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Environmental and private property contamination following the Norfolk Southern chemical spill and chemical fires in Ohio†

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In February 2023, a train derailment in Ohio caused a chemical spill and fires releasing contaminants into the air, soil, waterways, and buildings. The authors conducted a rapid response which included six field investigations and bench-scale experiments to understand the chemical identity, fate, and exposure pathways after the evacuation order was lifted. Multiple buildings were chemically contaminated and silicone wristband products inside a commercial building were found to have adsorbed derailment-related chemicals. The indoor air of this commercial building was found to be contaminated for 4.5 months after the derailment. Derailment chemicals were also found on building exteriors 5 weeks after the incident. Railcar chemicals were detected in the nearby creeks. Cleanup activities (sorbent pads, aerators) as well as creek hydraulic and environmental conditions influenced chemical fate in creeks. Creek mechanical aeration activities prompted VOC emission that contributed to human exposures and vapor intrusion. Atmospheric modeling revealed that the chemical plumes extended beyond the evacuation zone. Water was a consequential media associated with contaminant transport and human exposures found in the present study. Because the complexity, magnitude, and health threats posed to the community were not matched by efforts employed by the responding organizations, the population experienced continued exposures for months; workers as well as town visitors also experienced health symptoms. This study revealed unaddressed human exposure pathways. Also identified were crucial gaps requiring improved decision-making and technologies. Recommendations to better protect human health and the environment before and during a response to chemical incidents are provided.

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Water impact

Chemical disasters create public health and environmental risks. To best protect public health, a formalized hazard identification and decision-making process is lacking, and very much needed. For this disaster, chemical identification, fate, and exposures were poorly understood prompting injuries and illnesses.

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1. Introduction

On February 3, 2023, a train with 149 railcars derailed and was set aflame in East Palestine, Ohio releasing pollutants that impacted multiple U.S. states.[1] More than 50 fire departments and 300 firefighters responded, and a 1 mi radius evacuation was ordered (ESI†). A shelter-in-place order was also issued to residents in the 1–2 mi zone affecting counties in Ohio and Pennsylvania. On February 6, the rail company open burned nearly 900 000 pounds of vinyl chloride (VC) from five railcars,[2] while other railcars were found leaking. The open burn's black chemical plume traveled outside the evacuation and shelter-in-place area. Two days later, officials lifted the evacuation order.[3] Chemicals released into Sulphur Run, a creek adjacent to the railroad tracks, prompted downstream fish kills[4] and chemicals flowed 270 mi down the Ohio River (ESI-Context section†).[5] About 20 days after the spill, derailment chemicals were still entering the Ohio River. This incident prompted immediate safety concerns for the nearby residents, workers, wildlife, pets, farm animals, and agricultural areas supplying food to humans and animals.[2] Additional incident details are in ESI-Context section.†

During the following months, concerns were raised about the fate of chemicals released as the derailment occurred on the Eastern side of East Palestine next to Sulphur Run creek (Fig. 1). Sulphur Run received spilled chemicals and runoff from the firefighting operations. Chemicals from the derailment site and roadways reached storm drains and Sulphur Run during the initial response (ESI-Context section†). Chemicals spilled into Sulphur Run flowed through East Palestine, as well as directly by and underneath more than 130 residential, commercial, and municipal buildings through concrete boxed and corrugated metal culverts, and under bridges. Doors and windows of some buildings were less than 5 feet from the creek. At East

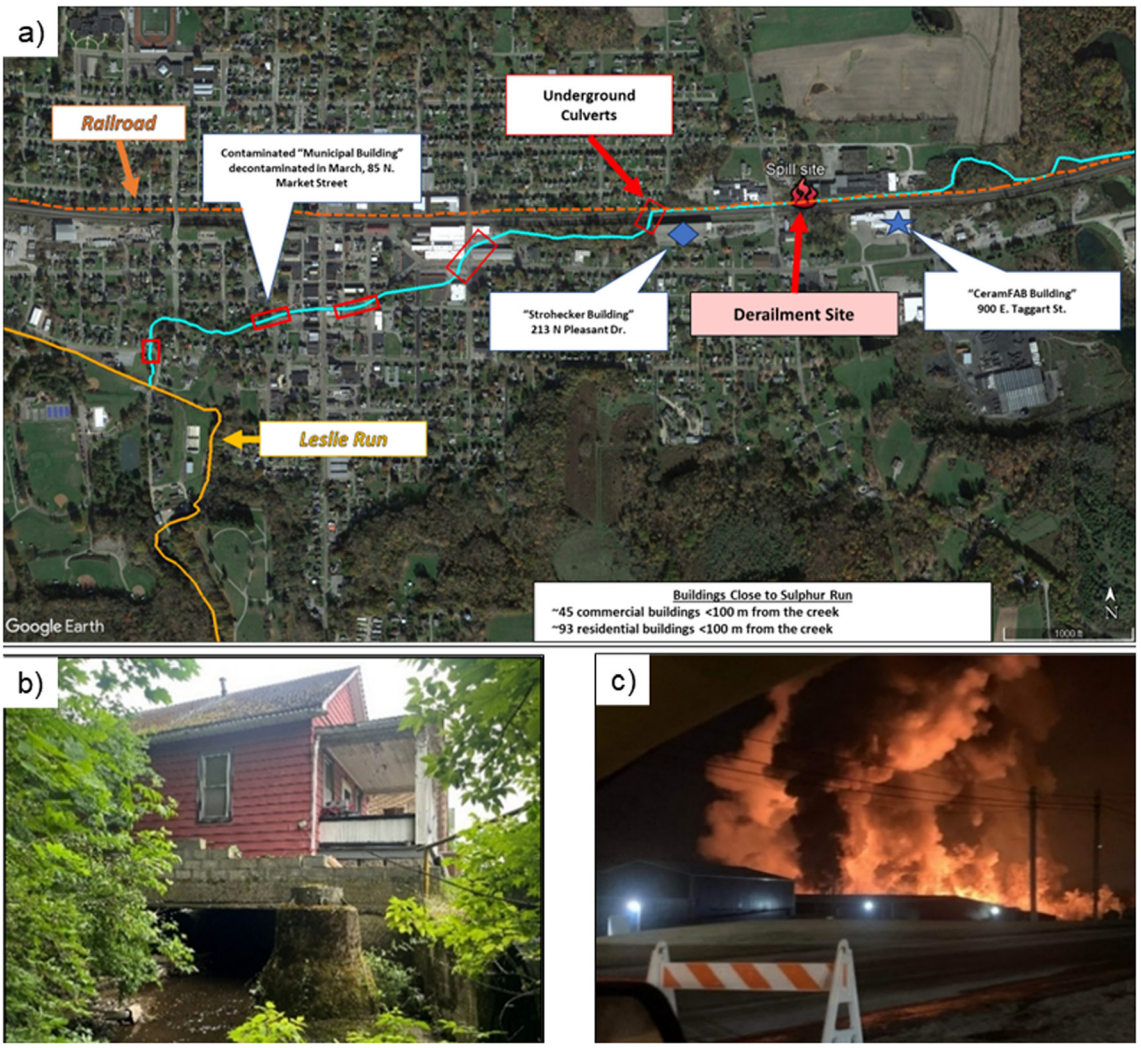


Fig. 1 a) Map showing the derailment site, culverts, and contaminated buildings near Sulphur Run, b) chemicals released from the derailment entered Sulphur Run and flowed into concrete culverts underneath residential, commercial, and municipal buildings, c) image of the chemical fire visible from East Taggart Street by the CeramFAB Building on February 3, 2023. This image was taken before the open burn was conducted February 6, 2023.

Palestine City Park, Sulphur Run drained into Leslie Run Creek which flowed to the south. East Palestine's municipal drinking water wells were located 1.25 miles west of the derailment site. According to public records, the groundwater in the area was "highly susceptible to contamination" due to the lack of a surficial clay layer, and Leslie Run was adjacent to mineral mines.[6,7] Some households in the area relied on private drinking water wells adjacent to Leslie Run, some of which had a water elevation of 3 ft below ground surface.

After the evacuation order was lifted, government employees, community members, and visitors in the area reported concerns about chemical exposure (ESI-Context section†).[8–12] On February 14, children returned to schools within the impact zone.[13] In February, Pennsylvania warned households to protect themselves from particulates while vacuuming their impacted homes.[14] At the same time, indoor cleaning contractors began approaching homeowners and claiming that buildings were not hazardous.[15] In March, schools had not yet cleaned their ventilation systems, and some faculty reported illnesses.[16] Illnesses were also reported by the Poison Control Center,[17] first-responders,[18] as well as citizens in Ohio and Pennsylvania.[18,19] Other people also reported illnesses such as the U.S. Centers for Disease Control and Prevention (CDC) employees who visited the area, remediation contractors,[20] politicians and their staffs, and visitors.[9] Questions were raised regarding the safety of commercial properties and commercial products (*e.g.*, crops, food products, retail items) near the derailment site (ESI-Context section†). Furthermore, concerns were expressed regarding the safety of residential gardens, produce, and livestock, as well as the potential economic impacts on businesses (ESI-Context section†). In June, four months after the derailment, indoor cleaning contractors coordinated by the USEPA and Norfolk Southern began offering to remove dust from residences.[21] During the incident response, questions were raised about whether remediation actions contributed to chemical exposures. However, the limited environmental testing information that was publicly available once the evacuation order was lifted did not provide a clear picture of the situation.

This study was initiated to better understand the chemicals present and exposure pathways after the evacuation order was lifted by conducting six field investigations and bench-scale experiments. The specific objectives were to (1) determine the chemicals present in the environment, (2) estimate primary chemical fate and exposure pathways of these chemicals, and (3) identify response and recovery research needs. Several main hypotheses impacting human and environmental exposures were tested: properties where contamination was found outdoors and indoors were within the zone of air quality impact from the initial burn and subsequent open burn; chemicals released by the railcars and firefighting operations were present in creeks downstream of the derailment site; contamination in creeks was heterogeneous during the initial response; creek sorbent pads and aeration caused by mechanical aerators and creek flow conditions influenced chemical fate in creeks. For this study, the authors designated private and public organizations responsible for the environmental recovery decision-making process as "responders" (RESP) (ESI-Context section†).

2. Experimental

2.1 Field and laboratory analysis

Six field investigations were conducted spanning areas in Ohio and Pennsylvania to collect environmental samples and interview households (February 25–27, March 3–4, 17–19, and 23–25, May 4–5, June 10–12) (Table 1). The study interviews were approved by the Purdue University Institutional Review Board (IRB-2023-833). The authors visited 17 homes to understand household experiences as well as conducted household inspections to identify property water system well and plumbing components. Some of these households had previously contacted the group United for East Palestine for assistance. Homes included in this study were close to the derailment site and along contaminated waterways. The authors also reviewed indoor air and private drinking water well testing results made available by households from railway company contractors, insurance companies, and other organizations. Feedback from commercial business owners was obtained and several buildings were visited that included a retail establishment and apiaries, where silicone wristbands and honey were collected for analysis, respectively. Residential and commercial buildings visited were located less than 0.5 mi up to about 6 mi away from the derailment site.

Sample collection and analysis methods are described in the ESI-Experimental,† and a general summary is described below. At the study outset, most of the RESP's water, air, and soil sampling results, methods and analytical methods were not publicly available. In absence of this information, the authors screened samples for chemicals declared present in the railcars, as well as potential products resulting from their combustion. Further, private well water, creek water and sometimes creek sediments were screened for total petroleum hydrocarbons (TPH) because RESP applied a similar analytical approach.[22] Per- and polyfluoroalkyl substances (PFAS) analysis of water and sediment was conducted by the authors because these constituents are associated with the firefighting foam used. Water samples were also screened for other VOCs and SVOCs that were released from the chemical spill, fires, and may be combustion products. Honey was sampled from hives at nearby apiaries to assess whether VOCs from the incident were found in the honey. Silicone wristbands from a business located directly above Sulphur Run creek were collected by the authors to investigate indoor chemical contamination, considering that silicone products are effective sorbents for VOC and SVOC exposure assessment.[23] To help describe chemical fate in creeks, bench-scale experiments were conducted to (a) examine chemical volatilization from

Table 1 Summary of samples collected during the field investigations

Media	Location/dates collected	Analytes	Analysis
Creeks			
Water	9 locations inside and 6 locations outside East Palestine, within 0.3 miles and 11.2 miles downstream of the derailment, OH; Feb 26–27, March 3, 17–18, 25, May 5	TPH,[a] VOC and SVOC,[b] PFAS,[c] pH, ions, heavy metals	UV-VIS spectroscopy,[d] GC/MS,[e] LC/HRMS,[f] ICP-OES,[g] IC[h]
Sediment	In and outside East Palestine, OH; Feb 26–27, Mar 3	VOC, SVOC, PFAS	GC/MS, LC/HRMS
Properties			
Private well water	15 private wells, 1 cistern within 0.4 miles north and 3.2 miles south of the derailment; Feb 26–27, March 18, 25, May 5	VOC, SVOC, PFAS, pH, ions, heavy metals	GC/MS, ICP-OES, IC
Surface wipes	Exterior of 4 buildings in East Palestine within 0.1 miles north and 1.5 miles west of the derailment site; March 17	VOC, SVOC	GC/MS
Air	Sulphur Run, Leslie Run; Feb 27–27	PID signal	Photoionization detector (PID)
Commercial products			
Honey	Four apiaries in Columbiana County, OH and Beaver County, PA; Mar 25	VOC	GC/MS
Silicone products	Products from a business located directly above Sulphur Run in East Palestine; May 5	VOC, SVOC	GC/MS
Chemical sorbent pads	Sulphur Run pads in East Palestine; Feb 27	Material identity and thermal properties, VOC, SVOC	ATR-FTIR,[i] TGA,[j] DSC,[k] GC/MS

[a] Total petroleum hydrocarbons. [b] Volatile organic compounds and semi-volatile organic compounds. [c] Per- and polyfluoroalkyl substances. [d] UV-VIS spectroscopy. [e] Gas chromatography-mass spectrometry. [f] Liquid chromatography high resolution mass spectrometry. [g] Inductively coupled plasma optical emission spectroscopy. [h] Ion chromatography. [i] Attenuated total reflectance Fourier transform infrared spectroscopy. [j] Thermogravimetric analysis. [k] Differential scanning calorimetry.

contaminated creeks because aerators were being used to remove contamination, and (b) examine the ability of sorbent pads to remove chemicals from water because RESP used these pads to remove contamination from creeks as one of the spill cleanup methods. The USEPA EPI Suite™ program was used to estimate the impact of creek flowrates on chemical volatilization from contaminated creeks.

To help interpret indoor and outdoor chemical results an atmospheric model was used. Specifically, the HYbrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model was run to estimate the trajectories of the chemical plume generated during the initial crash and fires and the fires caused by the subsequent open burning of the five railcars containing VC. The selection of methods for the atmospheric model was guided by the need to use observations to initialize the meteorology of the area. This is an extensively used model in the atmospheric sciences community, which calculates the trajectory of a single air parcel using a hybrid method between Largrangian and Eulerian methodology. The model was initialized with observational data – archived Global Data Assimilation System (1° × 1° resolution) meteorological data. The use of HYSPLIT model showed a disposal of the smoke plume over the area we are testing the samples collected on the surrounding area of the train derailment. The model initialization was same as that used in the USEPA model in the U.S. Federal Emergency Management Agency (FEMA) report.[24] Further details of the method followed for this experiment are in ESI-1.1.† Model results were compared with the soot deposition data released months after the incident by RESP and atmospheric modeling results released by other organizations.

3. Results and discussion

3.1 Contaminated buildings

3.1.1 Indoor contamination was found. The authors conducted inspections of several residential and commercial buildings and chemical analysis of silicone wristbands removed from a commercial building. The results indicated that derailment chemicals had entered and remained inside buildings after the evacuation order was lifted. Occupants of the 17 buildings visited within six miles of the derailment reported finding acrid odors inside their buildings following the evacuation. Occupants reported experiencing a range of symptoms, including headaches, rashes, throat irritation, and nausea. All building occupants reported that they had opened windows and doors to ventilate their buildings. Some occupants had acquired and were using indoor air purifiers when the authors first visited three weeks after the incident. Near where Sulphur Run intersects Leslie Run, several building owners explained that, prior to the authors' arrival, RESP had installed creek aerators outside their residences. These households believed that this action resulted in the introduction of chemicals into their homes, causing adverse health effects (headaches, nausea, dizziness), and compelled them to evacuate their residences (ESI-15 and ESI-21†). According to some occupants, insurance companies sometimes, but not always, paid for indoor air chemical testing, and one household purchased their own handheld air quality monitor.[25] A household north of and less than 0.1 mi from the derailment site reported that during the initial fire an acrid odor was present in the air. They also described observing "glittery dust" falling onto their property. Multiple

family members in this household complained of headaches, nausea, throat irritation, diarrhea, difficulty breathing, and upset stomach.

Of the buildings visited during the study, the authors identified only one commercial building with the distinct acrid chemical contamination odor that was also present in the contaminated creeks. The authors found that silicone wristbands inside the commercial building with the acrid odor were contaminated with chemicals from the derailment. This building was located directly above the concrete culvert that conveyed Sulphur Run through downtown and less than 0.1 mile from the derailment site. Wristbands removed from this building were found to contain several VOCs released from the railcars, including butyl acrylate (BA), 2-butoxyethanol (2-BE), and 2-ethylhexyl acrylate (2-EHA) (Fig. 2).[26] The contaminated wristbands also contained several VOCs that may be associated with incomplete combustion of petroleum products and other chemicals not listed in the chemical manifest for the railcars involved in the incident (2-chlorophenol, *p*-cresol, 2-ethylhexanol [2-EHL], isophorone, naphthalene [NAP], phenol).[27,28] SVOCs found in the wristbands may also be associated with the combustion of lube oil and petroleum-based fuels associated with the disaster (acenaphthene, fluorene).[29] 2-EHL was found in the surface water after the incident by RESP (as high as 580 ppb). The VOCs and SVOCs not previously identified by others found in the wristbands may be unidentified chemicals released or produced by the chemical spill and/or fires. None of the chemicals reported above were found in the new wristbands (control samples) obtained directly from the manufacturer. These control wristbands were never present at the contaminated building. While there are no specific exposure limits for chemicals in wristbands, general public and occupational airborne chemical exposure limits have been reported for some, but not all, of the chemicals (Table ESI-10†).

Separately, indoor air VOC sampling conducted by the business owner on February 14th corroborates the author's wristband finding that the building was contaminated with derailment chemicals. The business owner discovered the derailment chemicals BA (26 ppb) and 2-EHA (3 ppb) present in the air, as well as other VOCs, including benzene (0.6 ppb), toluene (0.6 ppb), *m*-, *p*-xylene (0.4 ppb), tetrachloroethene (0.6 ppb), 1-butanol (18 ppb), decane (4 ppb), carbon disulfide (0.4 ppb), and carbonyl sulfide (4 ppb).[30] The business owner also found ash and "soot" inside the building.[30] It is also noteworthy that the business's indoor air BA concentration 9 days after the incident was below the 2 week 50 ppb ATSDR screening level, but exceeded the >2 weeks to 1 y screening level (Table ESI-15†). In this building, the authors detected the acrid odor during the final sampling investigation, four and a half months after the derailment. Another business in the same building, sharing an adjacent space, was also found to have the acrid odor in their workspace during the same site visit.

Findings by the RESP also supported the author's conclusion that vapor intrusion into buildings occurred after

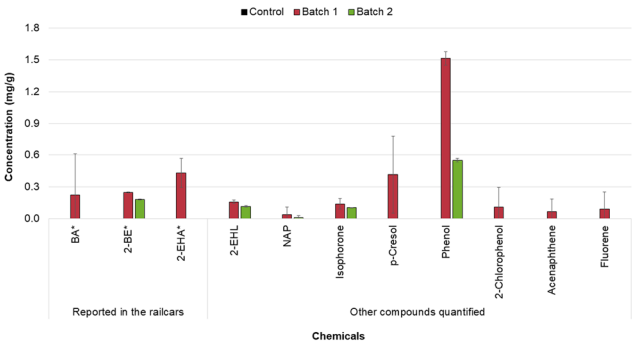


Fig. 2 Contaminants from the derailment were found in silicone wristbands in an impacted commercial building. The business owner conducted their own testing in February and found that indoor air was contaminated with BA, 2-EHA, in addition to other chemicals. None of the chemicals were detected in unexposed control wristband samples. (*) Chemicals were reported in the chemical manifest from Norfolk Southern (Table ESI-18†).

the derailment.[31,32] For instance, in the commercial building identified as contaminated with derailment chemicals by the authors, the rail company's air monitoring contractors visited that same building 11 days after the incident, and their own exposures prompted that team to leave the building within 10 minutes (Fig. ESI-10†). While their PID datasheet indicated "<0.1 ppm VOCs" in multiple rooms, the rail company contractor noted that "strong, super glue, pool, fruity, unpleasant, overwhelming odors prompted the air monitoring team to leave the building". In mid-February, the USEPA reported indoor air contamination in another structure in the city, the 85 North Market Street Municipal Building in downtown East Palestine, prompting health symptoms by one occupant.[33] As with the contaminated commercial building visited by the authors, this government building was located directly above the Sulphur Run concrete culvert, and chemicals entered the building directly beneath it, through unplugged drainpipes (Fig. ESI-17†). In March, the State of Ohio acknowledged that homes and business indoor air near Sulphur Run were contaminated with derailment chemicals.[34–36] To address these indoor exposures, Ohio reported that culverts that transported contaminated water beneath and next to buildings were pressure washed to remove contaminated sediment.[34–36] In May 2024, the U.S. Department of Justice declared that homes were damaged by Norfolk Southern in a proposed settlement agreement.[37]

3.1.2 Challenges with RESP indoor contamination assessments. A review of RESP's indoor air testing approach and information revealed that their methodology was inadequate for the purpose of identifying chemical health risks. Once the evacuation order was lifted, the indoor air was screened by railroad contractors using a PID. The building reentry air testing plan was approved by the USEPA[38] and implied that the PID could differentiate between chemicals such as BA, 2-EHA, isobutylene, and ethylene glycol monobutyl ether acetate. However, ethylene glycol monobutyl ether acetate has never been publicly reported as

been released from the chemical spill or generated by the fires. A similar named compound, but different CAS number, was released (2-BE) and was not screened for inside buildings. Limitations of using PIDs have been well-known; PID signal does not always correspond to actual chemical air concentration.[39–44] Indoor air PID testing records from February 12–16 indicated <0.1 to 41 ppm signals in more than 72 records.[45] RESP reported indoor air odors sometimes included acetone, smoke, burnt, and other descriptors. Sometimes odor was noted by contractors when a PID signal was not detected. As part of RESP's indoor air testing, USEPA encouraged workers to conduct "odor checks" to detect the presence of chemicals.[46] Prior worker safety advice was that odor alone should not be relied upon to determine hazardous exposures to BA.[47] Ten months after the incident, RESP concluded that the PIDs used could not have reliably detected either BA or VC at levels above health screening levels or at concentrations below 200 ppb.[48,49]

3.1.3 Derailment chemicals were found on the exterior of some buildings five weeks after the incident. Exterior residential building wipe samples revealed several compounds unique to East Palestine: 2-BE (4 of 5 locations), NAP (4 of 5 locations), benzo(*g*,*h*,*i*)perlyene, (3 of 5 locations), fluoranthene (2 of 5 locations), benzo(*k*)fluoranthene (2 of 5 locations), and phenanthrene (1 of 5 locations) (Table ESI-8†). The highest BA concentration was detected in East Palestine, and lower BA levels were found on new vinyl siding and new gauze. The release of BA, 2-BE, and NAP from the incident suggests that these building exterior contaminants may have originated from the disaster. Other contaminants were identified as likely the result of incomplete combustion products not reported in the chemical manifest of the derailed trains.[27–29] RESP did not conduct wipe samples for building exteriors. During the author's field investigations, some buildings were seen being power washed by individuals who were not wearing personal protective equipment (*i.e.*, respirator, goggles, gloves). In addition, homeowners were cleaning their own buildings.[50] According to the USEPA's building decontamination guide, water washing is not listed as an effective plastic siding remediation method for the types of chemicals released.[51] The lack of protective equipment and use of water washing likely contributed to exposures and removal of surface sorbed chemicals. But, VOCs that subsequently diffused to the surface of the materials likely continued to volatilize from building exteriors into ambient air.

3.2 Atmospheric modeling

To better interpret building occupant odor reports and the author's building chemical contamination results, the author's HYSPLIT model results and atmospheric simulations reported by other organizations were considered. All buildings visited by the authors were in the zone where >80% of the authors' HYSPLIT air trajectories were predicted (Fig. 3). The HYSPLIT modeling results indicated that chemicals were transported in the air from the derailment location in multiple directions, extending beyond the 1 mile evacuation zone. Polluted air traveled mostly to the immediate north of the burn (more than 19 out of 24 trajectories), with some likely blowing over Lake Erie and reaching Canada (Fig. 3). Before the open burn, air appears to have blown mostly to the east of the site. After the burn, air primarily traveled north, and trajectories used in the frequency calculation are in the ESI.† While the model applied did not include particulate deposition or transport, results suggest that atmospheric pollutants emitted travelled east and north of the derailment site. The residential and commercial buildings visited by the authors were also located within USEPA's soot footprint map,[24] and the modified High Resolution Rapid Refresh dispersion model impact zone identified by other investigators (Table ESI-7†). A limitation here is that the HYSPLIT model does not have the spatial resolution to capture the variability across the various sampling sites in this study.

3.3 Chemical fate, transport, and exposures with water

3.3.1 Creek water quality. Initial visits by the authors to East Palestine revealed the presence of significant chemical contamination in Sulphur Run and Leslie Run, with subsequent visits indicating a reduction in contamination levels (Table 2, ESI-Videos 1–3†). Some contamination was visually observed, while others required advanced sample analysis techniques. Sheen and white foam were observed in Sulphur Run and Leslie Run creeks during the first investigation, three weeks after the derailment, and sheen was observed during every subsequent visit during the study (Table 2, Fig. ESI-6 and ESI-7, ESI-Videos 4 and 5†). These phenomena were not observed at creeks outside of East Palestine. TPH and GC/MS creek water analysis did not help describe the sheen constituents. Multiple petroleum spills into Sulphur Run prior to the derailment[7] and nonspecific nature of TPH measurements, challenged the usefulness of TPH results. Similarly, after a 2023 chemical spill in Hawai'i, officials there found that TPH results indicated petroleum compounds were present, but no spilled petroleum VOCs and SVOCs could be linked to the TPH response.[53] That finding underscores that TPH measurements alone are not sufficient to detect chemical exposures associated with petroleum spills.

Several VOCs from the derailment (*i.e.*, BA, 2-BE, 2-EHA, and 2-EHL) were detected in the same creeks screened by the RESP, but levels in the present study sometimes differed significantly from RESP reports at similar locations and sample collection days. The VOC isophorone was detected in Leslie Run by the authors, three weeks after the incident. This compound was also detected by the authors in the contaminated silicone wristbands from the commercial building along Sulphur Run. Chemicals discharged at the derailment site onto land and nearby waterways traveled 270 miles down the Ohio River, according to RESP findings.[5]

Another contaminant detected in creek water included a biotransformation product of 2-BE, 2-butoxyacetic acid (2-BAA). 2-BAA was detected in the water and sediment of

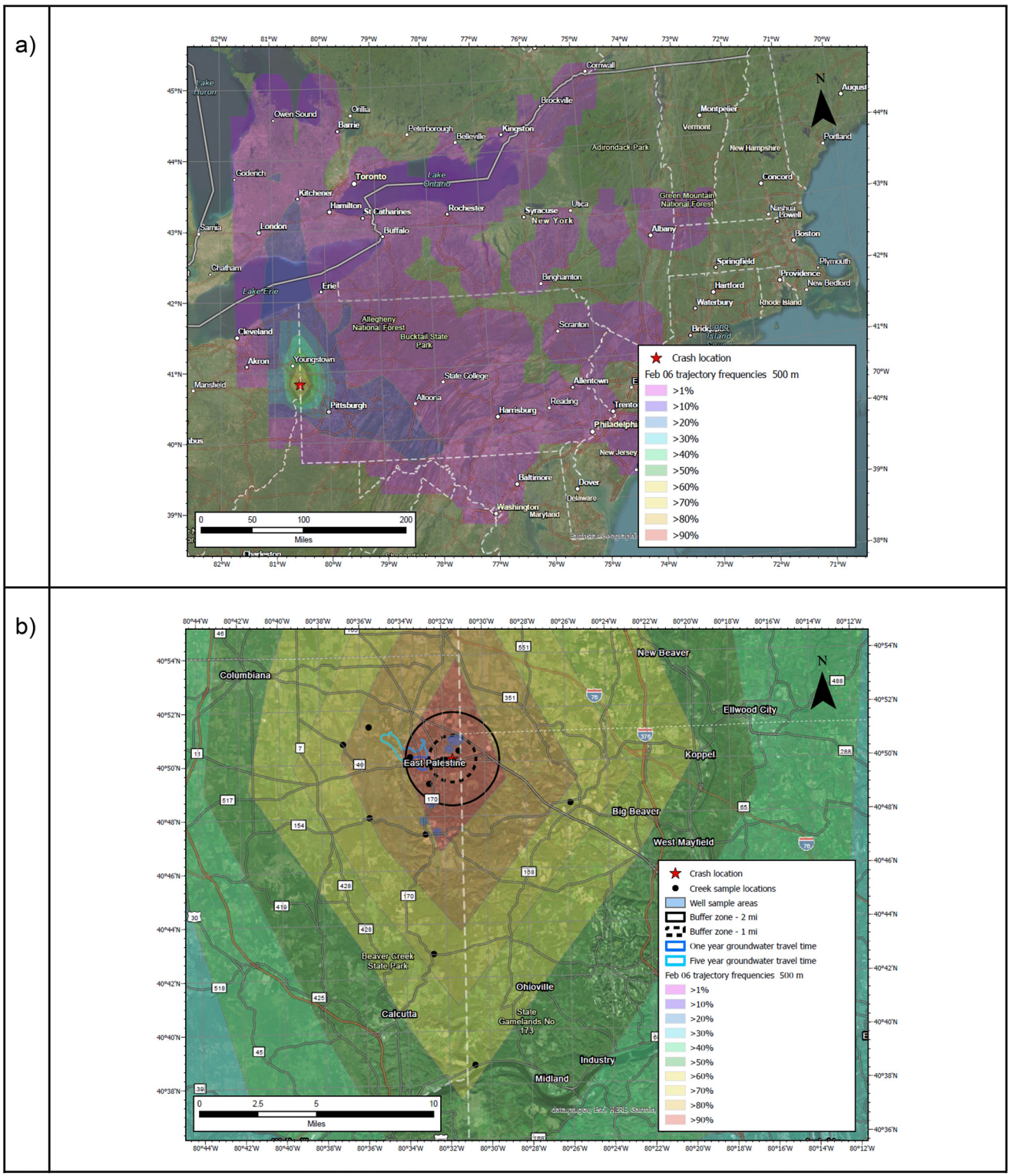


Fig. 3 The chemical plume area of impact (a) was simulated with the HYSPLIT model, (b) the chemical plume extended outside both the 1 mile evacuation zone and the shelter-in-place zone plotted with the creek sampling locations[52] and (c) East Palestine area, with shelter in place and evacuation zones highlighting the areas where the study sampled private wells. Each image panel represents a different spatial scale.

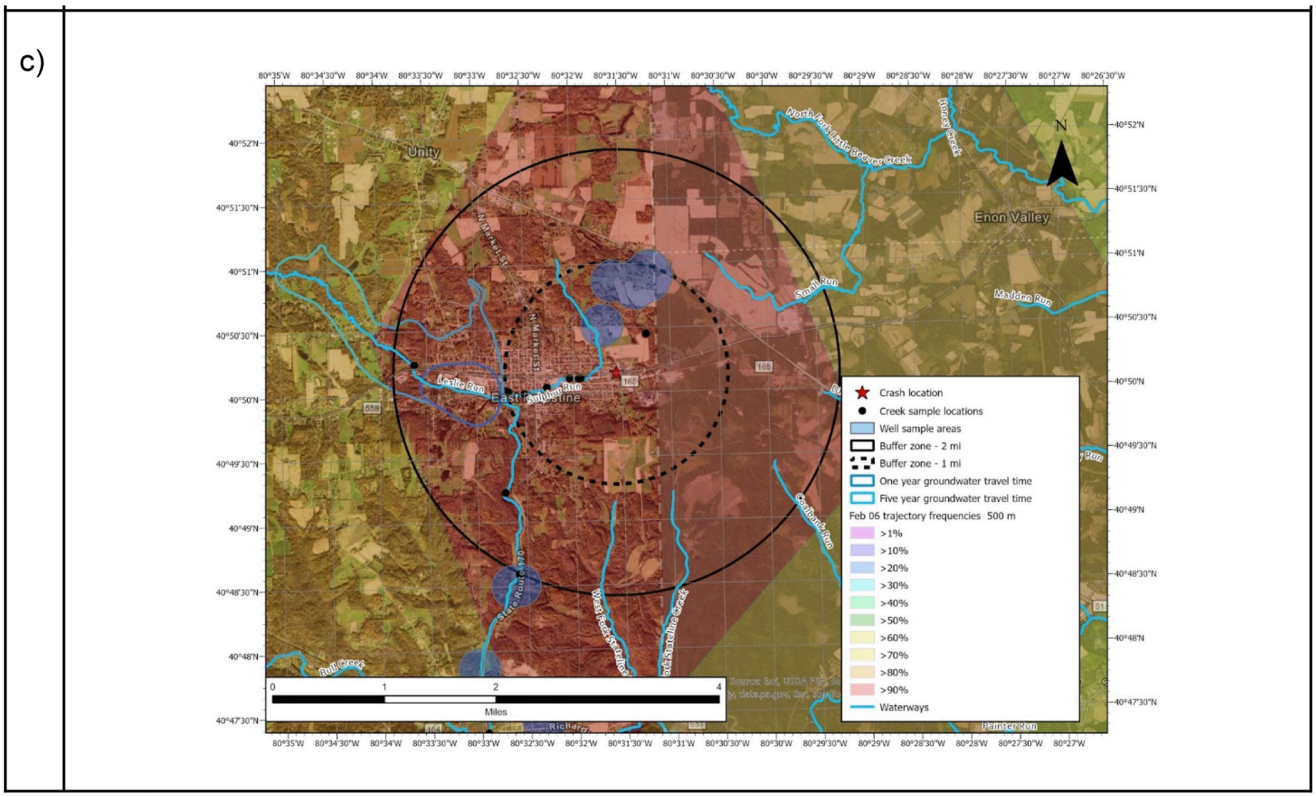


Fig. 3 *(continued)*

Table 2 Several contaminants of concern were detected in the impacted creeks during the author's field investigation that was conducted three weeks after the derailment and the maximum concentrations are shown in ppb (μg L^{-1} for water, μg kg^{-1} for sediment)

Creek and sample location		Foam/sheen	VOCs reported on the railcars			Other compounds quantified		
			BA	2-BE	2-EHA	2-EHL	Isophorone	2-BAA[a]
Downstream waterway maximum reported by RESP		Yes	180 000	848 000	122 000	580	NT	NT
Sulphur Run	C1	Yes	3.4	9594[d]	61.0	142.7	ND	13.65 (water) 9.17 (sediment)
	C2	Yes	ND	3784[d]	52.2	11.0	ND	14.21 (water) 0.98 (sediment)
	C3	Yes	9.2	4088[d]	6.8	33.1	ND	11.65 (water)
	C4	Yes	21.7	477.8	406.6	159.9	ND	10.38 (water)
Leslie Run	C5	Yes	ND	ND	23.9	ND	ND	NT
	C6	No	ND	ND	35.7	>1.6[c]	7.1	NT
Background	C7	No	ND	ND	ND	<LOQ[b]	ND	NT
	C10	No	ND	ND	ND	1.8	ND	NT

LOQ = limit of quantitation; ND = not detected; NT = not tested. [a] Butoxyacetic acid. [b] <limit of quantitation (LOQ). [c] First and third field sampling event detected 2-EHL bellow quantitation limit; location C14 revealed 2.24 ppb of 2-EHL; on the second field investigation a Sulphur Run creek water sample collected at C15, downstream of C4, revealed the presence of 2-EHL (<LOQ) and sheen; location C16 revealed the presence of 2.19 ppb of 2-EHA. [d] Values are estimates as the concentration exceeded the maximum point on the calibration curve; ** the minimum detection limit for the TPH test in the present study was 1 ppm as an additional calibration standard was created to help screen for lower levels; TPH was not detected at locations C1 to C6. TPH was not measured at locations C7 and C10; while RESP reported their highest TPH levels in Sulphur Creek during February 7–8 (TPH-DRO 12 ppm; TPH-ORO 15.3 ppm),[54] the authors did not detect TPH. On February 8, the USEPA reported that the Sulphur Run sheen contained TPH-GRO C6–C10 (2.2 ppm), TPH-DRO C10–C28 (1900 ppm), TPH-ORO C28–C40 (28 000 ppm), and 0.65 ppb vinyl chloride, and concluded this sheen was caused by hydrocarbons from the spill. All chemicals reported for samples C1, C2, C3, C4, C5, and C6 were from the first field sampling on February 26–27. For sample C6, 2-EHL was detected at levels <LOQ in the test conducted during the third field survey on March 25. The values reported for C7 and C10 were collected on March 3.

Sulphur Run creek through a nontarget analysis on samples collected during the first field investigation (Table 2). It is a metabolite of 2-BE that has been found in humans and mammals. This urinary metabolite is formed after compound ingestion, dermal absorption, and inhalation.[55] The 2-BAA detection could also be related to the discharge of 2-BE caused by the train derailment and firefighting activities, as 2-BE is one of the key solvents used to produce aqueous film-forming foam (AFFF) and fluorine-free AFFF.[56] While 20 gallons of AFFF was used for firefighting activities (ESI-20†), no PFAS, per EPA Method 1633, were observed (Table ESI-12†) above the detection limits (Table ESI-13†) for any tested samples. This suggests that if the AFFFs contained PFAS, PFAS had not transported this far from the derailment site at the time of sampling.

3.3.2 Creek water testing data and monitoring discrepancies. A review of Ohio EPA commercial laboratory creek water testing data sheets dated February 4–17 revealed that while RESP screened for 175 individual chemicals, tentatively identified compounds (TICs) sometimes numbered more than 278,[54] and these were not analytically confirmed. TICs had estimated concentrations of a few ppb to multiple thousands of ppb. TICs were reported differently by the two commercial laboratories used and included "unknown, unknown acids, unknown alcohols, unknown aldehydes, unknown alkanes, unknown alkenes, unknown amides, unknown aromatic hydrocarbons, unknown cycloalkanes, unknown esters, unknown ethers, unknown ketones, unknown organic acids, unknown PAHs", as well as individually tentatively named compounds. According to the sampling reports from the USEPA, analyzed from February 4–17, the greatest number of TICs reported occurred immediately after the derailment, from February 4–10, rather than from February 11–17.[54] Background and contaminated creek water samples from the present study did not reveal ion or metal levels outside expected water quality limits. During the June 2023 field investigation, small fish, crayfish, and other aquatic arthropods were observed in Leslie Run and portions of Sulphur Run near location C4.

Differences between the author's creek water quality monitoring results and those of RESP are likely due to numerous factors, including time of the day of sampling, sampling location, rainfall, and creek turbulence. During the first field investigation creek contamination was clearly heterogeneously distributed as RESP worked to clean up the impacted area. Further, RESP creek water quality results revealed that contamination was deposited immediately upstream of the derailment site, suggesting air transport of contaminants had occurred. This is supported by findings of the present study's HYSPLIT atmospheric model, which illustrated the dispersal of contaminated plumes in multiple directions. Rainfall events likely mobilized contamination downstream (Fig. ESI-11†). The installation and removal of RESP temporary hay bale check dams, sorbent pads, creek aerators, creek bottom diffusers, and soil washing and rock and creek bank pressure washing likely prompted variations in chemical water quality. During late February, contamination was released into Leslie Run by the RESP when a makeshift dam, separating the more contaminated Sulphur Run from the less contaminated Leslie Run, ruptured.[57] When the authors first visited the area to identify sample locations, agencies had not disclosed the footprint of the affected area by the disaster or shared many environmental monitoring results publicly (ESI-21†). No schedule and associated water quality monitoring for each RESP activity was found.

3.3.3 Chemical removal by creek sorbent pads. Bench-scale tests revealed that sorbent pads in Sulphur Run removed the more nonpolar chemicals (*i.e.*, 2-EHA, NAP) from a dilute aqueous solution but removed little to none of the more polar chemicals (*i.e.*, BA, 2-BE, or 2-EHL) (Fig. 4). ATR FTIR analysis

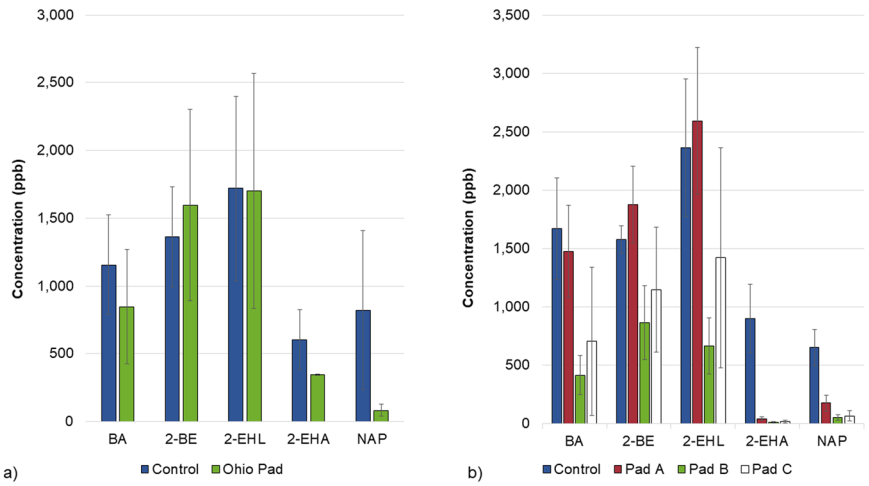


Fig. 4 Bench-scale experiments revealed that (a) sorbent pads used in Sulphur Run (b) and sorbent pads purchased from suppliers did not remove detectable amounts of the polar BA, 2-BE, or 2-EHL compounds from water, but the more nonpolar compounds (2-EHA and NAP) were significantly removed. Concentrations selected were lower than the maximum reported levels reported by RESP in the creeks (BA: 180 000 ppb; 2-BE: 848 000 ppb; 2-EHA: 122 000 ppb; 2-EHL: 580 ppb and NAP: 2.8 ppb). Mean and standard deviation values are shown for three replicates.

indicated that the new sorbent pads and those that were collected in the field were composed of polypropylene. The chemical sorption ability of a pad used in Sulphur Run cleanup and three distinct brands of new pads (pads A, B, and C) revealed varying removal effectiveness. Pad A performed similarly to the pads used in Sulphur Run, while pads B and C removed greater amounts of the chemicals examined. Chemicals not removed from the creeks by sorbent pads likely remained in the water, sorbed to sediment, or volatilized into the air. These findings highlight the complex challenges associated with the use of sorbent pads for environmental remediation in waterways like Sulphur Run. Future strategies should consider optimizing sorbent material selection and deployment methods to improve removal efficiencies across a broader range of contaminants, particularly those with polar characteristics that pose ongoing environmental and human health concerns.

3.3.4 Chemical volatilization from creeks. To remove chemicals from the creeks, RESP constructed and operated aeration units along Sulphur Run and Leslie Run from February into March (ESI-Videos 6–8†).[58] Bench-scale testing confirmed that aeration increased air emission of contaminants (Fig. ESI-12†). PID signals for aerated contaminated water in the laboratory were 2.7 to 25.6 times greater compared when aeration was not used, depending on the compound and concentration tested. During the authors' first visit, sheen was observed, and the authors' PID indicated VOCs were emitted from contaminated creeks. When contaminated creek sediment was physically disturbed (sheen became visible, odor became stronger), the authors' PID sometimes reported signals of 1200 to 2000 ppb (C15, trip 4) and 2494 ppb (C2, trip 4). Background PID signals taken 20 ft away from each location on land ranged from 0 to 26 ppb, respectively. PID signals from background creek locations ranged from 0 to 68 ppb. Sediment washing was also conducted by RESP in Sulphur Run and Leslie Run creeks, releasing VOCs into the air.[59,60] Air knifing was also applied to remove contaminants from contaminated sediments in Sulphur Run.[61]

Based on study findings, it is unclear why RESP publicly stated during their remediation that there was "no means of exposure" from contaminated creeks.[62] Further, agencies stated the aeration was used to "drive chemicals to the water's surface [to be] extracted from the water",[58] and "enhance the natural biological activity and bring contaminants to the surface to the sorbent booms".[63] Officials further claimed aeration "promotes a natural breakdown of the dissolved contaminants"[64] and that "enhanced oxygen enrichment is having a positive effect on breaking down chemicals in the water column".[52] The authors observed that RESP conducted creek aeration without VOC capture (Fig. ESI-12 and ESI-15†). Evidence indicates that aeration was a major pathway of chemical transfer from water into air.

3.3.5 Private well water. Contaminants of concern were not found in drinking water, aligning with the findings of the RESP for the same wells and others nearby during the study period. RESP tested for ethyl monobutyl ether acetate in drinking water,[65] which was never reported to have been spilled or created due to the fires. Instead, 2-BE was released, detected by RESP in the contaminated creeks, but drinking water was not screened for it until the authors brought it to their attention. As chemicals released did not have existing health-based drinking water limits, the RESP created drinking water screening levels (BA 560 ppb; 2-EHL 200 ppb; 2-EHA 500 ppb), but did not disclose the risk assessment assumptions (*i.e.*, exposure route, duration).[66] The authors' well water ion and metal concentrations were unremarkable and similar to wells elsewhere outside the contamination impact area (ESI-8†).

RESP installed monitoring wells around the municipal well field that was located Northwest of the derailment site and did not find well water contamination associated with the derailment.[52,67,68] RESP also sampled private wells located around East Palestine including along Leslie Run and did not find derailment related contamination. Due to little information about groundwater conditions, well owners remained concerned about their well's safety. For example, in March 2023, an activist claimed that residents were being informed by Ohio that their private drinking water wells were contaminated.[69] However, the authors' review of some lab reports indicated low levels of phthalates (ppb range), not any contaminants that had been associated with the spill and fires. In May 2023, a home water treatment company declared that VC was present in East Palestine's municipal drinking water at 5.28 ppb, exceeding the federal drinking water limit of 2 ppb.[70] The authors' discussion with the company owner and review of their commercial laboratory reports indicated that the conclusion was incorrect; VC had not been found in East Palestine's drinking water. Work by Chen 2024,[7] who examined the biodegradation potential of VC and BA discovered biomarkers of chemical degradation in some drinking water wells that were also sampled by the authors. Given the area's groundwater vulnerability, future sampling efforts should focus on identifying the transport and sorption behavior of the individual contaminants,[71] and sample groundwater accordingly. Additionally, the RESP should address the miscibility of nonaqueous phase liquids (NAPLs). This is important to consider because the density of the chemical of concern determines its environmental risk: chemicals with a density less than that of water are likely to float on the water's surface, while those with a greater density may sink into aquifers.[71,72]

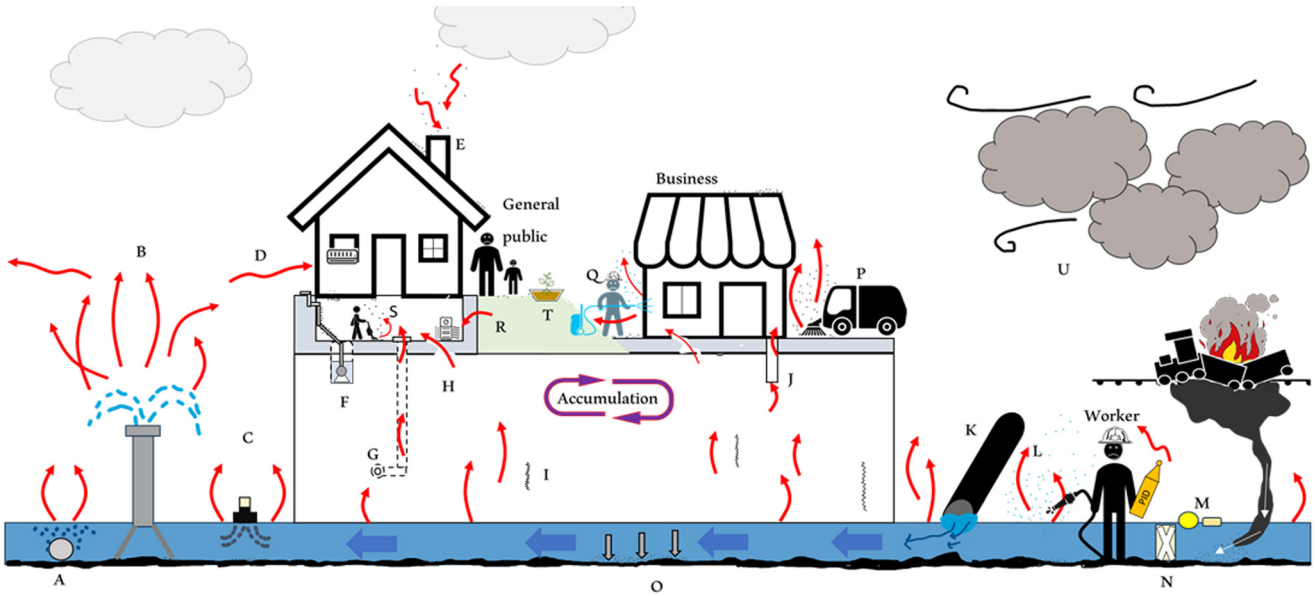
In summary, the absence of contaminants in drinking water wells, consistent with the RESP findings, and the identification of contaminants of concern in creeks highlight the need for follow-up groundwater safety investigations. Despite concerns raised by misinformation, our findings, along with Chen's discoveries pertaining to chemical degradation, the fate of the chemicals once they reach the groundwater is unclear. To improve future disaster response, it is critical to prioritize detailed studies of contaminant transport, sorption, and NAPL behavior. Extensive

groundwater sampling and a clear understanding of chemical miscibility should be an integral part of disaster management efforts to ensure accurate risk assessment and protection of water resources.

3.4 EPI Suite model chemical fate predictions: air, water, soil, and creek sediment

To help interpret water quality and air quality data and identify exposure pathways, EPI Suite™ modeling was applied. For the derailment site, the EPI Suite™ model predicted that the main VOCs spilled onto soil (*i.e.*, BA, 2-BE, 2-EHA, 2-EHL, NAP) would have remained with the soil system (26.7% to 86.6%) except for VC (3.3%) (Fig. ESI-13†). RESP derailment site aerial photogrammetry indicated that some railcars were in Sulphur Run creek and large volumes of liquids were spilled from the railcars (ESI-Video 9†). For this condition, some railcar products would not have been intercepted by soil.

Once the chemicals entered the creek, volatilization out of the creek was primarily influenced by mechanical aeration, creek hydraulics, atmospheric, and environmental conditions. Mechanical aerators were located along Sulphur Run and Leslie Run from February into March (Fig. ESI-14†). Because creek flow varied during the study period based on the author's inspections of creek depths (0.9 m to 2.7 m after rainfall), chemical air concentrations above the creeks were predicted to increase with creek flowrate (Fig. ESI-14†). Creek water depth and wind speed also varied during the study period and influenced chemical emission from the creeks (ESI-1.13†). During the author's final site investigation four and a half months after the derailment, Sulphur Run creek contained no water, exposing contaminated sediments directly to the atmosphere (Fig. ESI-16†). No creek water level and flowrate monitoring data from RESP were found. This study's EPI Suite™ model and a recent study show that biodegradation had a negligible short-term effect on chemical fate in creeks.[7] If VC and BA reach oxic and anoxic Sulphur and Leslie Run creek sediments, Chen 2024[7] found VC and BA degradation could take place on a scale of days to months.



A – Bubble diffuser
B – Stand aerator
C – Surface aerator
D – Window A/C unit
E – Chimney
F – Sump pump
G – Floor drain
H – Foundation crack
I – Leaking wall crack
J – Open drainpipe
K – Storm water culvert
L – Sediment washing
M – Sorbent booms and pads
N – Hay bale
O – Chemical transport to sediment and groundwater
P – Street sweeper
Q – Power washer
R – Air purifier
S – Indoor cleaning
T – Vegetable garden
U – Atmospheric transport

Fig. 5 Evidence indicates chemicals entered residential and commercial buildings by several pathways and Sulphur Run concrete storm water culverts likely enabled chemical air concentrations to have limited dilution before building entry. Sulphur Run flows right to left. Hay bales, sorbent booms, and sorbent pads were used by cleanup contractors. During rainfall events, storm water runoff from Taggart Street (where the trucks were hauling contaminated soil) would drain into Sulphur Run. The concrete culverts inspected were cracked, leaking water, and had open drains from the buildings above. Basement foundations were leaking, which allowed water to enter from drains when Sulphur Run had high water levels. Cleanup contractors also installed surface aerators, stand aerators, and bubble diffusers to transfer chemicals from the water and into the air. Some residential and commercial buildings nearby had open windows, doors, window air conditioning units, chimneys, sump pumps, floor drains, foundation cracks, and drainpipes.

3.5 Other chemical fate and transport pathways that went untested

Due to the limited resources of the present study, field measurements could not be collected for all chemical fate and transport pathways, but an overall exposure pathway assessment was developed (Fig. 5). This study also examined data from other organizations, such as reviewing the rail company's indoor air test results to provide context, since no indoor air testing was conducted by government agencies. However, RESP's data were sometimes incomplete and inconsistent, limiting the authors' efforts to fill in data gaps. In addition, while RESP occasionally posted individual data files online, they were often presented without interpretation. RESP's press releases and website postings were also often inconsistent with the underlying data. USEPA noted a few examples.[73] One example found by the authors was that RESP claimed to have tested creeks for all chemicals spilled from the train in drinking water two weeks after the derailment, but, in fact, they had not tested for the 25 000 gallons of 2-BE spilled during the initial response. Instead, RESP tested for 2-butoxyacetate, which was not released from the train. Human chemical exposure likely varied by location, time of day, environmental conditions, days post-incident, building ventilation, among other factors (Fig. 5). According to RESP, VOCs and SVOCs at the derailment site were removed through various methods, like soil excavation, wastewater collection and disposal, and fans. RESP attempted to limit contamination spread by using truck wheel cleaning stations, roadway pressure washing (ESI-Video 10†), but these measures were distant from direct exposure paths (*i.e.*, building vapor intrusion).

4. Implications

The results of this study provide a detailed understanding of the incident. Water was a consequential media associated with contaminant transport and human exposures found in the present study. Surface water was a primary contaminant transport pathway and natural and mechanical chemical volatilization from the waterways resulted in ambient and indoor air contamination. Stormwater culverts, including those that were directly under residential and commercial buildings, were also contaminated as surface water and runoff transported chemicals downstream. Groundwater contamination was a concern and should continue to be monitored.

The present study tested several hypotheses and revealed gaps in RESP environmental monitoring and human health protective actions.[73] Challenges with air testing efforts were also identified by others.[74] Here, we developed a descriptive characterization of chemical fate and human exposure pathways for the incident. After this study was completed, a federal investigation concluded that the open burning of the railcar products was not necessary.[75] Additionally, the U.S. Department of Justice had proposed a $310 million dollar settlement with Norfolk Southern to address some needs such as costs for cleanup, health monitoring, rail safety improvements, and a civil penalty.[37] Though, objections were asserted about the settlement by several parties including the Commonwealth of Pennsylvania noting deficient support for present and future health impacts as well as health and environmental monitoring provisions.[76,77]

The application of several analytical techniques (*e.g.*, GC/MS, LC/HRMS, LC/MS) enabled the authors to develop new knowledge, but the full extent of chemicals released, and their byproducts remains unclear due to the lack of thorough RESP testing. The author's February review of the RESP ambient air, creek water, municipal drinking water, and private well water monitoring results revealed officials were not testing for all the chemicals in water publicly declared having been released from the train (*e.g.*, 2-BE). Additionally, past disasters have shown that the chemical composition of substances declared on a material safety data sheet may compositionally differ greatly from those at a chemical spill event.[78] This underscores the need to conduct a detailed scan of all products associated with the chemical release *before* beginning the wide area environmental monitoring process and making broad safety claims. The approval of handheld PIDs and the lifting of the evacuation order with inadequate air testing allowed for human chemical exposures. Indoor air chemical specific sampling, identification, and quantification is recommended to understand health risks for these incidents.

Numerous lines of evidence documented in the Ohio and Pennsylvania public health surveys confirmed that exposures occurred even after the evacuation order was lifted. Symptoms included impacts to the nose, throat, nervous system, lungs, and eyes among workers and the public.[18,50] Since the present study was completed, the rail company and a contractor were cited for failing to protect workers from chemical exposure and not restricting spill site access.[79,80] The USEPA also released a cleanup work plan.[81] This plan noted that odors associated with the incident were detected inside buildings near the derailment site, and that vapor intrusion VOC monitoring and PFAS sampling were planned. Furthermore, the area of concern was expanded beyond the derailment site, reaching more into East Palestine. The work plan, however, did not identify any efforts to investigate contamination in residential buildings between the contaminated East Palestine Municipal Building and derailment site. There were more than 130 buildings within 100 m of Sulphur Run and some were contaminated by vapor intrusion and aeration activities. The USEPA did order continued waterway remediation for contamination described in the present study.[82] Because the area of concern was expanded beyond the derailment site and contamination traveled outside the shelter-in-place zone, there is a need for more precise public safety guidance following hazardous material incidents.[83] The Emergency Response Guidebook recommends a 1 mile evacuation in all directions for a single VC railcar involved in a fire.[83] However, only a 1 mile evacuation area was applied

for all five VC railcars burned in East Palestine. In some cases, inadequate and incorrect information prompted residents and businesses to lose confidence in authorities and take their own protective actions.[84]

Multiple chemical exposure pathways were identified including those caused by the RESP. Persons in buildings situated near and directly above contaminated creeks, as well as the nearby area, were likely the most chemically exposed. Aeration equipment used along Sulphur Run and Leslie Run discharged chemicals into the air, and creeks were sometimes located less than 5 ft from buildings. Laboratory bench tests showed that aeration effectiveness depended on the chemical and concentration. It is well-known that VOCs can remain in buildings for months after a disaster, and to remove them requires professional cleaning of carpets, ducts, and other personal items.[85–87]

The human health and environmental impacts caused by this incident warrant further investigation and continued monitoring. While the present study was limited by the methods applied as well as spatial and temporal sampling locations, findings here also identified numerous RESP gaps. The complexity, magnitude, and health threats posed to the community, workers, and visitors were not matched by the RESP efforts. The population experienced exposures for months and town visitors also experienced health symptoms. At least nine other groups have initiated post-disaster studies on the topics of creek water, soils, indoor surfaces, biomonitoring, and social science.[88–94] Community economic and mental health consequences are expected to continue as uncertainty remains about contamination and health impacts.[50,95]

To better protect human health and the environment in response to chemical incidents, the following actions should be conducted before a future incident: (1) develop a formal approach for rapid chemical characterization of complex matrices to provide initial chemical assessments, (2) develop a formal approach to investigate building exterior contamination by rapidly testing structures, (3) design indoor air and surface sampling protocols to rapidly characterize particulates and other contaminants that may reside in buildings, (4) develop spill response technologies that more effectively and safely remove VOCs from surface water, (5) create a model to predict chemical emissions and resulting nearby human exposures from heavily contaminated creeks and streams into air with and without mechanical aeration, and (6) create evidence-based decision making processes to protect worker and public safety following chemical disasters. Once an incident occurs, (1) identify all potential contaminant pathways and exposures (Fig. 5), (2) chemically characterize the raw materials spilled so that subsequent environmental testing can be optimized to protect health and maximize financial and labor resources available, (3) rapidly and continually make test results public and provide an accessible explanation of their significance and limitations, (4) quantitate the magnitude of chemical mass transfer for the affected natural and built environments, (5) consider issuing building safety warnings and consider decontamination principles applied following wildfires for smoke impacted carpet, upholstery, personal effects, HVAC system, and surfaces,[87] and (6) rapidly reevaluate contaminant pathway and exposure assumptions based on population feedback, third-party evidence, and actions by RESP to best protect public and occupational health. Recommendations provided should help guide response decision-making to limit the potential health and environmental impacts of future incidents.

Data availability

The data supporting this article have been included as part of the ESI.†

Conflicts of interest

The authors declare no conflicts of interest. Some preliminary results were shared with government agencies and the public as they were generated, and agencies considered them in their decision-making processes. Data created by third parties (*e.g.*, government agencies, private companies) and cited in this study were presented as-is. It is assumed that additional information may exist in legal proceedings that may or may not ever be made public. This could include chemical formulations, properties, exposure, toxicity, and medical data, soil as well as in-building testing air, surface, water quality, and medical results. The authors do not represent a legal position in litigation related to this spill or fires. At the time this study was completed, the National Transportation Safety Board, State of Ohio, Commonwealth of Pennsylvania, USEPA investigations, and more than 30 lawsuits were ongoing.

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