed levels below the threshold for action (U.S. Pacific Fleet Commander 2021a, 2021b, 2021c).

On 5 December 2021, the Navy submitted a letter to the HDOH confirming a 20 November 2021 release of a jet propellent (HDOH 2022b) (JP-5) from a fire suppression line in the downhill tunnel from the underground Red Hill Bulk Fuel Storage tanks. The tunnel is located approximately 30 m above the Southern Oahu Basal Aquifer, the primary drinking water source for the island. The JBPHH DWDS is supplied by three wells: Red Hill Shaft, Aiea Halawa Shaft, and Waiawa Shaft (HDOH 2021f). The system serves over 9,600 civilian and military households, schools, and workplaces (HDOH 2021d; JBPHH Emergency Operations Center 2022) all of whom had variable exposure to JP-5. Soon after, the Environmental Protection Agency (EPA), Navy, Army, and HDOH formed the Interagency Drinking Water System Team (IDWST) to develop and implement flushing and sampling plans to restore safe drinking water (Hawaii Department of Health 2021e). Many military-affiliated families living on base were relocated to hotels. Flushing began in December 2021, the JBPHH drinking water was fully restored in March 2022, and the health advisory was amended. Since 29 November 2021 and continuing through the time of this publication, water to the JBPHH water system has been sourced from the Waiawa Shaft, while the Red Hill Shaft remains disconnected from the system (HDOH 2022a). In a 2022 Navy report on the investigation into the November 2021 incident, an earlier contamination event on 6 May 2021 resulted in the release of nearly 73,350 liters of JP-5 (Figure 1; Department of the Navy 2022). The JP-5 from the May event entered the fire suppression system sump pumps and was subsequently transferred into the polyvinyl chloride (PVC) fire suppression system retention line, where it sat until the rupture on 20 November 2021 (Department of the Navy 2022).

After the contamination event, in addition to the HDOH receiving over 500 complaints, the Hawaii Poison Center (HPC) received a surplus of calls about exposure and symptoms attributed to the contaminated water, such as headaches, diarrhea, abdominal pain, rashes, and nausea. Emergency department (ED) visits related to water contamination also increased during this time. Though HDOH issued health provider guidance (HDOH 2021a), acute health effects directly related to petroleum exposure were not well described because the general symptoms of petroleum exposure may have been misdiagnosed. In addition, the onset of this event coincided with the surge of cases of the COVID-19 Delta variant in Hawaii, further complicating the picture. Soon after the discovery of the water contamination, the HDOH contacted the U.S. Centers for Disease Control and Prevention (CDC)/Agency for Toxic Substances and Disease Registry (ATSDR) for assistance in assessing the impacts of the contamination on the affected population (Troeschel *et al.* 2022).

JP-5 is a mixture of hydrocarbons and additives used in military aircraft. It is a colorless and flammable kerosene-based liquid with a fuel-like odor (ATSDR 2017). The exact composition of jet fuels can vary based on the crude oil it is refined from and the manufacturer. At the time of this incident, while there had been multiple reviews of the environmental impacts of hydrocarbon contamination in water (Ehrlich *et al.* 1985; Guiney *et al.* 1987; Hansen 1999; Custance *et al.* 2008), information regarding the human health impacts of exposure to JP-5 and other hydrocarbon mixtures remained limited (Ana *et al.* 2009; Aguilera *et al.* 2010; Kponee *et al.* 2015). Most health literature is related to inhaling kerosene or petroleum hydrocarbon fumes through occupational exposures or residing near an airport or military base (Ritchie *et al.* 2003; Bendtsen *et al.* 2021), effects in animal models (Mattie & Sterner 2011), and kerosene ingestion in children (Kumar *et al.* 2019). Potential health effects depend on various factors, such as individual susceptibility, contamination amount, and duration of exposure. The toxicity of kerosene-based jet fuels was reviewed by ATSDR and published in their Toxicological Profile for JP-5, JP-8, and Jet A Fuels, which reported potential impacts on the nervous system, respiratory system, and gastrointestinal system (ATSDR 2017). However, given the limited literature regarding the human health impact of exposure to these kerosene-based fuels, the review relied heavily on studies in animal models and the toxicity of kerosene, and we still know very little about their adverse health effects in humans. Moreover, given that JP-5 exposure typically occurs in occupational settings, the potential health effects of exposure to JP-5 and other kerosene-based jet fuels in children, who may be especially vulnerable to environmental toxicants (National Research Center (NRC) 1993; Landrigan & Goldman 2011; Carroquino *et al.* 2012; Hauptman & Woolf 2017), are virtually unknown. However, we do know that water contamination events, in general, are associated with long-term adverse psychological and social effects like anxiety and health worries, decreased trust in public health officials, financial hardships, stigma, and difficulties seeking help (Brooks & Patel 2021; Sandifer *et al.* 2021; Reuben *et al.* 2022).

To our knowledge, this is the first known widespread jet fuel exposure in a public DWDS. A short report on the preliminary findings of ATSDR's Assessment of Chemical Exposures (ACE) survey of this event, including routes of exposure to the potentially contaminated water (e.g., drinking, bathing), self-reported symptoms experienced, and medical care sought, was previously published (Troeschel *et al.* 2022). In this study, the team sought to expand upon the previous report and provide more detailed information on the methods used to carry out the ACE survey and the broader health and social impacts of the contamination event using complementary surveillance data from poison center caller records and ED visits. By combining these data sources, the team provides a multifaceted picture of acute health effects and collateral impacts after a water contamination. In addition, since previous evidence suggests that children may be uniquely vulnerable to the effects of environmental toxins, we investigated health impacts separately among adults and children, when possible.

METHODS

ACE survey

The CDC/ATSDR and HDOH team administered the ACE survey from 7 January to 10 February 2022 (Troeschel *et al.* 2022) while many families were still displaced in hotels and before the HDOH water advisory was amended for all affected zones. The team employed a convenience and snowball sampling methodology via digital and in-person methods to reach as many people as possible within the contaminated water distribution system geographic area (Figure 2). The team used an interviewer-administered survey from the ATSDR ACE toolkit (ATSDR 2014). It was adapted to be completed by participants online using Epi Info™ (version 7.2.4.0) similar to a previous ACE investigation (Surasi *et al.* 2021). People present (e.g., for work, school, residence, or visiting) in the affected area after 20 November 2021 were eligible to complete the

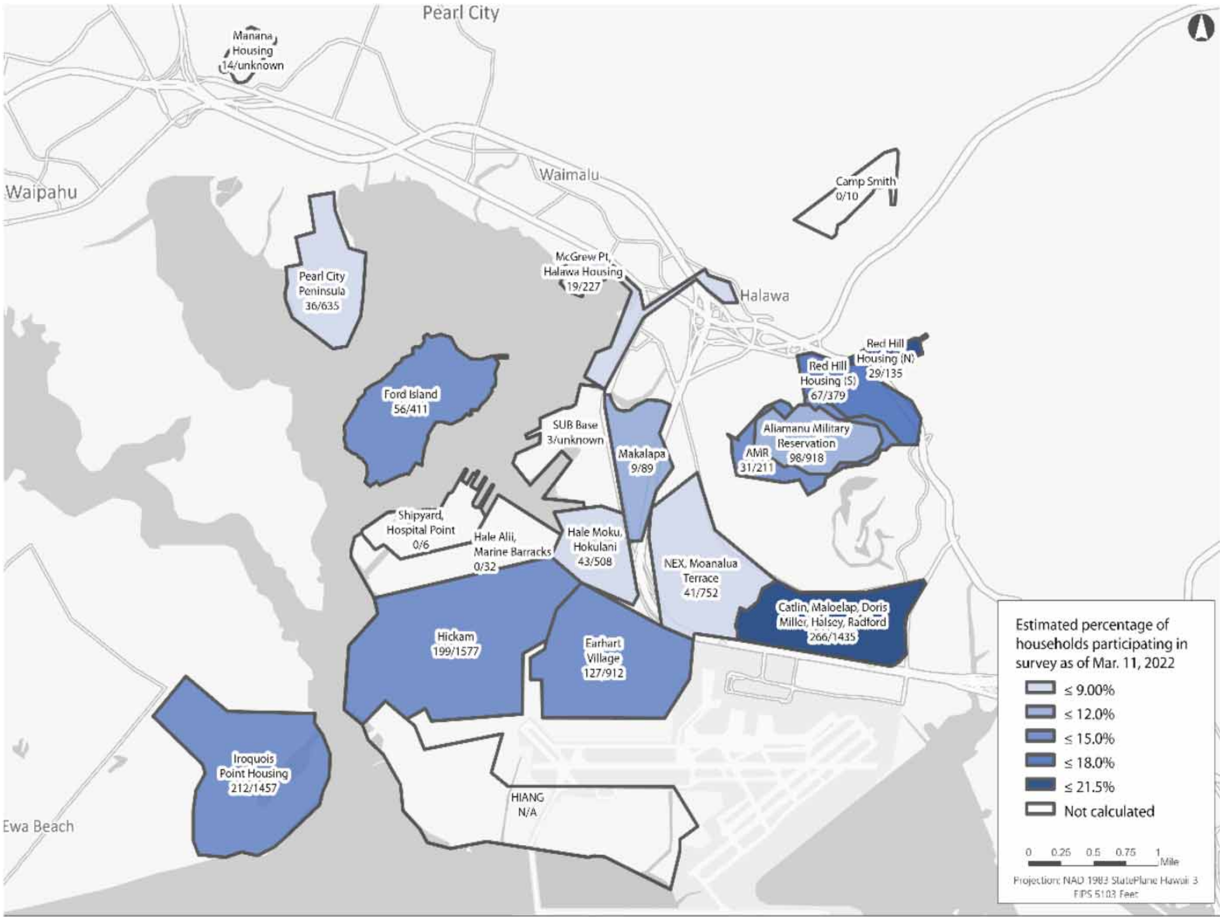


Figure 2 | Zones* affected by the water contamination event on 20 November 2021, and estimated household-level health impact survey participation rates† by zone – Oahu, Hawaii, November 2021–February 2022. *Data sources*: Participant addresses: Hawaii ACE Survey Data. Navy Drinking Water System health advisory zones: Hawaii State Department of Health, Map No. SR2022_2120220106-1-CC, 6 January 2022. Total households by area: Water system Flushing Zone Map. Base map: Esri. *The affected zones are outlined in the above map. †The estimated household participation rate was 14% (1,389/9,694).

survey. Before starting the survey, potential respondents were asked eligibility questions and were consented if they agreed to participate. Parents and guardians completed the survey on behalf of children aged <18 years. Using primarily multiple choice questions, the survey asked about potential exposure to contaminated water, health symptoms experienced, medical care sought, and the incident's impacts on pets, employment, and school. For health symptoms, participants were asked if they experienced any new onset or worsening of symptoms related to seven body systems (eyes, ears/nose/throat, nervous system, cardiopulmonary/heart and lungs, stomach/intestines, skin, and mental health). If the participant responded 'yes' to a symptom category (e.g., nervous system), they then selected whether they experienced individual symptoms (e.g., headaches, seizures/convulsions) related to that system and if they experienced that symptom $\geq$30 days. In total, the survey queried 32 individual symptoms related to seven body systems; participants had the opportunity to write in additional symptoms not covered in the survey. At the end of the survey, there was an option for open-text responses to allow participants the opportunity to bring up anything not included. Per HDOH's initial request, the team planned to assess health impacts among civilians but expanded the eligible population to include affected military-affiliated persons before the survey launch (Troeschel *et al.* 2022). The survey was promoted through electronic and in-person outreach.

The field team started in-person recruitment at the Kapilina Beach Homes community in Iroquois Point (Figure 2), where a large proportion of civilian residents were affected by the water contamination. The Kapilina Beach Homes leasing agent sent emails to all residents containing information about the survey. Residents could complete the survey online, over the phone, or in-person with a trained interviewer at select neighborhood sites. The team also went door-to-door in the neighborhood to distribute flyers with a QR code and web address for the survey to encourage residents to participate. To optimize engagement and increase awareness of the survey, the team performed multiple additional outreach activities and broadly promoted it through bottled water distribution sites, community activities (farmers' market, blood drives), press releases, news outlets, social media, and websites, such as the HDOH website and the JBPHH water updates page. The team emailed, called, or visited primary schools ($n = 13$), daycares ($n = 11$), health clinics ($n = 19$), veterinary clinics ($n = 18$), faith organizations ($n = 11$), hotels ($n = 77$) that housed displaced military families, and housing companies ($n = 5$) in the affected areas to ask them to distribute information about the survey to potentially affected people. The estimated household-level response rate for the ACE survey was 14% ($n = 1,389$) (Troeschel *et al.* 2022).

Descriptive statistics were calculated using R software (version 4.1.1; R Foundation). The proportions of participants experiencing new or worsening symptoms were calculated separately among adults (aged $\geq$18 years) and children (aged $<$18 years). Upon further examination of the pre-defined symptoms, the team noticed some symptoms would be difficult to assess in children, especially in infants and toddlers (e.g., headaches, mental health-related symptoms). Therefore, we conducted a supplemental analysis examining symptoms we thought to be equally observable across all age groups (including runny nose, nose bleeds, seizures/convulsions, loss of consciousness/fainting, coughing, vomiting, diarrhea, skin rash, and skin blisters) and examined the prevalence of these symptoms across several age groups (0–2, 3–5, 6–12, 13–17, and $\geq$18 years). A qualitative analysis of open text from the ACE health survey was performed, and thematic content was identified. Multiple researchers independently coded the data to achieve intercoder reliability. This activity was not considered human research; therefore, further human subjects review was not required.

Hawaii Poison Center calls

The HPC is a subsidiary of Rocky Mountain Poison and Drug Safety, a certified regional center of the American Association of Poison Control Centers (AAPCC). HPC takes calls for information about poisons and poisoning management from members of the public and healthcare professionals 24 hours per day, 7 days per week. Specialists in poison information (SPIs) (trained nurses, pharmacists, and toxicologists) enter call data into an electronic medical record system. A unique medical record was created for each person or animal reporting exposure to incident-related water. HPC collected information on caller location (i.e., ZIP code), route of exposure, reported health effects, therapy received, and health outcome for each record. Calls related to the incident were coded as 'contaminated water', 'jet fuel', 'petroleum', or 'gas/gasoline' by HPC staff. The jet fuel leak was the only contamination event that used this code during that time. The call was categorized as an informational call if it was determined that the person was never in the area where contamination occurred. Case records were uploaded in near real-time to the National Poison Data System (NPDS). All reports of records and shared data were run from a de-identified database. Records were analyzed from 28 November 2021 to 15 February 2022, the dates of the first and last calls coded as related to the incident at the time of this investigation.

Emergency department visits

The National Syndromic Surveillance Program (NSSP) is a collaboration between CDC, health departments, and federal, academic, and private sector partners to support the collection and analysis of electronic health record (EHR) data from healthcare facilities and laboratories. NSSP receives anonymized records of visits to these facilities, which include chief complaint text and administrative discharge diagnosis codes (CDC 2022a). ED visits likely related to the event were found utilizing the NSSP Electronic Surveillance System for the Early Notification of Community-Based Epidemics (ESSENCE) web-based tool. Data are received from this system in near real-time. Visits of interest were identified using International Classification of Diseases, Tenth Revision, Clinical Modification (ICD-10-CM) diagnosis codes, discharge diagnosis, Systematized Nomenclature of Medicine (SNOMED) codes, clinical impressions, chief complaint terms, and triage notes. The scope of queries utilized was narrowed to those living in potentially exposed areas who mentioned the event directly or were visiting affected areas. Initial cases were identified by including keywords that related specifically to the event utilizing the 'triage note' search field (e.g., Red Hill, Kapilina, Iroquois Point, Pearl Harbor, Pearl City, water contamination, jet fuel, gas). Data gathered from this query served as the baseline to identify common ICD-10 codes, additional keywords, and related symptoms among potential cases to further improve search parameters. Refined queries were then developed to analyze recurring symptoms found among potential cases (cough, rash, vomiting, dizziness, vertigo, headache, etc.) and combined with inclusionary keywords that involved potential exposure to contaminated water (drank, wash, shower, bath, etc.). The team reviewed ED visit data from three non-Department of Defense (DOD) affiliated hospitals on the island of Oahu that contributes data to Hawaii's Syndromic Surveillance Program and NSSP. Records were analyzed from 28 November 2021 to 10 January 2022. After 10 January 2022, no documented ED visits were associated with the incident.

Key informant questionnaire

During the multiple in-person interactions with affected community members and sectors, the team identified a need to collect additional qualitative data to assess how the incident impacted key sectors, such as businesses, schools, and community organizations. The team developed a key informant interview questionnaire using Research Electronic Data Capture (REDCap) (Harris *et al.* 2009) that included yes/no and open-text questions about the overall impact of the incident tailored to each sector, including staffing changes, financial impacts, changes in day-to-day operations, access to water, absenteeism among students, and patient loads. Our team used a convenience sampling strategy via email and in-person recruitment of key informants in schools, businesses, community organizations, medical, and veterinary offices from January to February 2022. Multiple researchers independently coded the data and assessed it to ensure intercoder reliability. Thematic content was analyzed to identify emerging themes.

RESULTS

ACE survey results

In total, 2,289 eligible participants submitted surveys (1,551 adults aged ≥18 years, 721 children aged <18 years, and 17 participants with unknown ages), with 99% ($n = 2{,}256$) completing it online. Table 1 presents the demographic breakdown of participants. As previously reported, the median age of participants was 33 years (range: 0–84). More participants were female ($n = 1{,}341$, 59%), non-Hispanic ($n = 1{,}861$, 81%), military-affiliated (i.e., active and retired military, their spouses and dependents, and some military contractors with a military ID) ($n = 2{,}019$, 88%), and identified their race as white ($n = 1{,}700$, 74%) (Troeschel *et al.* 2022). The team's analysis showed that 78 (3%) respondents reported being pregnant during or after the water contamination.

Most respondents ($n = 2{,}129$, 93%) reported that they were exposed to the water in their homes, while some adults were exposed at their workplace ($n = 310$, 14%). The home was the most frequent place of exposure for children ($n = 688$, 95%); however, 222 (31%) children were exposed both at home and school, and 32 (4%) children were exposed to the contaminated water in school only. Adult participants indicated they consumed potentially contaminated water through oral hygiene ($n = 1{,}229$, 79%), drinking ($n = 1{,}102$, 71%), or cooking ($n = 1{,}126$, 73%) (Troeschel *et al.* 2022) and dermal (skin) exposure through bathing ($n = 1{,}348$, 87%) and cleaning ($n = 1{,}397$, 90%). Adults reported marginally higher proportions of exposure than children from bathing, cooking, and cleaning, but children reported higher proportions of exposure from oral hygiene ($n = 576$, 80%) and drinking ($n = 532$, 74%). As previously reported, almost half of respondents ($n = 1{,}115$, 49%) reported at least one sign that their water was contaminated (i.e., petroleum smell or taste, visible oily sheen). Most respondents ($n = 2{,}123$, 93%) switched to an alternate water source for consumption after learning of the incident (Troeschel *et al.* 2022).

Table 1 | Health impact survey participant demographics[a] – Oahu, Hawaii, November 2021–February 2022

Characteristic[b]	Participants No. (%)
Sex ($n = 2,281$)	
Female	1,341 (59)
Male	925 (41)
Decline to answer	15 (1)
Race ($n = 2,812$)[b]	
American Indian or Alaska Native	63 (2)
Asian	312 (11)
Black	193 (7)
Native Hawaiian	86 (3)
Other Pacific Islander	312 (11)
White	1,700 (60)
Decline to answer	146 (5)
Ethnicity ($n = 2,274$)	
Hispanic	344 (15)
Non-Hispanic	1,861 (82)
Decline to answer	69 (3)
Age in years ($n = 2,100$)[c]	
0–2	95 (4)
3–5	113 (5)
6–12	315 (14)
13–17	146 (7)
18–34	475 (21)
35–49	735 (35)
50–64	187 (9)
65 and over	28 (1)
Military affiliation ($n = 2,288$)[d]	
Military affiliated	2,019 (88)
Civilian (non-military affiliation)	269 (12)

[a]Participants were able to select more than one category for race.
[b]Some categories offered a 'Decline to answer' option, and some questions did not require a response.
[c]Participants were not required to enter their age/date of birth.
[d]Participants were asked if they had a military ID.

Many participants ($n = 853$, 37%) sought medical care after the incident. When asked to report the highest level of care they had received, the proportion of adults who visited the emergency room ($n = 146$, 9%), contacted Hawaii Poison Control ($n = 15$, 1%), and were hospitalized overnight ($n = 11$, 1%) was marginally higher than the corresponding proportions in children. The proportion of participants who reported consulting their primary care provider or another doctor was similar in children ($n = 202$, 28%) and adults ($n = 403$, 26%). Seventeen participants, including 11 adults (1%), five children (1%), and one participant of unknown age, indicated that they were hospitalized overnight. Participants reported being hospitalized for a median of two nights (interquartile range: 25% = 0, 75% = 3) (not shown). Efforts to reach these respondents and healthcare providers for medical records were unsuccessful.

Symptoms in adults

A large proportion of adult respondents ($n = 1,368$, 88%) reported experiencing at least one new or worsening symptom since the contamination event (Table 2). The most frequently reported symptoms in adults were headache ($n = 1,027$, 66%), dry or

Table 2 | Reported[a] new or worsening symptoms, and symptoms persisting for ≥30 days after the water contamination event on 20 November 2021 among participants in the health impact survey[b] – Oahu, Hawaii, November 2021–February 2022

Reported or observed symptoms	All adults (*n* = 1,551) (%)	Adults with symptoms ≥30 days[c]	All children[d] (*n* = 721) (%)	Children with symptoms ≥30 days[c]	Children aged 0–2 years (*n* = 95)[e]	Children aged 3–5 years (*n* = 113)[e]	Children aged 6–12 years (*n* = 315)[e]	Children aged 13–17 years (*n* = 146)[e]
Any symptom	1,368 (88)	1,102 (71)	596 (83)	377 (52)	75 (79)	92 (81)	259 (82)	128 (88)
Headache	1,027 (66)	578 (56)	277 (38)	139 (50)	10 (11)	22 (19)	144 (46)	81 (55)
Dry or itchy skin	815 (53)	567 (70)	320 (44)	195 (61)	37 (39)	54 (48)	144 (46)	69 (47)
Sleepy or fatigued	813 (52)	579 (71)	193 (27)	109 (56)	11 (12)	15 (13)	99 (31)	55 (38)
Diarrhea[a]	772 (50)	294 (38)	339 (47)	98 (29)	44 (46)	55 (49)	148 (47)	70 (48)
Anxiety	716 (46)	581 (81)	116 (16)	79 (68)	3 (3)	7 (6)	58 (18)	38 (26)
Dizziness	712 (46)	383 (54)	153 (21)	75 (49)	2 (2)	10 (9)	75 (24)	57 (39)
Eye irritation/ burning	658 (42)	348 (53)	213 (30)	101 (47)	19 (20)	28 (25)	103 (33)	51 (35)
Nausea	650 (42)	297 (46)	269 (37)	88 (33)	23 (24)	36 (32)	122 (39)	73 (50)
Difficulty sleeping	606 (39)	490 (81)	133 (18)	95 (71)	14 (15)	18 (16)	59 (19)	33 (23)
Skin irritation/ burning	604 (39)	341 (56)	245 (34)	127 (52)	28 (29)	35 (31)	107 (34)	64 (44)
Skin rash[a]	604 (39)	347 (57)	312 (43)	153 (49)	53 (56)	47 (42)	134 (43)	61 (42)
Difficulty concentrating	589 (38)	425 (72)	142 (20)	100 (70)	5 (5)	11 (10)	75 (24)	45 (31)
Agitation/ irritability	574 (37)	462 (80)	116 (16)	81 (70)	7 (7)	18 (16)	51 (16)	32 (22)
Tension/ nervousness	550 (35)	444 (81)	101 (14)	75 (74)	1 (1)	10 (9)	51 (16)	33 (23)
Difficulty remembering	546 (35)	411 (75)	91 (13)	66 (73)	2 (2)	6 (5)	44 (14)	34 (23)
Burning nose or throat	534 (34)	64 (12)	195 (27)	21 (11)	13 (14)	27 (24)	91 (29)	53 (36)
Runny nose[a]	459 (30)	250 (54)	249 (35)	134 (54)	44 (46)	48 (42)	94 (30)	52 (36)
Feeling depressed	418 (27)	324 (78)	40 (6)	36 (90)	0 (0)	2 (2)	13 (4)	23 (16)
Increased tearing	370 (24)	228 (62)	123 (17)	73 (59)	16 (17)	18 (16)	54 (17)	30 (21)
Confusion	356 (23)	232 (65)	64 (9)	36 (56)	4 (4)	5 (4)	29 (9)	24 (16)
Ringing in ears	350 (23)	234 (67)	53 (7)	27 (51)	1 (1)	9 (8)	22 (7)	18 (12)
Difficulty breathing/ shortness of breath	346 (22)	225 (65)	64 (9)	41 (64)	6 (6)	8 (7)	30 (10)	16 (11)
Coughing[a]	343 (22)	205 (60)	173 (24)	94 (54)	33 (35)	33 (29)	62 (20)	38 (26)
Chest tightness or pain/angina	306 (20)	167 (55)	53 (7)	36 (68)	3 (3)	6 (5)	25 (8)	14 (10)
Vomiting[a]	219 (14)	58 (26)	148 (21)	40 (27)	31 (33)	28 (25)	55 (17)	27 (18)
Paranoia	192 (12)	152 (79)	31 (4)	24 (77)	0 (0)	4 (4)	19 (6)	5 (3)
Wheezing in chest	141 (9)	97 (69)	44 (6)	26 (59)	9 (9)	10 (9)	12 (4)	11 (8)
Burning lungs	140 (9)	76 (54)	43 (6)	30 (70)	1 (1)	4 (4)	20 (6)	17 (12)
Nose bleeds[a]	117 (8)	54 (46)	70 (10)	29 (41)	3 (3)	15 (13)	32 (10)	15 (10)
Skin blisters[a]	112 (7)	71 (63)	55 (8)	28 (51)	6 (6)	11 (10)	21 (7)	13 (9)

(*Continued*.)

Table 2 | Continued

Reported or observed symptoms	All adults (n = 1,551) (%)	Adults with symptoms ≥30 days[c]	All children[d] (n = 721) (%)	Children with symptoms ≥30 days[c]	Children aged 0–2 years (n = 95)[e]	Children aged 3–5 years (n = 113)[e]	Children aged 6–12 years (n = 315)[e]	Children aged 13–17 years (n = 146)[e]
Loss of consciousness/ fainting[a]	39 (3)	21 (54)	13 (2)	8 (62)	0 (0)	1 (1)	7 (2)	5 (3)
Seizures/ convulsions[a]	17 (1)	12 (71)	6 (1)	6 (100)	1 (1)	1 (1)	2 (1)	2 (1)

[a]Symptoms were self-reported among adults aged ≥18 years, participants could view all categories and options. Children aged ≤17 years had a parent/guardian report their symptoms on their behalf.
[b]Of the 2,289 total participants, $n = 15$ did not indicate age and $n = 2$ were child proxy variables with ages >17 years.
[c]Among those who reported experiencing symptom.
[d]Includes all children by the proxy variable who had no age, NA values, or an age <18 years.
[e]Age groups have a denominator of 669 and include children by the proxy variable without blank or NA values and age <18 years.

itchy skin ($n = 815$, 53%), feeling unusually sleepy or fatigued ($n = 813$, 52%), diarrhea ($n = 772$, 50%), and dizziness ($n = 712$, 46%). Although less common, 17 (1%) adults reported experiencing new or worsening seizures/convulsions. The survey also included questions regarding mental health and wellness. Many respondents ($n = 1{,}653$, 72%) with no self-reported history of mental health conditions reported new symptoms, which often lasted ≥30 days. The most common mental health symptoms reported were anxiety ($n = 716$, 46%; ≥30 days = 581, 81%), difficulty sleeping ($n = 606$, 39%; ≥30 days = 490, 81%), agitation ($n = 574$, 37%; ≥30 days = 462, 80%), tension or nervousness ($n = 550$, 35%; ≥30 days = 444, 81%), and feeling depressed ($n = 418$, 27%; ≥30 days = 324, 78%).

Among adults who reported experiencing at least one symptom, most ($n = 1{,}102$, 81%) reported their symptoms persisted for ≥30 days. The most common symptoms that persisted in adults who experienced a particular symptom were mental health-related: anxiety (81%), difficulty sleeping/insomnia (81%), tension/nervousness (81%), agitation/irritability (80%), paranoia (79%), and feeling depressed (78%).

Symptoms in children

Like adults, a large proportion of children (596 of 721 (83%) surveys completed by parents/guardians of children) experienced at least one new or worsening symptom since 20 November 2021 (Table 2). The most common pediatric symptoms were diarrhea ($n = 339$, 47%), dry or itchy skin ($n = 320$, 44%), rash ($n = 312$, 43%), headache ($n = 277$, 38%), and nausea ($n = 269$, 37%). In general, a lower proportion of child participants, compared with the corresponding proportion of adult participants, reported experiencing new or worsening symptoms for most symptoms (e.g., 66% of adults reported headaches compared with 38% of children). However, when limited to symptoms that are most likely to be equally observable across all age groups, the proportion of participants who experienced new or worsening symptoms appeared more similar, or even marginally higher, in children than in adults for many of the symptoms, including vomiting (22% of children vs. 16% of adults), runny nose (37% of children vs. 33% of adults), skin rashes (46% of children vs. 42% of adults), coughing (25% of children vs. 24% of adults), nose bleeds (11% of children vs. 9% of adults), and seizures/convulsions (1% of children and adults) (Table 2). For many equally observable symptoms across age groups, the proportion of participants experiencing new or worsening symptoms was highest among the youngest participants. For example, the proportions of children aged 0–2 years who experienced vomiting, runny nose, skin rashes, and coughing (33, 46, 56, and 35%, respectively) were higher than the corresponding proportions in children aged 13–17 years (19, 36, 42, and 26%, respectively) and adults (16, 33, 42, and 24%, respectively).

Although the proportion of children who experienced persistent symptoms was lower than the corresponding proportion in adults, more than half of children ($n = 377$, 52%) continued to experience symptoms for ≥30 days (Table 2). While fewer children reported mental health symptoms overall, high proportions of children who did report mental health symptoms experienced them for ≥30 days. The most common symptoms that persisted for ≥30 days in children who experienced that symptom were seizures/convulsions ($n = 6$, 100%), feeling depressed ($n = 36$, 90%), paranoia ($n = 24$, 77%), tension/nervousness ($n = 75$, 74%), trouble remembering things ($n = 66$, 73%), and difficulty sleeping ($n = 95$, 71%).

Impact on pets

The survey also inquired about possible effects on pets. Among 1,389 households participating, 409 homes (29%) reported at least one pet that developed new or worsening symptoms, illness, or death since the incident. Pet symptoms reported in the open-text field included diarrhea, lethargy, weakness, itching/rash, and loss of feathers or fur (not shown). An owner of one of the 94 (7%) ill cats stated, '…our cats were drinking the tap water and got sick – vomiting, lethargy [*sic*]'. Some reported that pet symptoms resolved after switching to an alternate water source. One owner of one of the 316 (23%) ill dogs stated, 'Our German Shepherd Dog had regular and uncontrolled diarrhea for weeks, but after switching to bottled water, his symptoms went away completely'.

Qualitative analysis of ACE open-text field

Qualitative analysis of the open-text field identified several themes regarding long-term concerns, including new or increasing mental health symptoms, worries about exposures pre-dating November 2021, and unknown long-term health impacts. A healthcare provider stated, 'As physicians, we need guidance on what health impacts to monitor for long-term, and how to monitor for long-term health impacts of this exposure for patients'. One parent articulated concern about the effects of exposing their child with special needs: 'My children are on the autism spectrum and I don't know … how they will react long term to the exposure of the contaminated water. Only time will tell'. Respondents also expressed interest in testing for sustaining effects: 'What labs should be requested from Doctors to check on health & possible long term side effects that we should know about [?]'

Hawaii Poison Center calls

From 28 November 2021 to 15 February 2022, HPC received 147 calls regarding the incident. This excludes callers requesting information only ($n = 6$) and calls about animals ($n = 2$). Among the HPC callers, 84 (57%) were female, 51 (35%) were male, and the sex of 12 (8%) was not recorded. Five (3%) reported being pregnant. Ages were recorded for 122 callers, and the mean age was 22 years (range, 0–69 years). Among the callers reporting exposure to the contaminated water, the most commonly reported clinical effects (signs and symptoms) were headache ($n = 45$, 31%), diarrhea ($n = 32$, 22%), abdominal pain ($n = 27$, 18%), rash ($n = 25$, 17%), nausea ($n = 24$, 16%), throat irritation ($n = 17$, 12%), coughing/choking ($n = 16$, 11%), dizziness/vertigo ($n = 14$, 10%), shortness of breath/dyspnea ($n = 11$, 7%), and vomiting ($n = 11$, 7%). Among callers, 35 (24%) received treatment recommendations (e.g., non-prescription topical hydrocortisone, non-medicated lotion, new water source, or fresh air) over the phone and did not require a medical referral. Forty-one people (28%) were documented as en route to a healthcare provider, and 34 (23%) people who reported more than minor symptoms were referred to a healthcare provider.

Emergency department visits

From the available syndromic surveillance data from 28 November 2021 to 10 January 2022, 22 non-military hospital ED visits contained potential symptoms of hazardous chemical exposure while also mentioning the water contamination event or the exposure to water in affected areas. Among the most frequently reported chief complaints were coughing or sore throat ($n = 9$, 41%); nausea, vomiting, or diarrhea ($n = 6$, 27%); headache ($n = 5$, 23%); and rash ($n = 4$, 18%). Figure 3 shows the timeline of the ED visits overlaid with poison center calls. While most poison center calls were at the end of November to early December 2021, the first identified ED visit was 10 December 2021. There was a subsequent increase in ED visits and poison center calls on 15 December 2021.

Key informant questionnaire

Thirty-nine key informants (businesses (14), schools/daycares (10), medical facilities (6), community groups (3), veterinary clinics (1), and others (5)) responded to the questionnaire. Analysis of the responses identified the following areas of concern: disruption of daily activities, distrust of official communication, need for resources, experiences of financial loss, changes in water use, and a desire for incident resolution. In schools, disruption presented as increased tardiness and absenteeism among students often related to family relocation. Businesses reported financial impacts from closure or reduced hours. Both businesses and schools reported overwork and the additional burden of obtaining water from an alternate source or implementing new processes for drinking water, hygiene, cooking, dishwashing, laundry, and other daily tasks. Both schools and businesses had to develop new hand washing, hygiene, and dishwashing procedures. Self-reported needs at the time of the questionnaire included clean water, financial compensation, and a resolution to the contamination. A more robust examination of the key informant questionnaire responses will be presented in a future report.

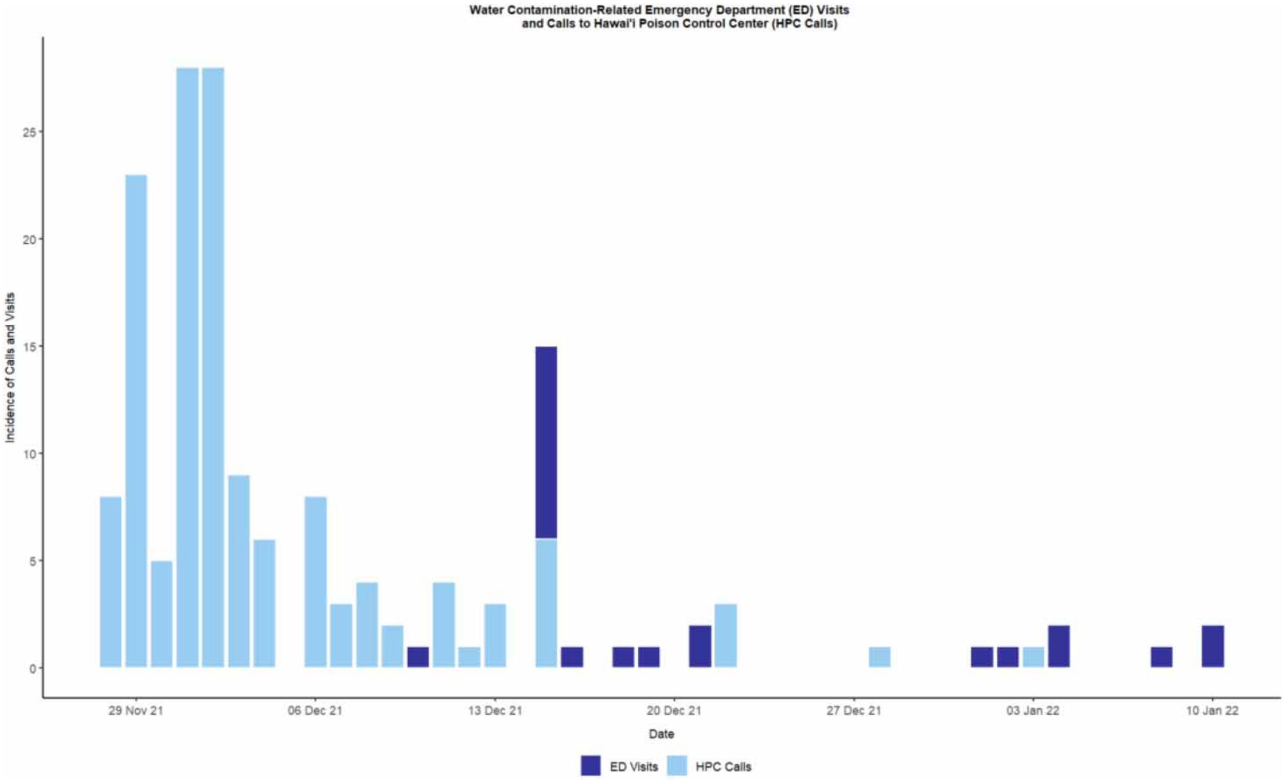


Figure 3 | Poison center calls* and emergency department visits† coded as associated with the contaminated water incident§ on 20 November 2021 – Oahu, Hawaii, November 2021–February 2022. *The jet fuel leak was the only contamination event that used the codes 'contaminated water', 'jet fuel', 'petroleum', or 'gas/gasoline' during this period. †Keywords in the triage note search field included 'Red Hill', 'Kapilina', 'Iroquois Point', 'Pearl Harbor', 'Pearl City', 'water contamination', 'jet fuel', and 'gas'. §After 10 January 2022, there were no documented ED visits associated with the incident, but there were four HPC calls included in the text analysis.

DISCUSSION

This study is the first to report health symptoms experienced by adults following exposure to JP-5-contaminated drinking water. Our multi-modal investigation revealed this large-scale water contamination event led to widespread disruption of community water use, negative impacts on overall community wellness, and concerns about long-term health effects. Across all data sources, our investigation found adverse health effects reported in adults and children after variable and unknown levels of exposure to JP-5 in the water supply. Most adult and child participants experienced one or more new or worsened symptoms consistent with petroleum hydrocarbon exposure, with the most frequently reported complaints and symptoms related to the nervous system, gastrointestinal system, skin, ear/nose/throat, mental health, eyes, and cardiopulmonary (heart and lung) system. In addition, when symptoms were limited to those easily observed across all age groups, we found that some symptoms, including vomiting, runny nose, skin rashes, and coughing, appeared to be most frequent among the youngest participants (aged 0–2 years). Many respondents also reported new or worsening mental health symptoms. Over half of symptomatic participants experienced health effects lasting ≥ 30 days, and many expressed concerns about possible long-term health consequences. One-third of respondents reported their pets also exhibited symptoms associated with the contaminated water.

It is challenging to compare our results to existing research. Prior literature is focused mainly on inhaling kerosene or petroleum hydrocarbon fumes through occupational exposures or residing near airports or military bases (Ritchie *et al.* 2003; Bendtsen *et al.* 2021). In those instances, the effects of JP-5 and other hydrocarbon mixtures like kerosene exposure in adults include harm to the respiratory and gastrointestinal tracts and the nervous system, with notable symptoms like coughing, difficulty breathing, abdominal pain, vomiting, drowsiness, and restlessness (Ritchie *et al.* 2003; ATSDR 2017; Kumar *et al.* 2019; Bendtsen *et al.* 2021). Only one previous study (Kponee *et al.* 2015) specifically examined petroleum contaminated water ingestion and adverse health outcomes. It indicated that the most frequent self-reported symptoms among the respondents who used the contaminated water for drinking or cooking included irritation of the eyes, rash, runny nose, cough, and neurological effects like headaches, sleepiness, and dizziness (Kponee *et al.* 2015). These results are consistent with the adults in our survey who most frequently reported headache, dry or itchy skin, feeling unusually sleepy or fatigued, dizziness, or eye irritation or burning. Unlike Kponee *et al.* (2015), our adult participants also frequently reported diarrhea and anxiety, which is consistent with occupational exposure literature (Ritchie *et al.* 2003; Bendtsen *et al.* 2021).

The Red Hill water contamination event is the first reported incident of JP-5 exposure in children. Like adults, we found that children reportedly experienced a wide range of new or worsening symptoms related to the nervous system (e.g., headaches, seizures/convulsions), gastrointestinal system (e.g., diarrhea, vomiting), respiratory system (e.g., coughing), skin (e.g., rashes), and mental health (e.g., anxiety). These findings are consistent with previous studies among adults exposed to hydrocarbon mixtures similar in composition to JP-5 (summarized in the above paragraph) and children who accidentally ingested kerosene. Kerosene ingestion is associated with harmful effects on the respiratory, central nervous, and gastrointestinal systems (ATSDR 2017; Kumar *et al.* 2019). In our survey, while adults experienced more individual symptoms compared with children, it should be noted that many of the symptoms (e.g., headaches, difficulty concentrating) listed in the survey may be more easily assessed in adults than children, particularly very young children, and therefore are not directly comparable. Our findings suggest that young children may be more vulnerable to the effects of JP-5 exposure, at least concerning observable symptoms. A landmark report published by the National Academies in 1993 was among the first to draw attention to the idea that children, whose bodies continue to grow and develop, are uniquely susceptible to the exposure and effects of toxic chemicals for several reasons (NRC 1993). For example, children have a higher metabolic rate than adults, resulting in a faster respiratory rate (breathing more air), drinking more water, and eating more food per kilogram of body weight; thus, children may be more proportionally exposed to toxic chemicals than adults and may experience greater effects (Landrigan & Goldman 2011; ATSDR 2013). Moreover, children's organs are still developing and not well-equipped to metabolize many toxic compounds. Additionally, exposure to toxic chemicals during certain developmental stages, even at minute levels with no reported adverse effects in adults, can cause detrimental effects and lifelong impairments in children (NRC 1993; Landrigan & Goldman 2011; Carroquino *et al.* 2012).

Survey respondents reported concerns about the long-term health impacts of the contamination, which contributed to increased, ongoing stress among those affected. Unsurprisingly, many respondents also reported new or worsening mental health symptoms, consistent with other documented large-scale water contamination events (Brooks & Patel 2021; Reuben *et al.* 2022). While there is limited scientific literature on the long-term effects of exposure to petroleum hydrocarbons in drinking water, there is research on the impact of chemical exposure and disaster events. For example, after a catastrophic fireworks depot explosion in the Netherlands, a study found survivors with preexisting mental health diagnoses or those already experiencing stressful living situations continued to report physical and mental health complaints 18 months post-disaster (Dirkzwager *et al.* 2006). Similarly, after a large-scale chlorine gas exposure in South Carolina, a third of participants were experiencing post-traumatic stress symptomatology, many of which were classified as severe (Ginsberg *et al.* 2012). Increases in mental health symptoms like depression and stress associated with perceived health risks and financial concerns have also been documented in populations subjected to long-term oil spill exposures (Aguilera *et al.* 2010; Sandifer *et al.* 2021). Furthermore, other research has identified comorbid physical health effects associated with traumatic stress (Stein *et al.* 2000; Weisberg *et al.* 2002; Ford *et al.* 2004; Norman *et al.* 2006; Kubzansky *et al.* 2007). The delayed nature of adverse health outcomes associated with the chemical contamination of drinking water poses a challenge to examining the long-term health effects of petroleum exposure from this incident. Resources like those from ATSDR's Community Stress Resource Center (ATSDR 2021) may aid in developing and implementing public health strategies to identify and mitigate psychosocial stressors related to contamination events. Moreover, transparency in sharing exposure data with affected communities may help people seeking additional information. A registry of individuals affected by the contamination incident could also add to, clarify, and support what is known about potential long-term human health impacts, as seen with some biomonitoring programs after large-scale oil spills (Aguilera *et al.* 2010).

Many respondents described new or worsening symptoms experienced by their house pets, such as vomiting, diarrhea, lethargy, and loss of feathers or fur. At the time of this report, there was no literature on the effects of JP-5-contaminated water on domesticated animals. One research article on the impacts of JP-4 and JP-8 in animal models described the acute effects of inhalation, like dermal irritation and respiratory tract irritation (Mattie & Sterner 2011). When male rats ingested

JP-8 for 90 days, they were found to exhibit decreased body weight, kidney damage, gastritis, perianal dermatitis, and increased liver enzymes (Mattie & Sterner 2011). Female rats exhibited multiple immunosuppressive effects ingesting JP-8 for 2 weeks (Mattie & Sterner 2011). Domesticated animals may be more susceptible to the health effects of contaminated water since they drink only water, whereas humans may drink other types of liquids.

In September 2022, HDOH and CDC/ATSDR conducted a follow-up health survey to evaluate if symptoms persisted (HDOH 2022c). At the time of this paper, a robust examination of the participants' responses was in progress and will be presented in a future report. Follow-up health surveys or interventions should give special consideration to longer-term physical and mental health, especially children, due to their unique sensitivity to environmental exposures. It is vital to note that engaging the affected community and its leaders to gather their ideas and gauge support is crucial when deciding whether to undertake a longer-term investigation. It is also imperative to offer additional education for local healthcare providers to build their knowledge of the event and its potential health impacts. For example, HDOH distributed guidance to local healthcare providers with treatment guidance and resources early in the event timeline (HDOH 2021a). Future information can also include guidance for clinical care, including using relevant diagnostic codes, when and how to take an exposure history, and the need for longer-term physical and mental health support.

Analyzing data from multiple sources, including an online survey, facilitated a more complete understanding of the immediate health impacts of water contamination on adults and children, previously missing from research. Moreover, an adaptable online survey paired with robust in-person and electronic promotion facilitated rapid data collection from thousands of affected people. In the past, ACE investigations have been conducted as face-to-face interviews with residents, responders, and workers in area businesses affected by the incident. In-person interviews are time-, resource-, and labor-intensive. For this response, the team utilized a digital survey flier with a QR code and a short web address to be shared among community members to recruit as many participants as possible. Survey data showed the importance of online outreach, with over half of respondents reporting they received information about the incident from social media. This is consistent with a 2021 survey that reported nearly half of Americans get news from social media sites (Pew Research Center 2021).

This study had several limitations. First, the convenience and snowball sampling strategy may have impacted participation and representativeness of the survey. There was higher participation among women and people with symptoms and likely lower participation among unhoused persons. Second, symptoms experienced by survey participants were all self-reported rather than from medical records. No standard clinical case definition for JP-5-related toxicity exists, which made it difficult to distinguish between health effects attributable to JP-5 and those attributable to another cause. As noted previously, the water contamination event coincided with the surge of cases of the COVID-19 Delta variant in Hawaii. Multiple general symptoms of COVID-19 include symptoms of petroleum exposure, like cough, shortness of breath or difficulty breathing, fatigue, headache, sore throat, congestion or runny nose, nausea or vomiting, and diarrhea (CDC 2022b). This overlap could have led to misdiagnoses of COVID-19 rather than acute petroleum exposure or vice versa. Additionally, the syndromic surveillance data of ED visits did not include military health system visits despite a large proportion of the affected population being affiliated with the military. Third, the investigation lacked objective exposure measurements and had to rely on self-reported proxy measures such as smell, taste, and visual sheen to determine exposure. Also, weeks of extensive news coverage of possible health effects might have influenced individual reporting of symptoms and exposures. Moreover, as the survey was administered several weeks after the incident occurred, participants may have had difficulty recalling specific routes of exposure (e.g., drinking, bathing) and symptoms. In addition, parents/guardians completing the survey on behalf of their child may have over- or under-reported symptoms. Finally, these methods did not allow for prevalence estimates and may still fail to capture the full scope of the community impact.

CONCLUSION

This incident had significant disruptive effects on people and institutions in the affected area. The JBPHH JP-5 water contamination tainted the public water supply of thousands of people, and water use was not fully restored to the affected community for 118 days. Thousands of people reported adverse physical and mental health impacts. This incident underscores the importance of protecting public drinking water to safeguard human health. When a public water system is compromised, rapid assessments by public health agencies to examine health effects can aid in understanding exposure, formulating risk communications, and improving understanding of acute and long-term public health needs. The adaptable online survey and in-person and electronic promotion facilitated rapid information collection from thousands of affected people across a wide geographic area, including many displaced people. Supplementing the survey with qualitative interviews and surveillance system data allowed us to better understand how the community was impacted. Follow-up of the affected population may improve our awareness of the overall impacts of this and other petroleum exposure incidents. Establishing trust through transparency, open communication, and providing sector-specific guidance can help community members and organizations adapt to health threats during an emergency or similar events.

After the ACE survey closed in February 2022, IDWST launched a website (JBPHH 2022) to publicly share information regarding the status of the drinking water flushing plans and updated drinking water sampling laboratory data for all affected zones. JBPHH maintained an updated site with water updates, relevant resources for residents, and a link to the IDWST page (JBPHH Emergency Operations Center 2022). The consequences of the JBPHH JP-5 jet fuel leaks into the DWDS led to a 6 May 2022 Emergency Order issued by the HDOH to the Navy to defuel the Red Hill facility because it poses an imminent and ongoing threat to 'human health and safety and the environment' (Figure 1; HDOH 2022b). The DOD announced that it plans to defuel and permanently close the Red Hill Bulk Fuel storage facility in Oahu (DOD 2022b). Still, they estimate the process will take at least two years (DOD 2022a). At the time of this report, the HDOH, EPA, and DOD continue to work on the process to defuel and decommission the Red Hill Bulk Fuel Storage Facility safely and rapidly.

DISCLAIMER

The findings and conclusions in this article are those of the authors and do not necessarily represent the official position of the U.S. Centers for Disease Control and Prevention or the Agency for Toxic Substances and Disease Registry. This activity was reviewed by CDC and was conducted consistent with applicable federal law and CDC policy (45 C.F.R. part 46.102 (2), 21 C.F.R. part 56; 42 U.S.C. Sect. 241(d); 5 U.S.C.0 Sect.552a; 44 U.S.C. Sect. 3501 et seq.). The American Association of Poison Control Centers (AAPCC) maintains the National Poison Data System (NPDS), which houses case records of self-reported poisoning exposures collected from callers during exposure management and poison information call managed by the country's poison centers (PCs). NPDS data do not reflect the entire universe of exposures to a particular substance as additional exposures may go unreported to PCs; accordingly, NPDS data should not be construed to represent the totality of a poisoning or overdose event. AAPCC is not able to completely verify the accuracy of every report. Findings based on NPDS data do not necessarily reflect the opinions of AAPCC.

ACKNOWLEDGEMENTS

The team thanks the Hawaiian community, Rene Funk, and Krishna Surasi for assistance with this article.

FUNDING

The author(s) received no financial support for the research, authorship, and/or publication of this article.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 22 February 2023; accepted in revised form 20 June 2023. Available online 3 July 2023