ATTACHMENT E

ATSDR Survey Results

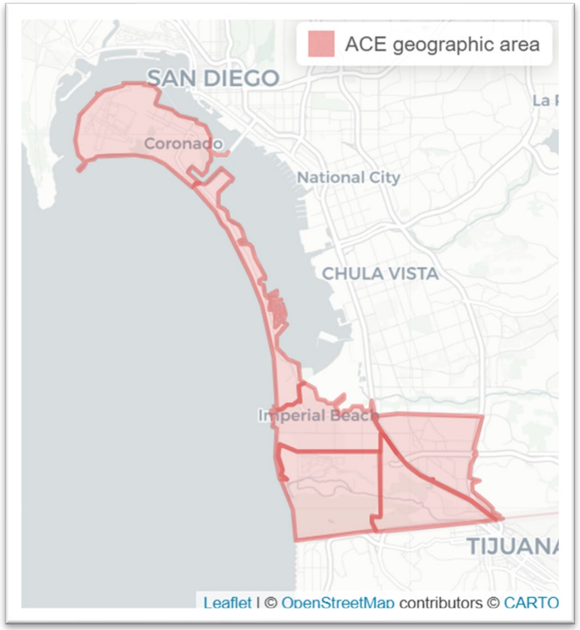
Centers for Disease Control and Prevention (CDC), Agency for Toxic Substances and Disease Registry (ATSDR), and San Diego County

Community Health Survey, October 2024

SANDIEGOCOUNTY.GOV/SOUTHREGIONHEALTH

About

- To assess the community health impact of the Tijuana River Valley Sewage Crisis, the County of San Diego (CoSD) and the Centers for Disease Control and Prevention (CDC) Agency for Toxic Substances and Disease Registry (ATSDR) created a community survey adapted from the ATSDR Assessment of Chemical Exposure (ACE) toolkit.



Sampling frame showing survey coverage

About

Why conduct an ACE investigation?

- Collect individual-level responses.
- Include open-ended questions.
- Obtain parents' responses on behalf of their children under 18 years old.
- Participation beyond local residents, including people who worked in or visited the affected area for recreation.
- Allow participants to participate at their own convenience.

About

COMPLETED SURVEYS

2,099

Surveys analyzed

SURVEY PARTICIPATION

99%

Of surveys completed online

86%

Of participants reported home as the most common reason for being in the affected area

Demographics

8%

Completed survey in Spanish

19%

Were in the 50 – 59 age group

66%

Respondents were female

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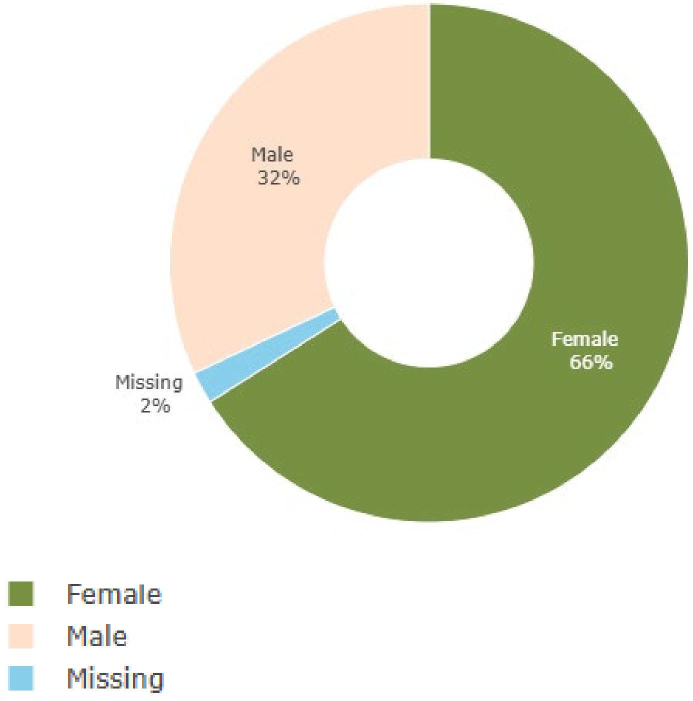
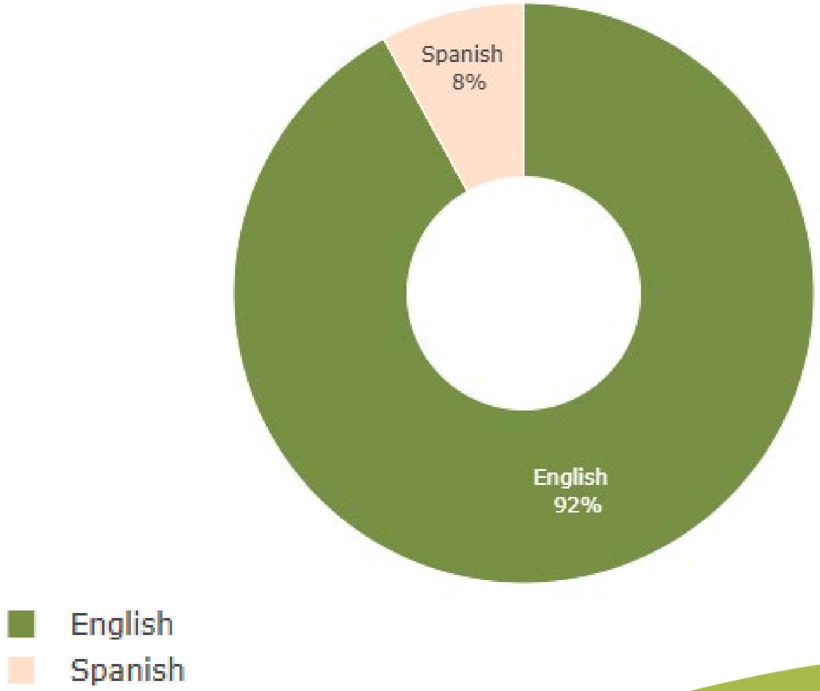
Demographics

Sex



Language survey was completed in



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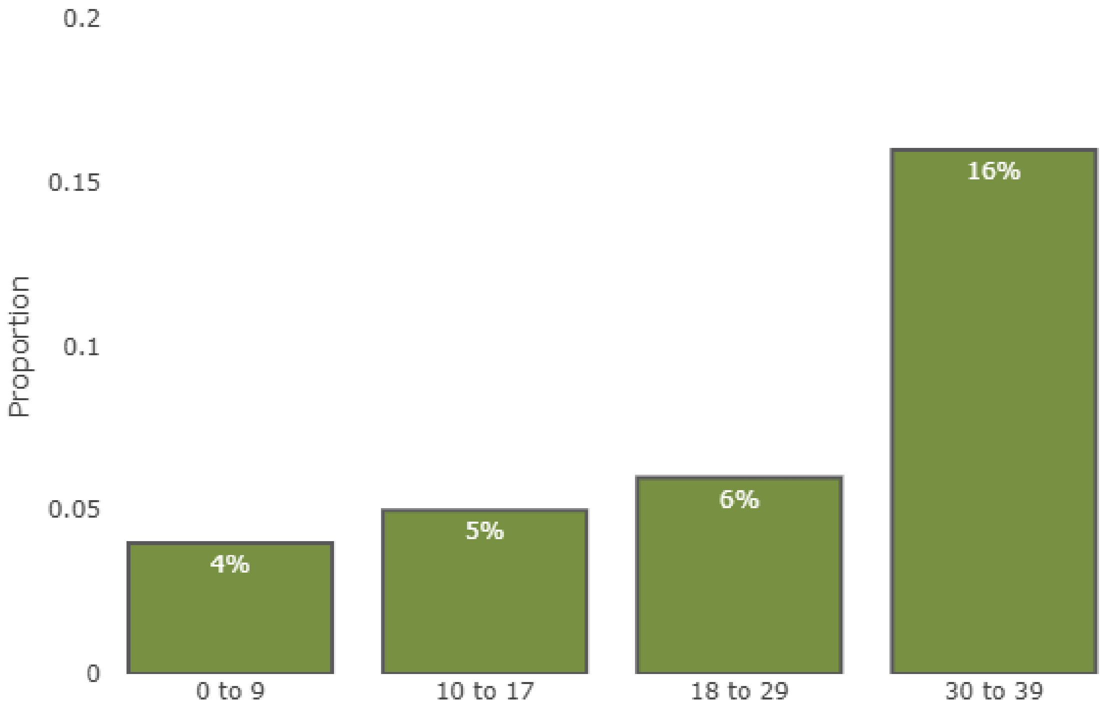
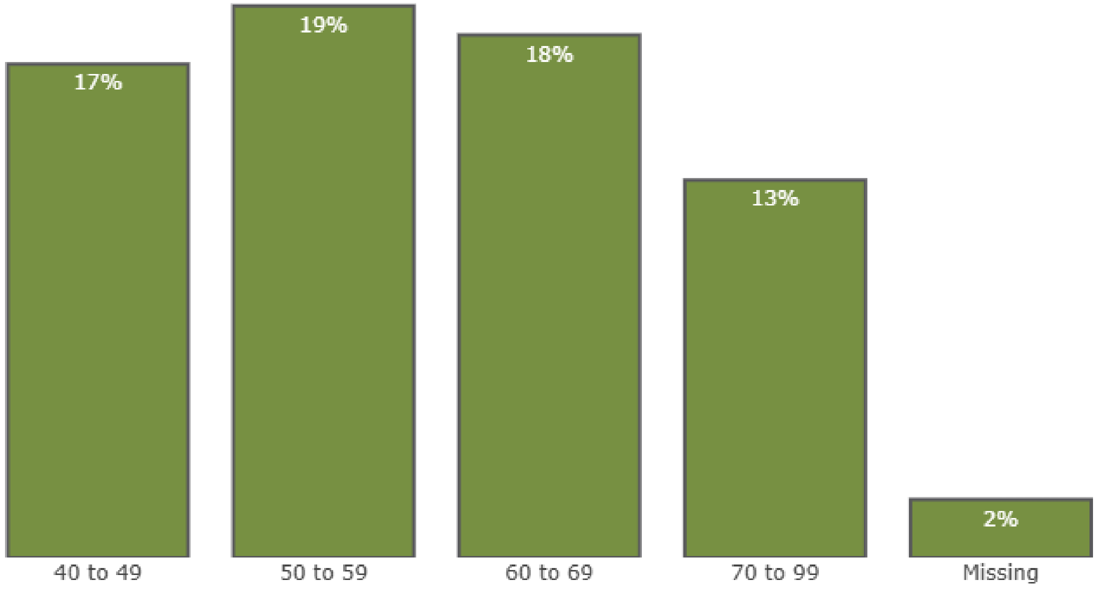
Demographics

Age



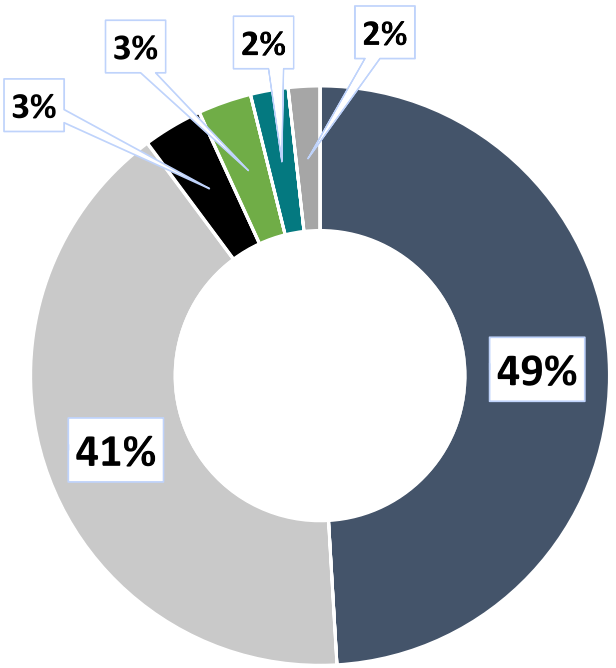
Demographics

Age (Continued)



Demographics

Race & Ethnicity

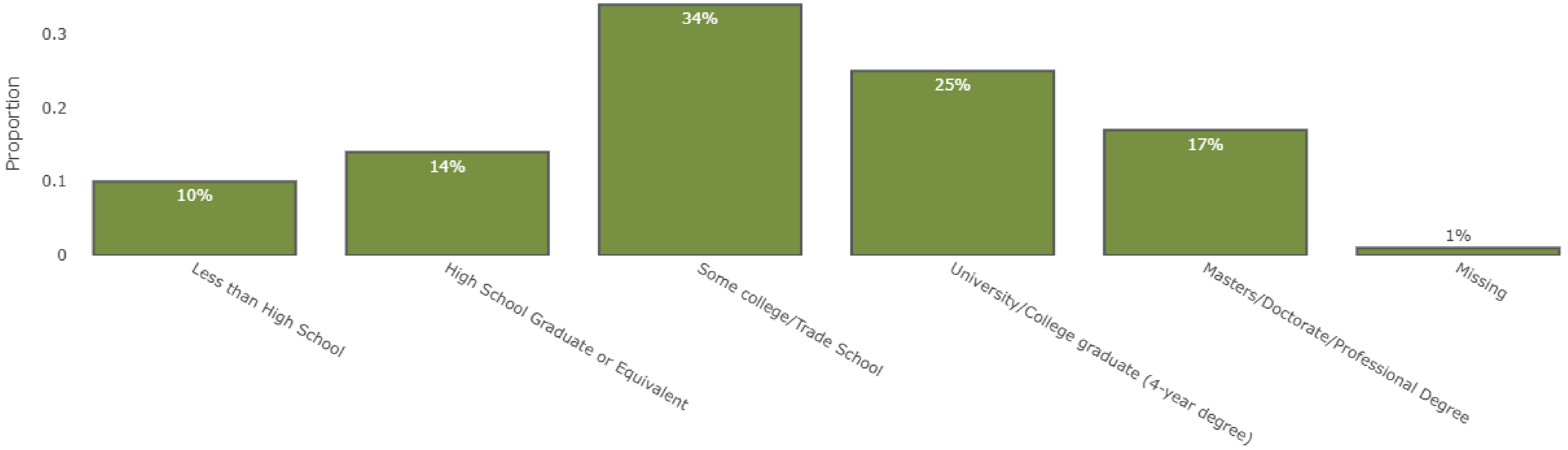


- Hispanic/Latino (n = 1,003)
- White* (n = 833)
- Asian* (n = 68)
- Multiracial*(n = 61)
- Black/African American* (n = 43)
- Other** (n = 36)

*Non-Hispanic; **Includes non-Hispanic Native Hawaiian or Pacific Islander, American Indian or Alaska Native, and Middle Eastern or North African

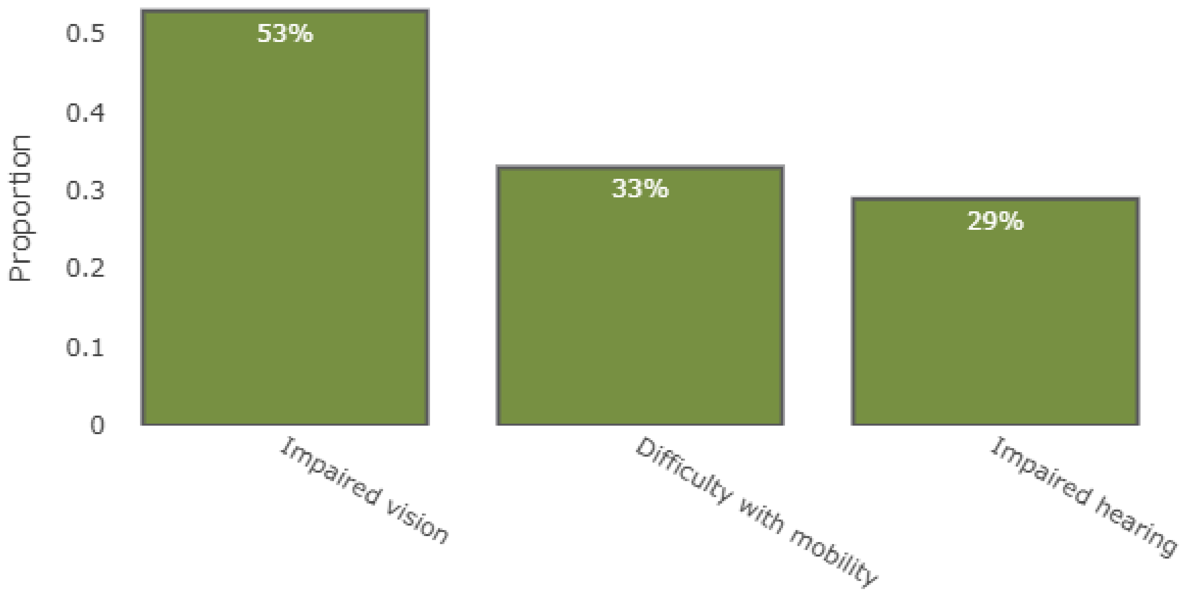
Demographics

Highest Level of Education



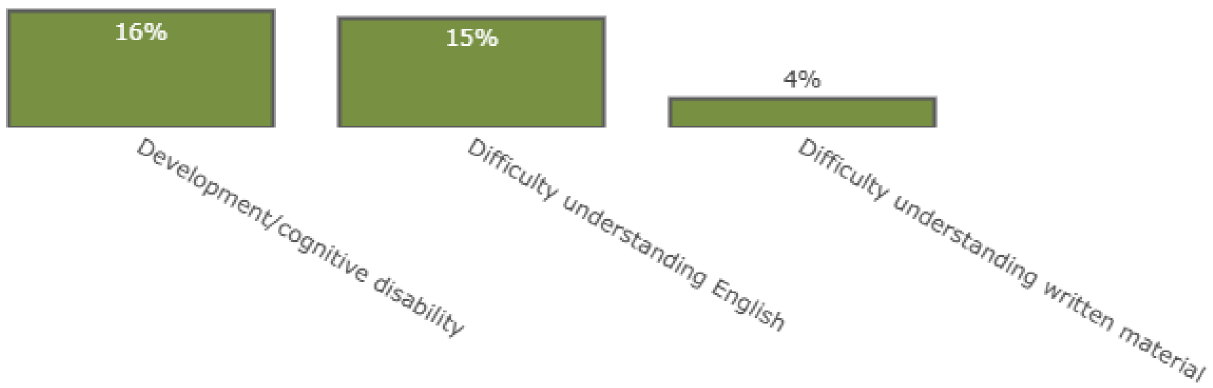
Demographics

Do you have any of the following impairments?



Demographics

Do you have any of the following impairments? (Continued)



Reason for Visiting the Area

86%

Of people live in the affected area

21%

Of people spent time in the affected area for work

31%

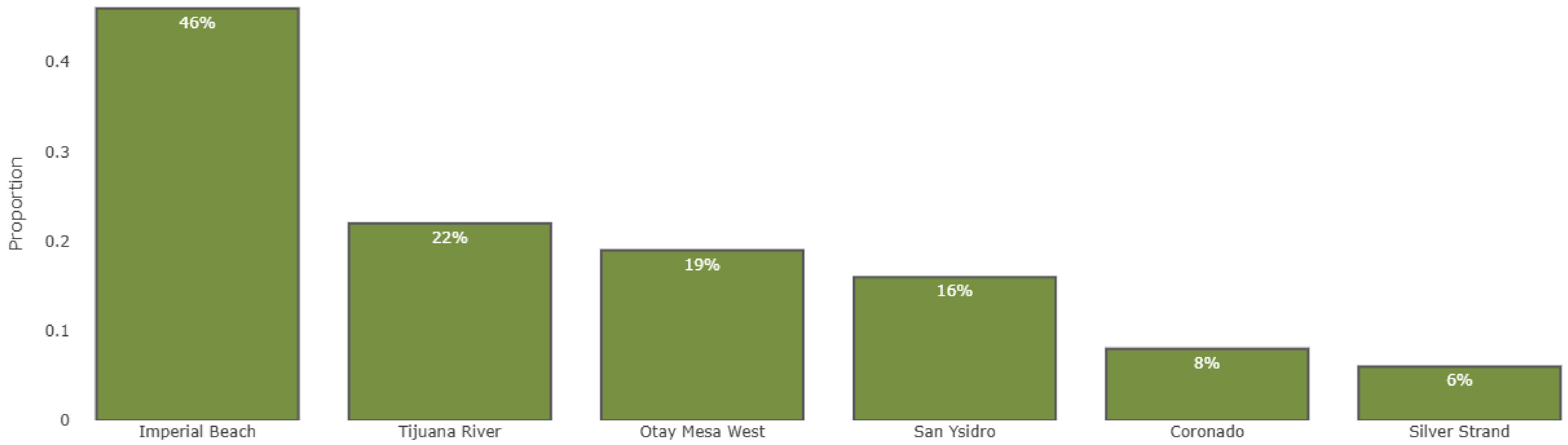
Of people spent time in the affected area for recreation

16%

Of people spent time in the affected area for school/daycare

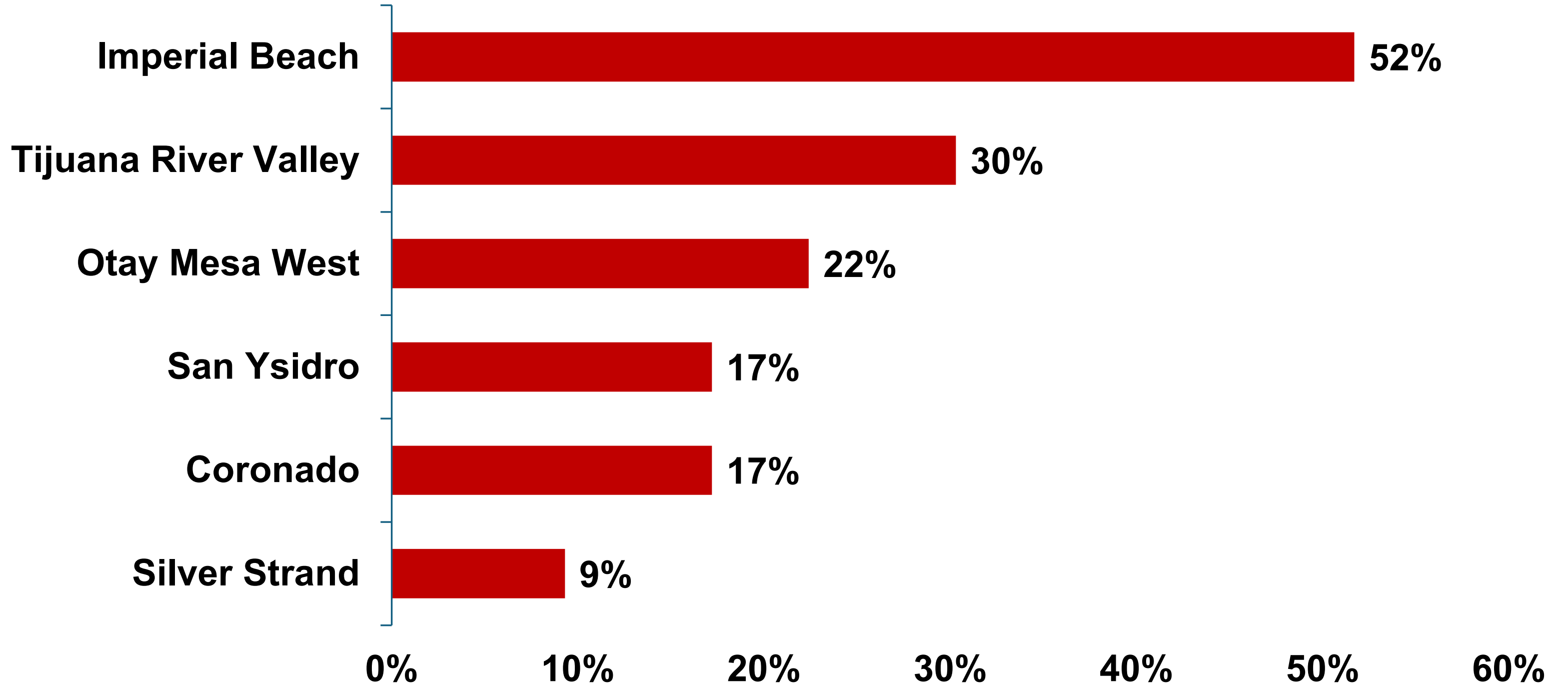
Reason for Visiting the Area

In the past 30 days, in which zone did you/your child live in?



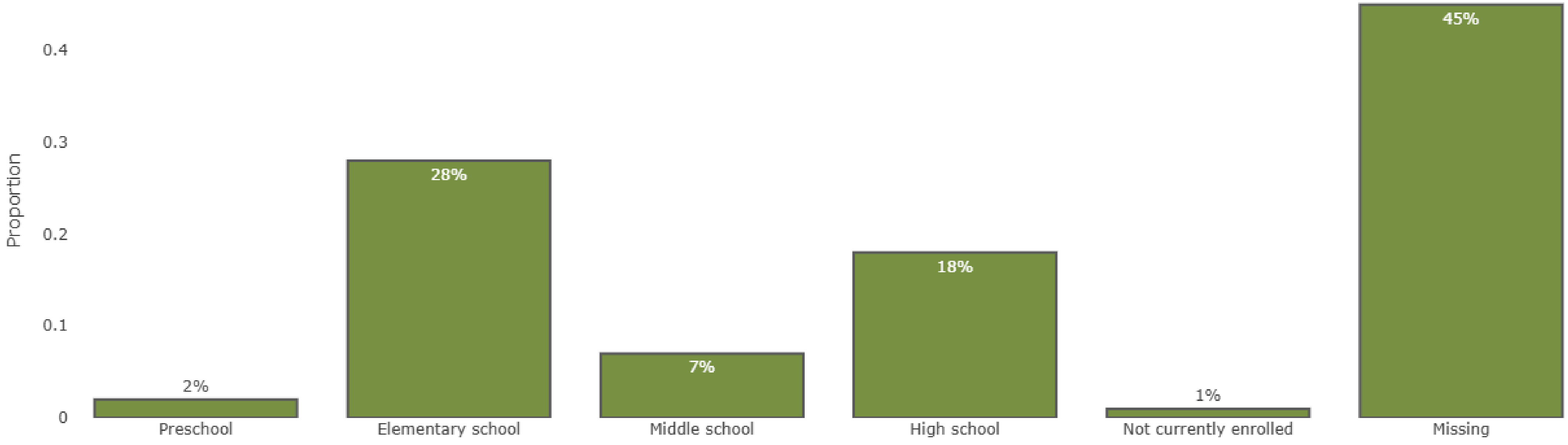
Reason for Visiting the Area

Areas of Work



Reason for Visiting the Area

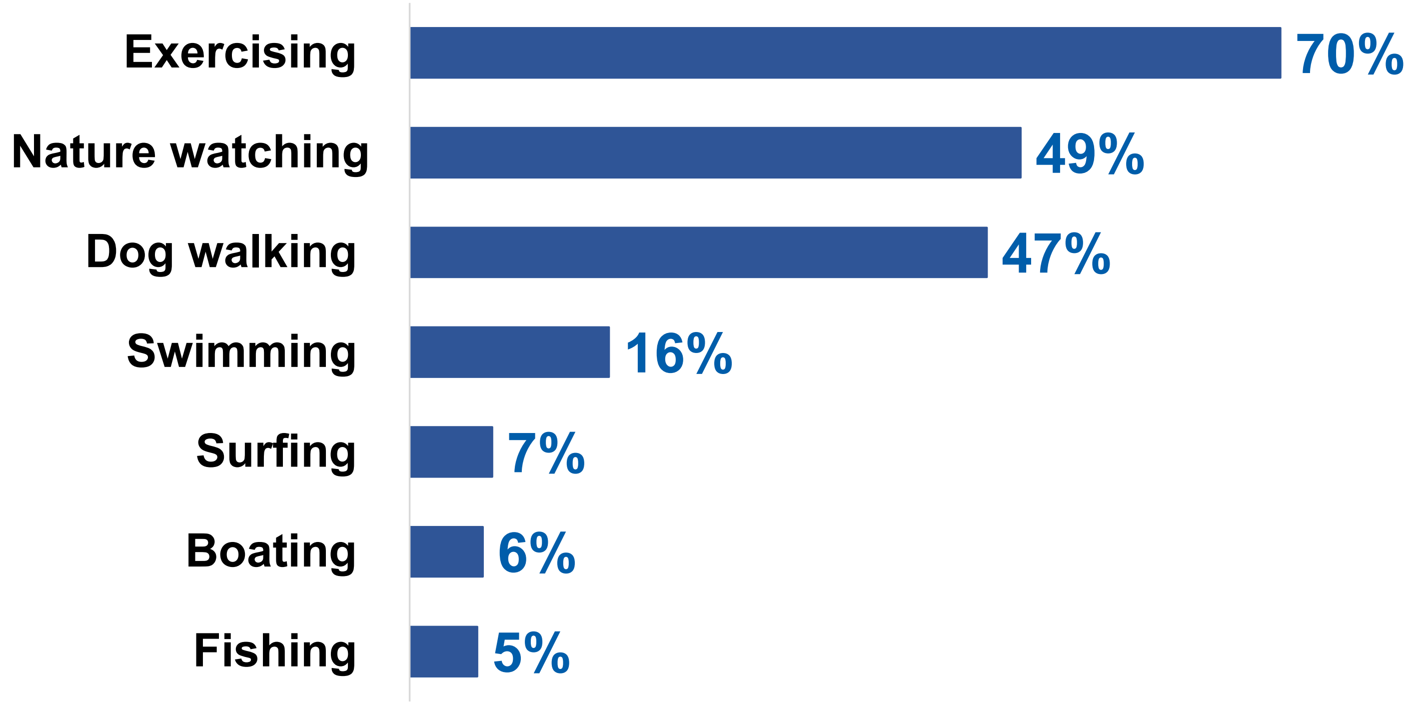
Is your child attending any of the following schools?



LIVE WELL SAN DIEGO

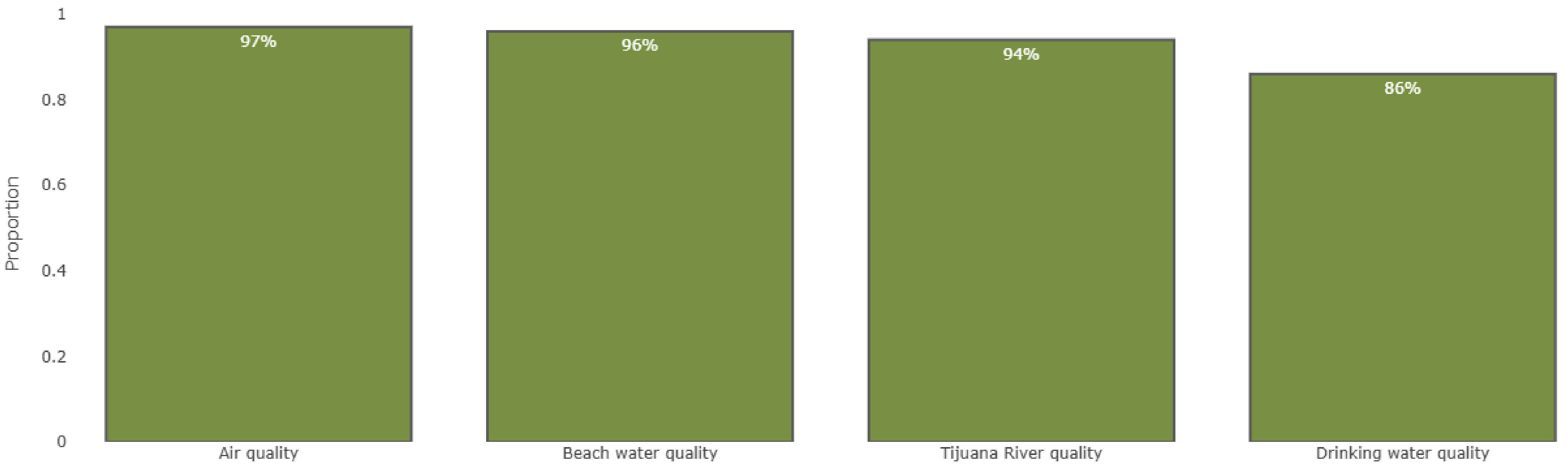
Reason for Visiting the Area

In the past 30 days, what recreational activities were you/your child doing in the affected area?



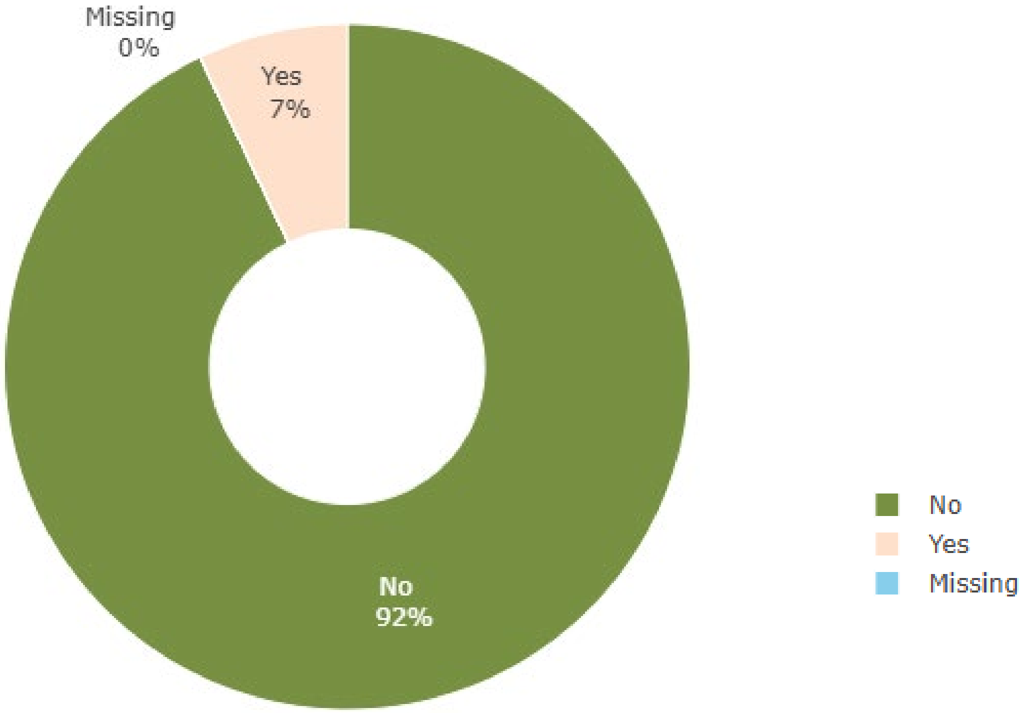
Concerns and Disruptions

Because of the sewage crisis, are you concerned about the:



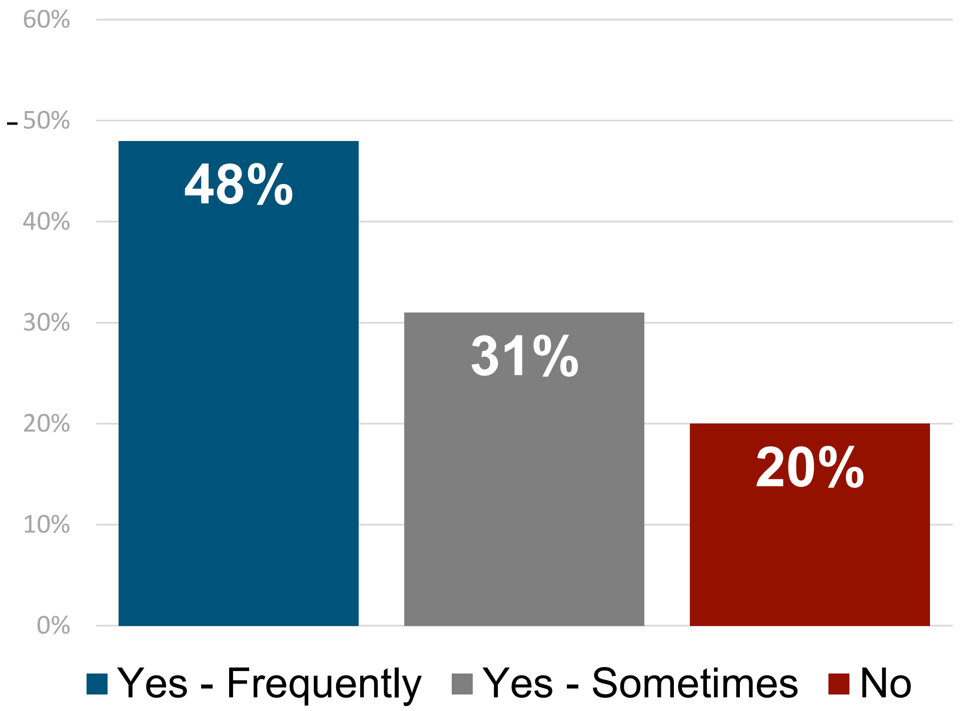
Concerns and Disruptions

Do you/your child believe the affected area is a safe place to visit, work, or live?



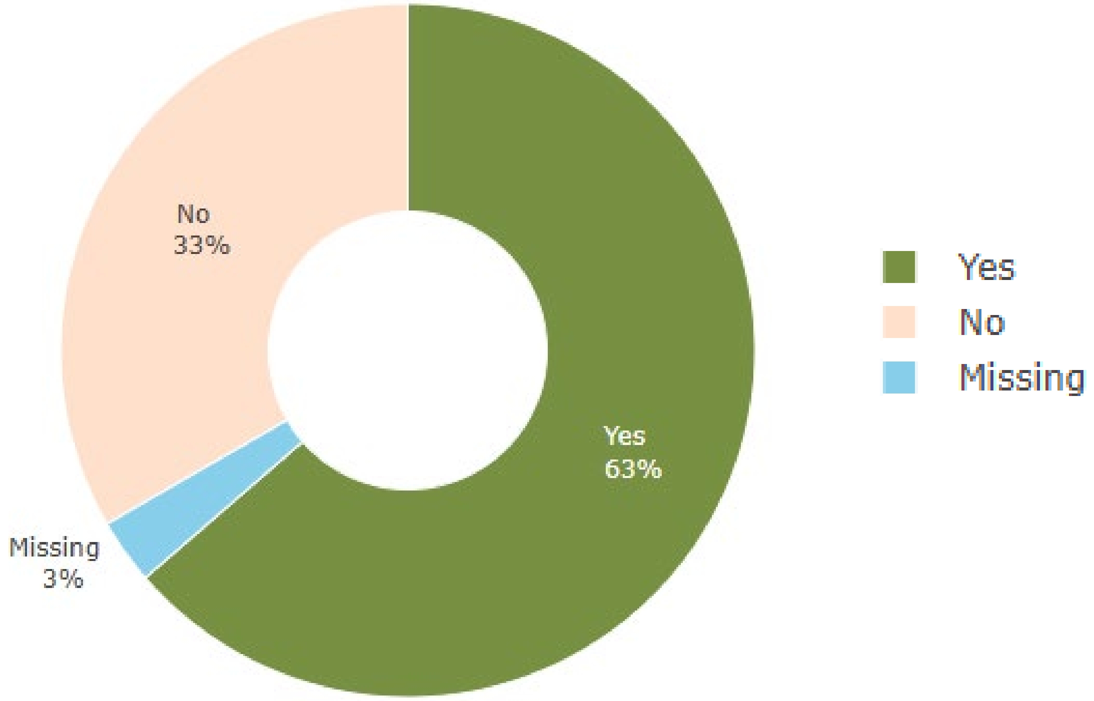
Concerns and Disruptions

In the past 30 days, have you/your child taken extra steps to avoid the affected area (or any part within the affected area) because of the Sewage Crisis?



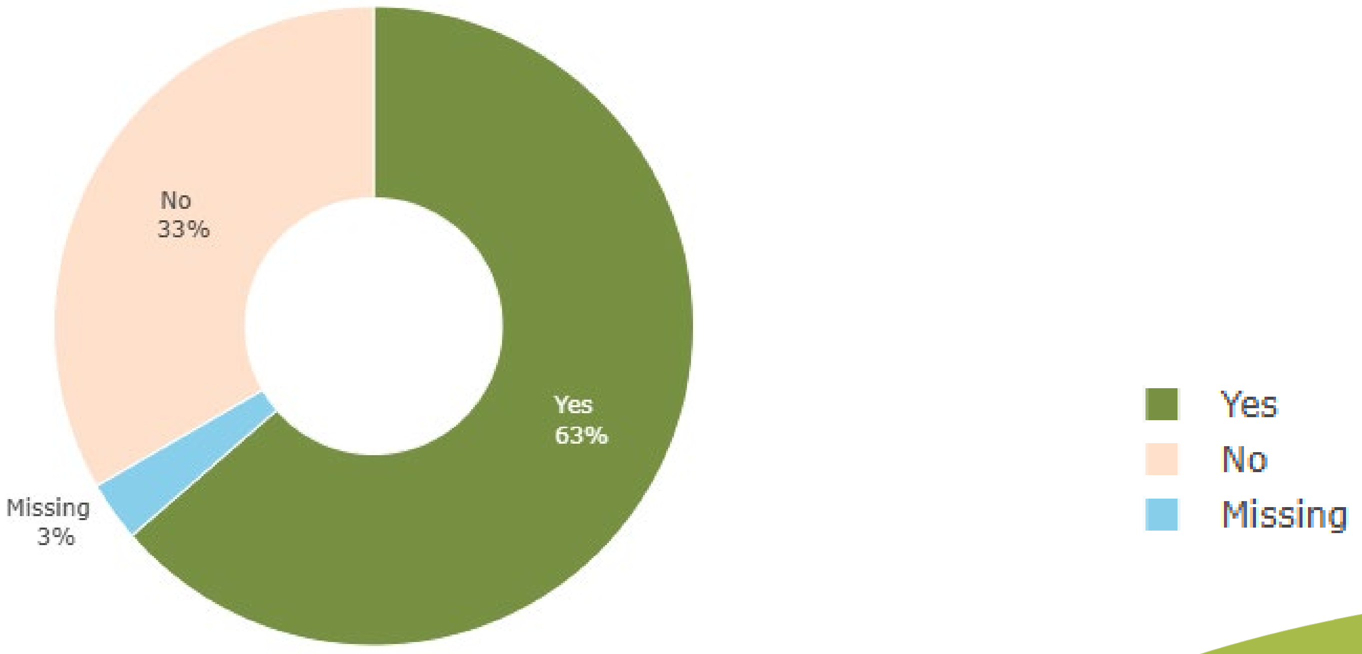
Concerns and Disruptions

In the past 30 days, did your child miss school/daycare due to symptoms they experienced that you believed are related to the Sewage Crisis?



Concerns and Disruptions

In the past 30 days, did you miss work due to symptoms you experience that you believe are related to the Sewage Crisis?



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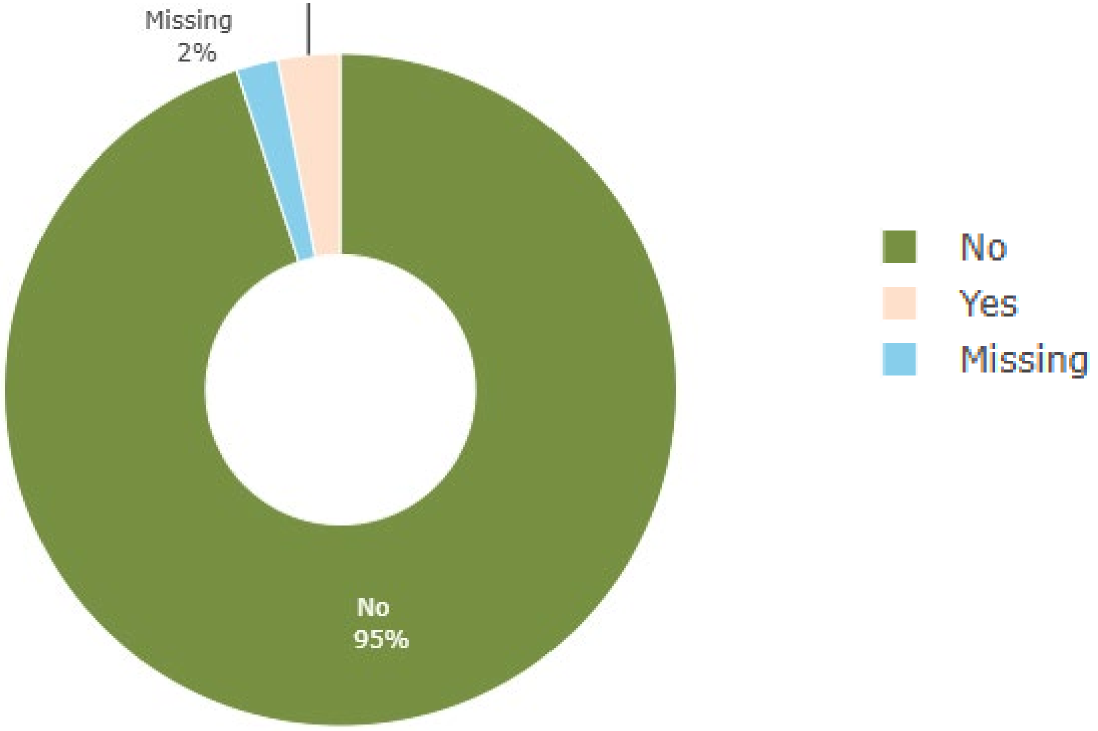
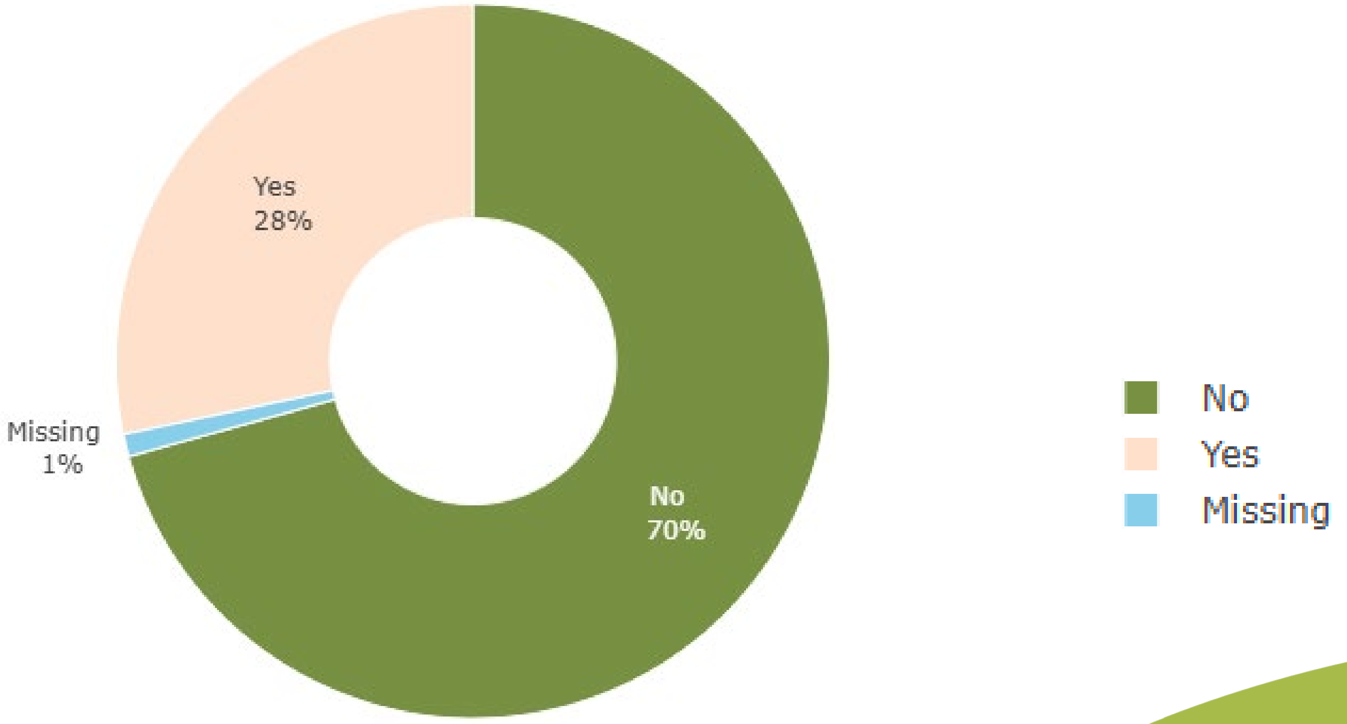
Concerns and Disruptions

In the past 30 days, have you/your child changed jobs/schools because of the Sewage Crisis?



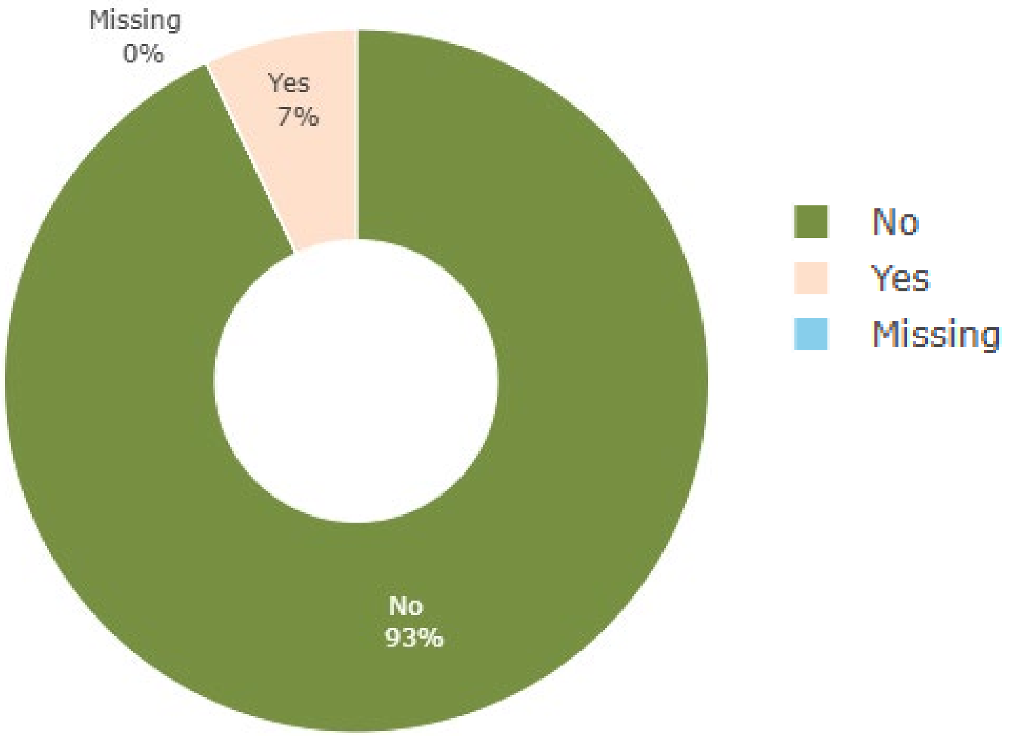
Concerns and Disruptions

Are you/your child thinking about changing jobs/schools because of the Sewage Crisis?



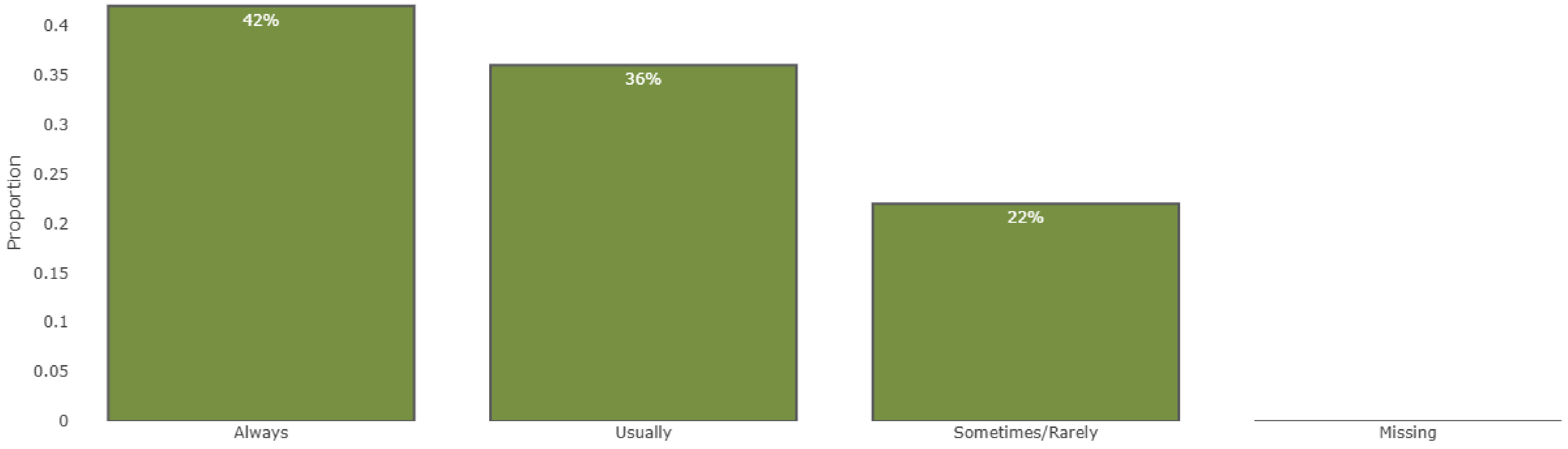
Concerns and Disruptions

Do you/your child believe the sewage cleanup in the affected area is sufficient?



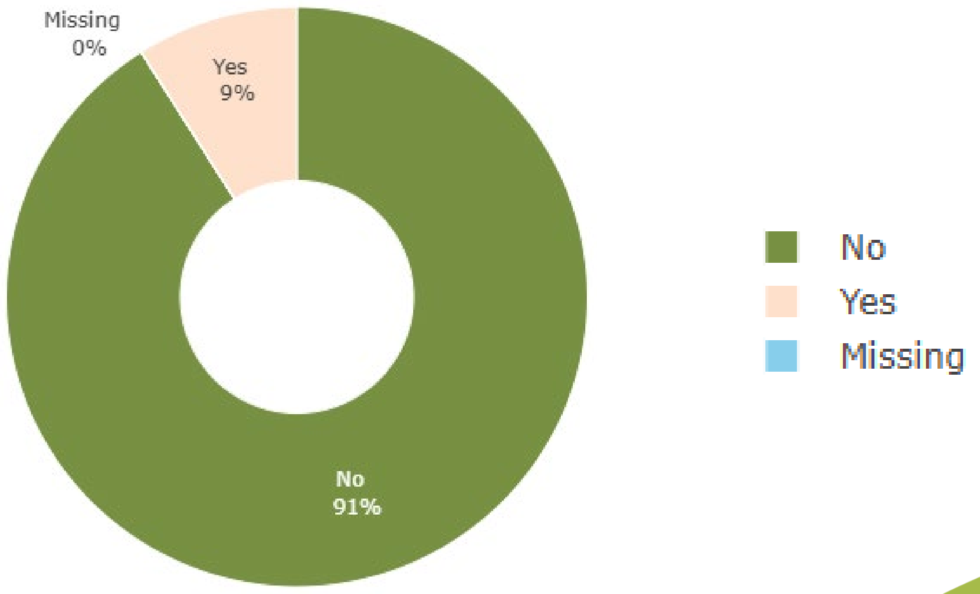
Smell Frequency and Direct Contact with Contaminated Water

In the past 30 days, how often did you/your child notice the sewage smell in the affected area?



Smell Frequency and Direct Contact with Contaminated Water

In the past 30 days, have you/your child had any direct contact with water from the Tijuana River? (Direct contact is defined as Tijuana River Valley Don't know water touching your skin, eyes, or getting inside your mouth or nose)



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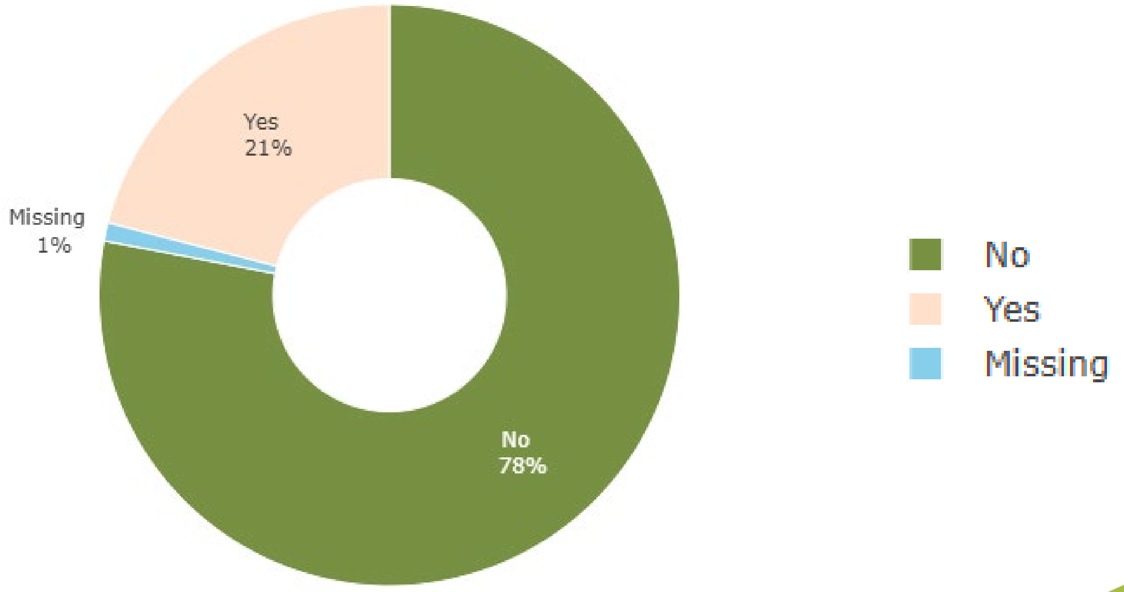
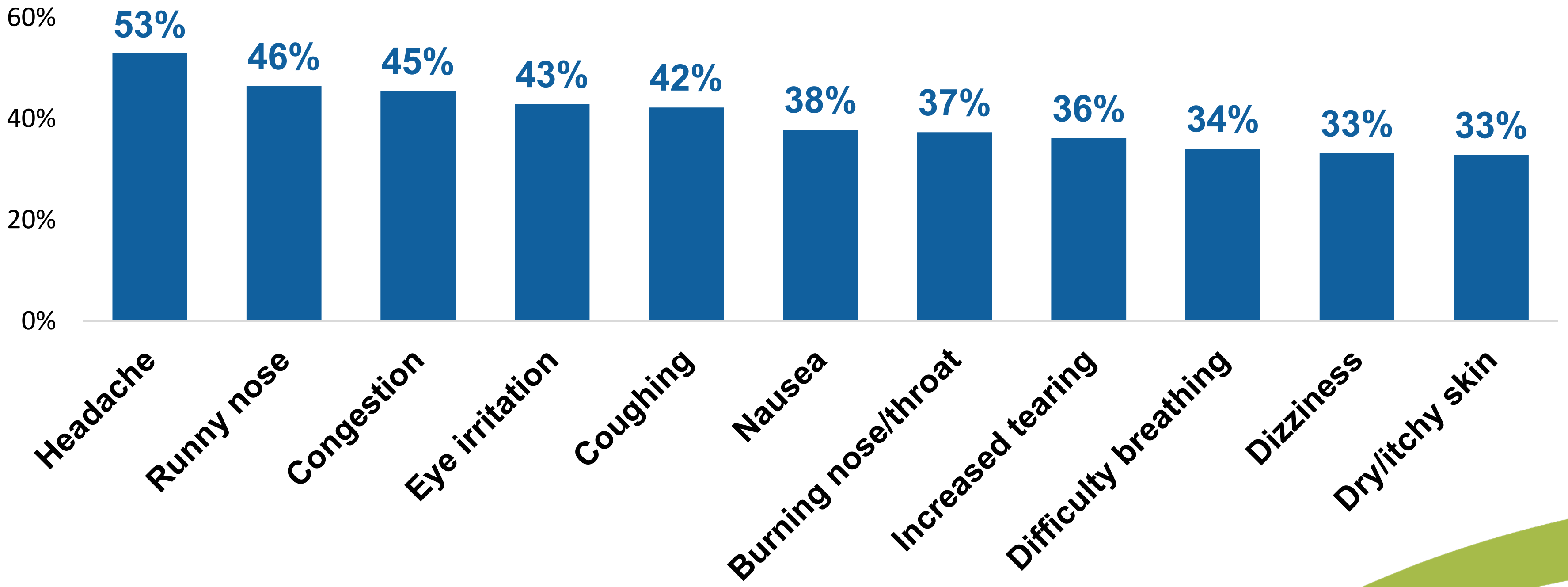
Smell Frequency and Direct Contact with Contaminated Water

In the past 30 days, have you had any direct contact with beach water from Tijuana Slough, Imperial Beach, Silver Strand shorelines, or Coronado beaches while these beaches have been closed?



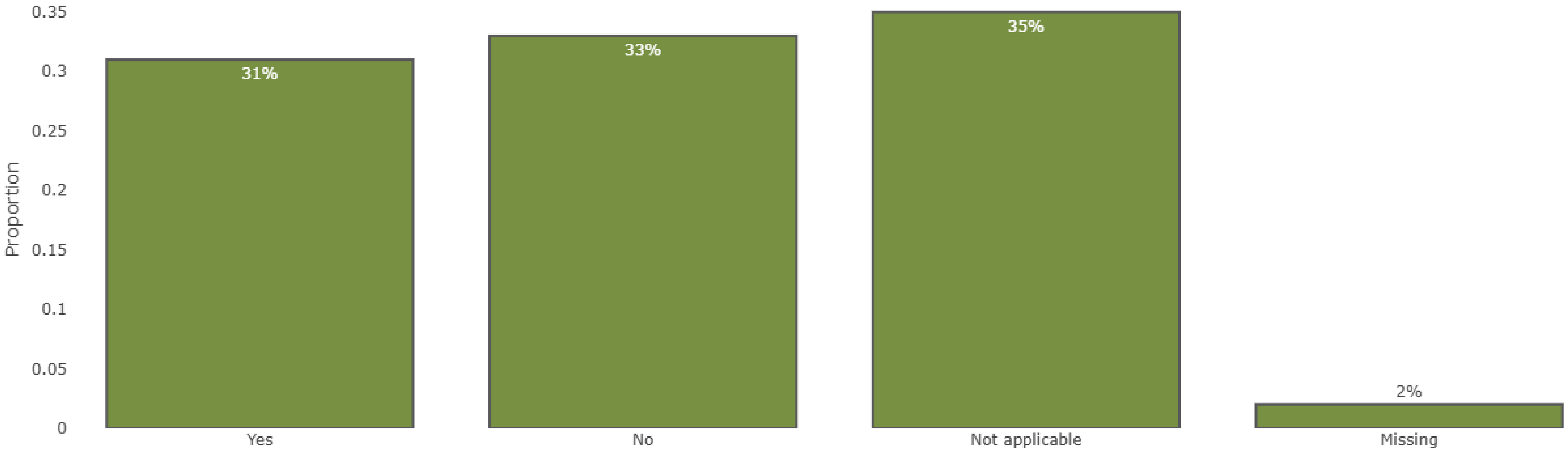
Physical Health

In the past 30 days, have you had any of the following health symptoms you believe are because of the Sewage Crisis?



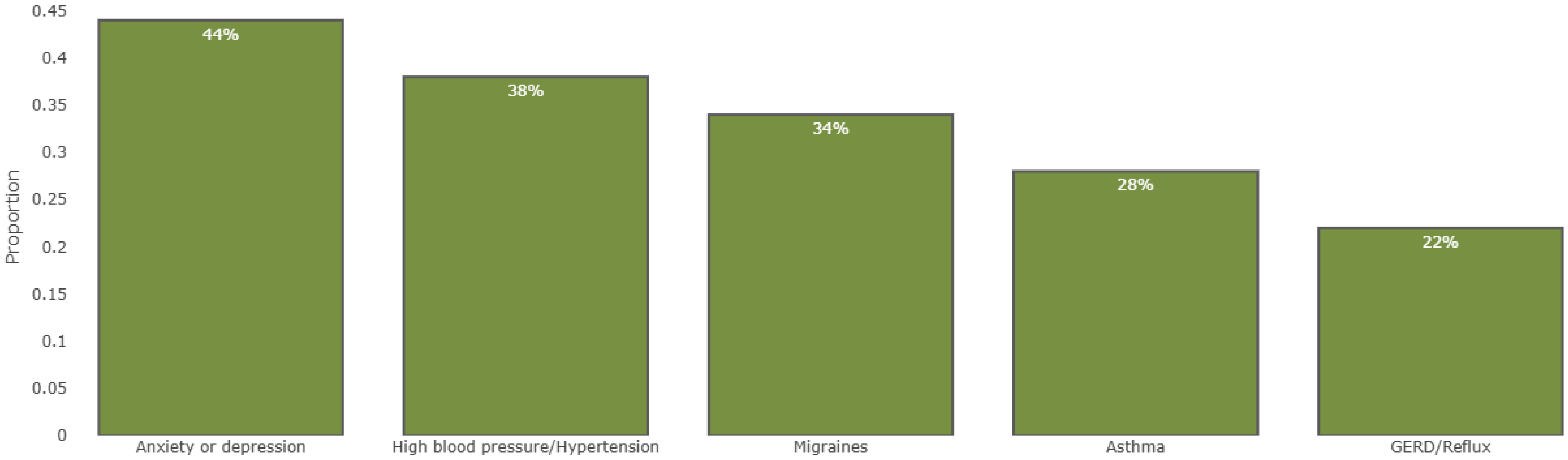
Physical Health

In the past 30 days, has your/your child's health symptoms related to the Sewage Crisis gotten better when you spent time away from the affected area?



Physical Health

Have you been diagnosed with any of the following health conditions?

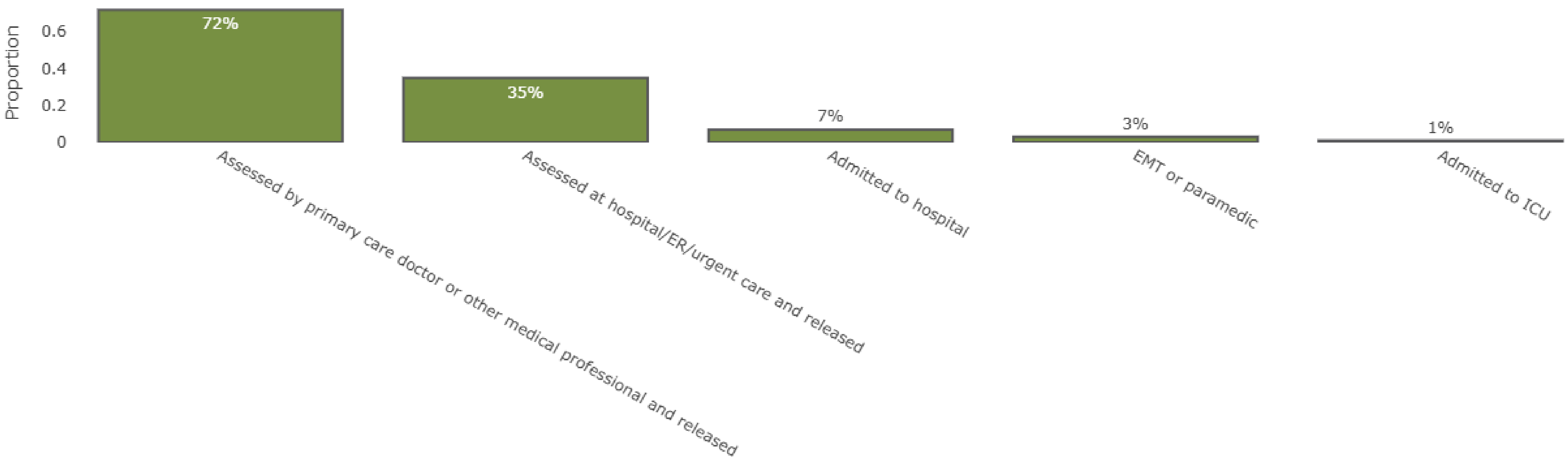


Physical Health

In the past 30 days, have any of your previously diagnosed health conditions worsened?

Physical Health

Type of medical care among those reporting seeking/receiving medical care



Behavioral Health

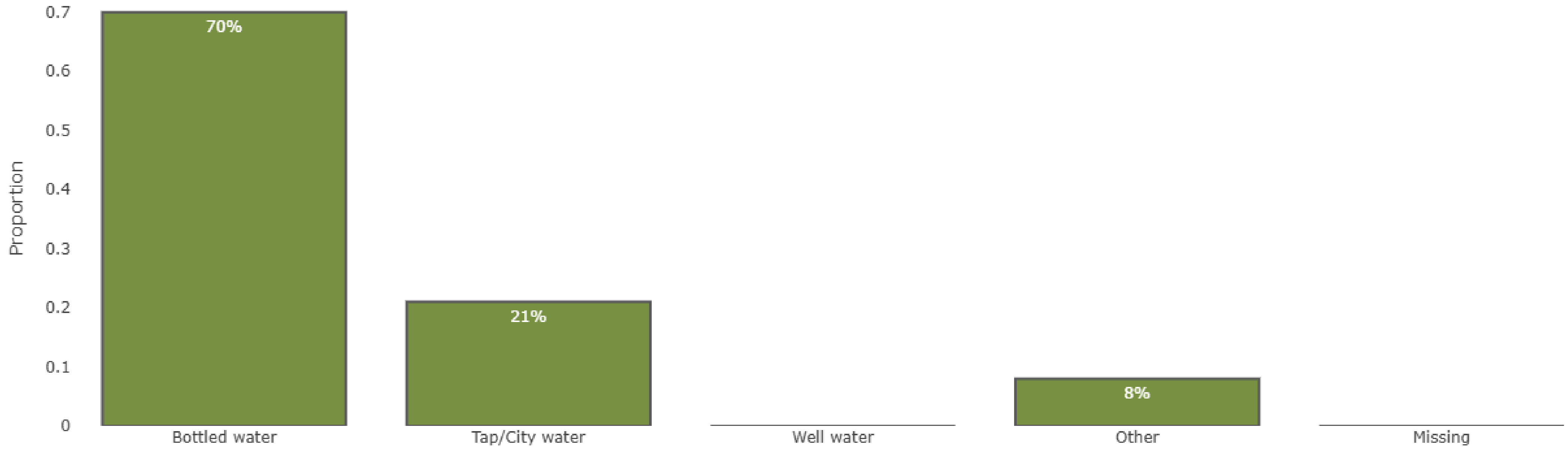
Anxiety Screener: In the past 2 weeks would you have been identified as a possible cases for generalized anxiety disorder for which further diagnostic evaluation would be warranted? (*note this is a score generated from a series of questions modified from the GAD-2)

Behavioral Health

Depression Screener: In the past 2 weeks would you have been identified as a possible cases for depression for which further diagnostic evaluation would be warranted? (*note this is a score generated from a series of questions modified from the GAD-2)

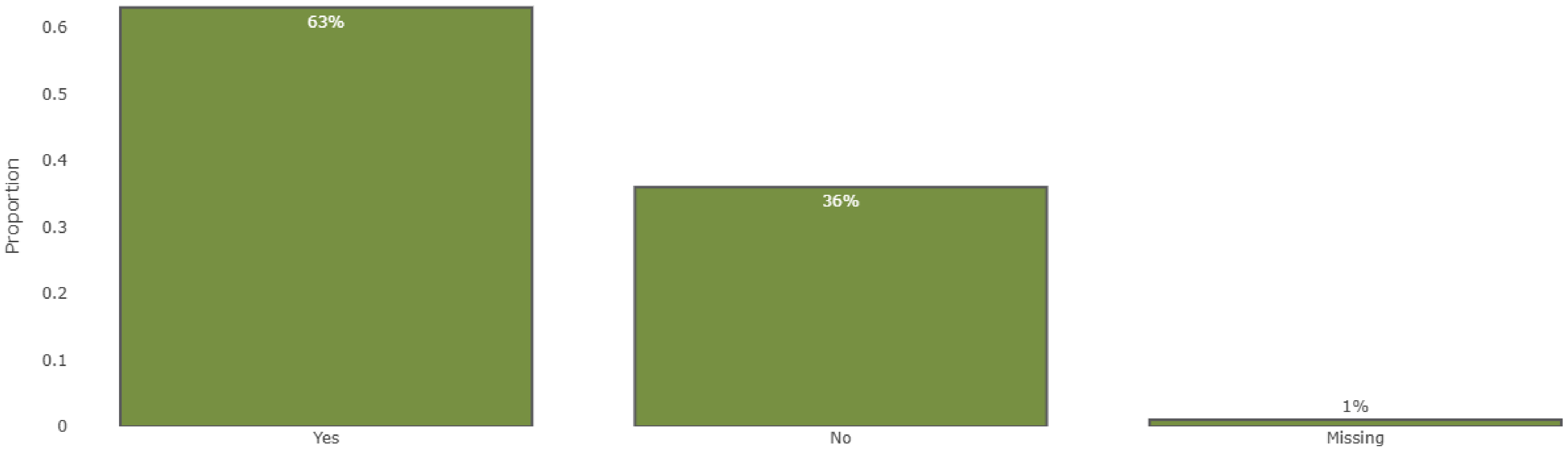
Drinking Water Analysis

When you/your child spend time in the affected area, where do you/your child get most of your drinking water?



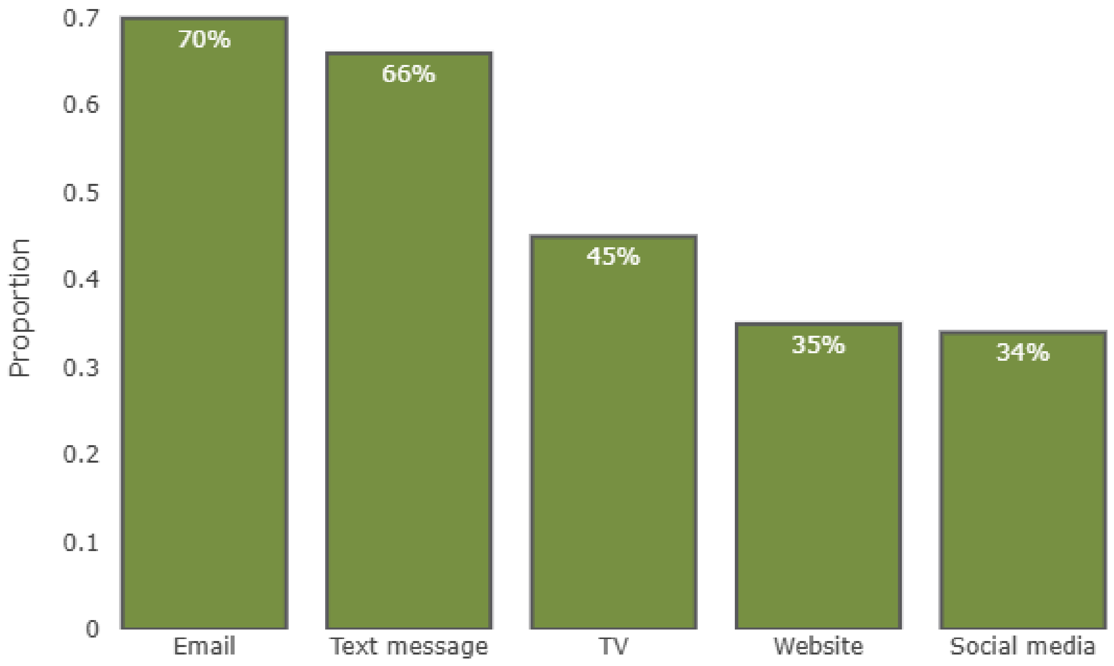
Drinking Water Analysis

Do you filter your drinking water?



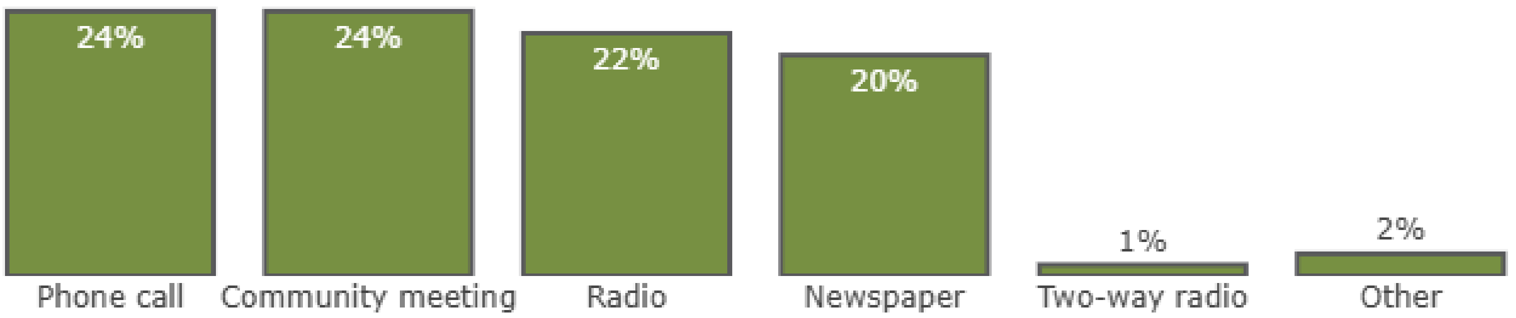
Communication Preferences

Moving forward, what are the best ways for local authorities or the health department to reach you with information regarding the Sewage Crisis?



Communication Preferences

Moving forward, what are the best ways for local authorities or the health department to reach you with information regarding the Sewage Crisis? (Continued)



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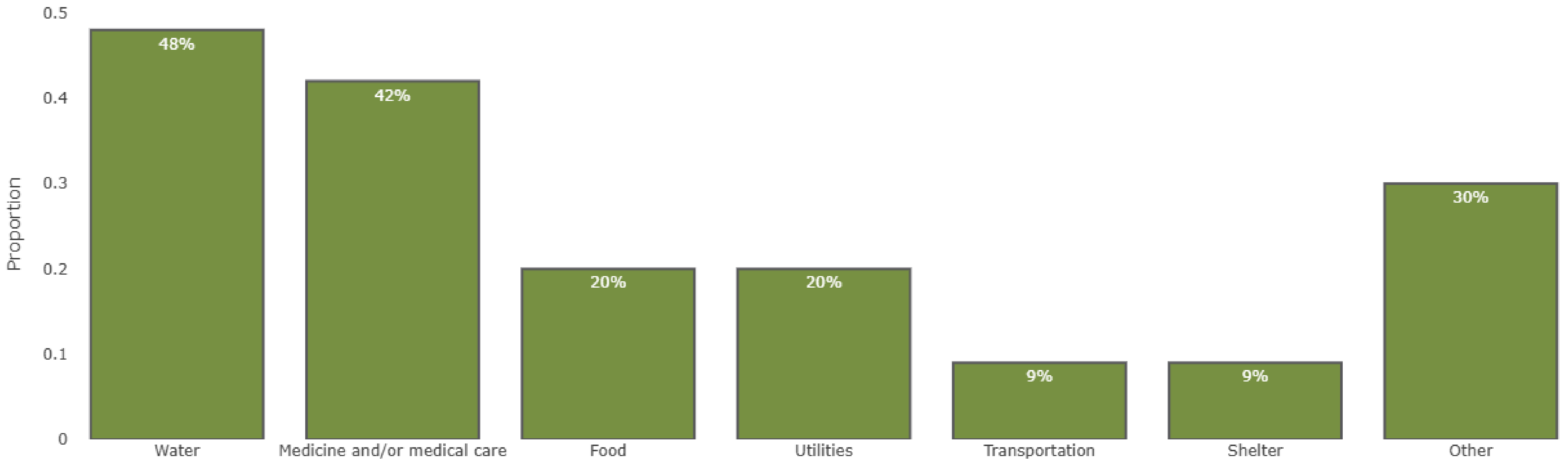
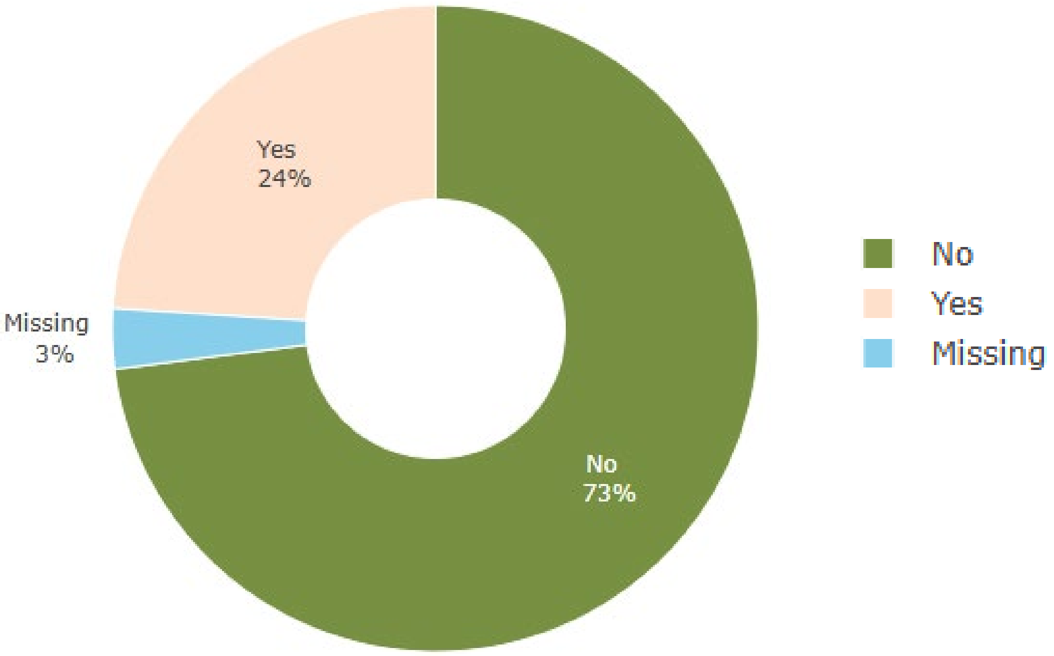
Unmet Needs

As a result of the Sewage Crisis, are you in need of any of the following?



Household Pets

In the past 30 days, have you owned, fostered, or boarded any pets (dogs, cats, birds, fish, reptiles etc.) with health symptoms you believe are due to the Sewage Crisis?



THANK YOU

For more information, contact the Health & Human Services Agency at phs.southregionhealth.hhsa@sdcounty.ca.gov

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The Public Health Services department, County of San Diego Health and Human Services Agency, has maintained national public health accreditation, since May 17, 2016, and was re-accredited by the Public Health Accreditation Board on August 21, 2023.

ATTACHMENT E

Tijuana River Valley Community Assessment for Public Health Emergency Response (CASPER)

October 2024

6 January 2025

South Region, San Diego County

Table of Contents

Executive Summary

The Tijuana River Valley has been severely impacted by contamination from untreated sewage, urban runoff, and industrial waste for decades. Over the past five years, over 100 billion gallons of pollutants have been discharged into the Tijuana River, raising major concerns about water quality and public health in the San Diego region. This pollution, primarily from raw sewage flowing into the Tijuana River Valley and nearby beaches, affects both the environment and human health.

The situation worsened with Tropical Storm Hilary in August 2023, which led to a boil water advisory issued by the California-American Water Company and prompted an immediate public health assessment by the County using data from various sources. Further complications arose from severe flooding caused by an atmospheric river in January 2024, which intensified the sewage contamination.

The crisis has drawn significant attention from public health officials and elected representatives, leading to ongoing efforts by federal, state, and local agencies to address the contamination through improved wastewater treatment, regulatory oversight, and international cooperation. However, residents continue to face challenges, including unpleasant odors, perceived poor air quality, increased health concerns, and disruptions to daily activities, impacting their overall quality of life.

In response to the ongoing crisis, the County of San Diego Health and Human Services Agency (HHSA) requested technical assistance from the Centers for Disease Control and Prevention (CDC) to conduct a Community Assessment for Public Health Emergency Response (CASPER). CASPERs are designed to help quickly determine community needs and provides evidence-based information to guide public health actions. The door-to-door data collection process also helps build trust and improve community cooperation.

County of San Diego HHSA, with technical assistance from the CDC, created a two-page survey covering household demographics, health experiences related to sewage contamination, communication preferences, concerns about air and water exposure from the sewage, and health needs and status, including behavioral and mental health. The survey, available in English and Spanish, was designed to take a household approximately 20 minutes to complete.

Interview teams conducted the CASPER over three days (October 17–19, 2024), using both paper and electronic formats. The survey aimed to assess household experiences and perceptions of sewage exposure, identify preferred communication methods, and determine the community's health needs and status.

This report describes weighted findings from the 189 surveys collected. Data analysis was performed in EpiInfo™ 7 to calculate frequences and weighted estimates, percentages, and 95% confidence intervals for all responses.

Based on the findings/analyses and discussion with the County, the following suggestions were considered. A detailed list is available in the Discussion section:

1. Rebuild trust through continued local multiagency coordination to help address concerns.
2. Distribute resources and educational materials in Spanish and English using communication channels preferred by households.
3. Collaborate with partners on further investigating drinking water sources, supplying specific air purifiers to residences, and other data-driven efforts to enact positive change.
4. Supplement behavioral health services to address ongoing needs, including the promotion of hotlines.
5. Consider a follow-up assessment or study to obtain additional insight on issues highlighted in this report.

Background

The Tijuana River Valley, located along the U.S.-Mexico border, has faced a severe environmental and public health crisis because of contamination from untreated sewage, urban runoff, and industrial waste.[1] Over the past five years, more than 100 billion gallons of pollutants have been discharged into the Tijuana River, resulting in significant concerns about water quality and public health in the South region of San Diego County.[2] The pollution primarily originates from raw sewage flowing from the Tijuana River estuary into the Tijuana River Valley and adjacent beach waters, causing potential impacts on both the environment and human health.[3]

The situation was further exacerbated by Tropical Storm Hilary, which struck Southern California on August 20, 2023.[4] On August 24, 2023, the California-American Water Company issued a boil water advisory, alerting the County of San Diego of the ongoing public health concerns related to contamination,[5] prompting the County's Epidemiology Program to conduct an immediate and comprehensive assessment of the contamination's impact on public health. The assessment used a range of data sources, including syndromic surveillance, hospital records, school absenteeism data, and clinic reports.[6] Additionally, retrospective data from the South Bay Urgent Care facility were reviewed by the County to better understand the basis of the community's concerns.

The crisis continued to unfold with further complications from an atmospheric river on January 22, 2024, which caused severe flooding in San Diego County.[7] This flooding widened the spread of the existing sewage contamination in the Tijuana River Valley and surrounding beaches. From February 5–18, 2024, County Public Health Services Epidemiology Program staff were deployed to South Bay Urgent Care to investigate potential increases in gastrointestinal (GI) illnesses, but the investigation did not show an excess rise in acute GI symptoms.[8]

The crisis has drawn considerable attention from the media, public health officials, community members and organizations, and elected representatives in San Diego County's South region and represents a complex, multi-faceted challenge.[9-10] The U.S.-Mexico-Canada Agreement mandates that the U.S. Environmental Protection Agency (EPA) address these environmental issues by identifying pollution sources, improving water quality monitoring, and upgrading infrastructure to reduce contamination.[2] The EPA collaborates with Mexican authorities and other partners to implement effective solutions and ensure compliance with environmental standards. In California, the Regional Water Quality Control Board formulated a comprehensive strategy in 2022 to address the sewage contamination. This strategy focuses on enhancing wastewater treatment facilities, strengthening regulatory oversight, and increasing coordination with Mexican counterparts. Monitoring water quality, mitigating immediate health risks, and planning long-term solutions are central to this strategy.[11] However, these are not short-term solutions, and the potential public health risks remain.

Residents have reported a challenging and uncomfortable experience living in the area, leading to decreased quality of life.[1,12] Many describe unpleasant odors and perceive the air quality as poor because of the contamination. Residents also report increased health concerns (including GI and respiratory issues), although there is limited evidence from syndromic surveillance. Daily activities and routines have been disrupted, with some accounts of avoiding outdoor activities, like swimming or fishing, because of the polluted water. There are also reports of increased stress and anxiety related to health risks and the impact on the environment.

Therefore, in response to the ongoing crisis, the County of San Diego Health and Human Services Agency (HHSA) requested technical expertise and assistance from the Centers for Disease Control and Prevention (CDC) to conduct a Community Assessment for Public Health Emergency Response (CASPER).[13] A CASPER is an epidemiologic technique designed to quickly determine a community's needs. It provides valuable, evidence-based information that can guide public health actions and help address or clarify any rumors. By identifying immediate public health needs, CASPER helps prioritize interventions effectively. It is tailored to the local context, making the findings relevant and actionable for addressing specific community needs. Additionally, going door-to-door in the data collection process can build trust and improve cooperation within the community.

A CASPER is designed to provide information about a community's needs in a timely manner for situational awareness and as a basis for follow-up.

This report presents findings from the CASPER conducted in October 2024. The specific objectives of the CASPER were the following:

- Determine the community's health needs and status, including household behavioral and individual mental health.
- Understand household concerns of air and water exposure from the sewage.
- Describe household health experiences related to the sewage contamination.
- Identify households' preferred methods of communication and resource needs.

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Photo taken by Amy Helene Schnall

Methods

To accomplish these objectives, County of San Diego HHSA and CDC subject matter experts developed a two-page survey that included questions on household demographics, health experiences related to sewage contamination, communication preferences, concerns of air and water exposure from the sewage, and health needs and status, including behavioral health (Appendix A). In addition, the survey included a few questions on mental health at the end of the survey that were specific to the survey respondent rather than the household. It was estimated that the survey would take 20 minutes to complete. Questionnaires were available in both English and Spanish. Eligible respondents were community members (e.g., not tourists) who were 18 years of age or older, lived in the household, and could speak on behalf of the entire household.

The CASPER cluster sampling methodology was applied to select a representative sample of households to be interviewed. This was modified to a three-stage design with one adult randomly selected (by next birthday) for the final individual-level questions. The sampling frame was defined as all households (n=40,911) within the South Tijuana River Valley region of San Diego County according to the 2020 U.S. Census. Using the Geographic Information Systems (GIS) CASPER toolbox, 30 clusters (blocks) were selected with a probability proportional to the number of households within the clusters (Appendix B). In the second stage of sampling, interview teams used systematic random sampling to select seven households from each of the selected clusters, with a goal of completing 210 total interviews (30 clusters of 7 households).

On Thursday, October 3, 2024, households in the selected clusters were notified via door hangers and community flyers that the survey data collection would begin in two weeks.[14] In addition, County of San Diego HHSA developed a webpage with information and promotional videos about CASPER, the purpose of the survey, field dates, and more to help ensure the community was aware.[15]

On Thursday, October 17, 2024, CDC provided a four-hour just-in-time training to the interview team members on the overall purpose of the assessment, field materials (e.g., tracking forms, consent forms, maps, public health information), questionnaire content, household selection, safety, logistics, and their emotional wellbeing during fieldwork. Interview teams collected data on both paper and electronic (tablet) format. Teams were primarily comprised of one volunteer from San Diego State University (SDSU) or the County of San Diego and one CDC staff member. Most teams (~83%) had at least one fluent Spanish speaker.

These two-person interview teams were assigned one to two clusters each day and were provided street level and Google Earth paper and electronic maps of each of the selected clusters to aid them in navigating clusters. Each team discussed specific cluster methodology and potential safety concerns for their specific cluster(s) prior to leaving headquarters. Teams made three attempts at each selected household before substitution.

Twenty-nine (29) teams deployed into the field on October 17, 2024, 26 teams on October 18, 2024, and 14 teams on October 19, 2024. Teams conducted interviews between approximately 2:00 p.m. and 6:30 p.m. on October 17th and 18th, leaving their cluster areas at sundown, and between 10:00 a.m. and roughly 2:00 p.m. on Saturday the 19th.

All potential respondents approached were given a copy of the consent sheet containing a contact email address for County of San Diego HHSA (Appendix C). The survey was voluntary and confidential, with no personally identifiable information collected. Teams were instructed to complete confidential referral forms whenever they encountered urgent needs (Appendix D).

Data Entry, Cleaning, and Analysis

All surveys were reviewed by the interview team members for completeness and accuracy before being uploaded into the database. Paper questionnaires, which were completed in unison with electronic questionnaires, were cross-checked and reviewed by CASPER field leadership upon the teams' return to ensure there was no missing data or inconsistencies.

Once all data were uploaded into the database, the field leadership team added the household and individual weights and cleaned the database. Weighted cluster analysis was conducted to report the estimated number and percent of households with a particular response in the sampling frame. The weight was calculated to account for the probability that the responding household was selected.

To assess mental health, individual respondents were asked the following:

1. CDC's national Behavioral Risk Factor Surveillance System (BRFSS) Quality-of-life questions
2. Patient Health Questionnaire-2 (PHQ-2)
3. Generalized Anxiety Disorder-2 (GAD-2)

Responses for both the PHQ-2 and GAD-2 are scored from zero (not at all) to 3 (nearly every day), and a combined score is calculated by use of the two questions within each module. PHQ-2 scores of ≥3 have a sensitivity of 83% and a specificity of 92% for major depression;[16] GAD-2 scores of ≥3 have a sensitivity of 92% and a specificity of 76% for generalized anxiety disorder, and a sensitivity of 65% and a specificity of 88% for any anxiety disorder.[17] For these questions, we calculated an individual weight to account for the probability that the individual was selected within the household.

All data analysis were conducted in EpiInfo™ 7 to calculate the unweighted frequencies, weighted frequencies, and weighted percentages with 95% confidence intervals. Weighted analysis and confidence intervals were only calculated for cells with ≥5 observations as shown in the tables. All data presented in the text are weighted frequencies and percentages.

Preliminary findings were presented to the County of San Diego HHSA and other leadership the morning of Monday, October 21st to help facilitate immediate action and decision-making. This report serves as a follow-up to that initial presentation. Additional communication materials are also being developed.


Photo taken by Fuyuen Yip

Results

Response Rates and Demographics

A total of 189 surveys (90.0%) were completed from October 17–19, 2024 (Table 1). The field teams completed interviews in 39.4% of the households approached. Of the households with somebody answering the door, 56.8% completed an interview. The response rates are comparable to other CASPERs conducted in non-emergent settings and are understandable given the timing of the data collection. Teams double-checked all surveys prior to uploading via tablet into the database.

A quarter (24.3%, n=46) of the surveys were completed in Spanish. Seven confidential referral forms were submitted to County of San Diego HHSA for immediate follow-up, primarily focused on air quality, water concerns, and behavioral health support requests.

Approximately 45.0% of households (n=19,543) lived in single-family homes and 53.0% (n=22,942) in multiple unit (Table 2). Most households (58.0%, n=24,987) reported renting their homes, with 39.0%, (n=16,944) owning their home. Over three quarters (86.8%, n=37,469) had one or more members aged 18−64 years. Roughly 43% (42.9%, n=18,539) of households had one or more children in the home (aged 17 years or less), and roughly one-third (33.6%, n=14,489) of households had one or more members aged 65 years or older. The mean number of household members was 3.2, with a minimum of 1 and a maximum of 8 people living in a household. Most households spoke English as their primary language within their homes (52.7%, n=22,748) with 44.8% (n=19,329) speaking Spanish. Other languages (2.5%, n=1,093) included Tagalog, Swedish, and Persian. Approximately 56% (n=24,191) of households reported having pets.

Household Experiences

Most households (85.1%, n=36,730) were either somewhat or very aware of the Tijuana River Valley sewage crisis, while only 3.6% (n=1,542) were completely unaware (Table 3). Eight percent (7.7%, n=3,303) reported that at least one household member had come into direct contact with water from the Tijuana River in the past month, and 16.2% (n=6,986) had been in contact with beach water from Imperial Beach, Tijuana Slough, or Silver Strand shorelines during their closures. Several households (44.2%, n=19,072) have taken frequent measures to avoid certain areas because of the sewage contamination, while a smaller portion (21.2%, n=9,143) reported sometimes taking steps to avoid certain areas, and 34.6% (n=14,955) reported not taking any steps at all.

Most households (93.6%, n=40,412) noticed a sewage smell in the past month, with 74.1% (n=31,980) reporting a smell inside their home, 88.6% (n=38,231) outside their home, and approximately 90% (n=38,754) in their neighborhood. Roughly 72% (n=30,896) of households reported noticing a smell in all three locations in the past month. Of the households who noticed a smell inside, outside, or in their neighborhood, 69.2% said the smell was strongest in the evening or night, followed by morning (19%, n=7,670), then afternoon (11.8%, n=4,762).

94% of households noticed a smell in the past month, mostly at night (69%)

The most common action reported to reduce the sewage smell was closing windows (72%, n=31,069), followed by using candles, incense, oil (52.3%, n=22,582), and air freshener or deodorizer (49.2%, n=21,236). Other methods included a portable air purifier, cleaner, or filter

(35.2%, n=15,178), using ammonia or bleach cleaning products (31.7%, n=13,682), and using a humidifier or de-humidifier inside the home (20.4%, n=8,797). Roughly 89% (n=38,406) tried at least one solution to reduce the smell, with a third of households (33.7%, n=14,566) attempting at least three separate actions to reduce the smell; 5.1% of households (n=2,201) reported not using anything. Of those who took any action to reduce the smell in their home, most (66.0%, n=25,360) said it did not help remove the smell (23.2%, n=8,906) or only helped sometimes (42.8%, n=16,454).

Roughly 90% of households (n=37,870) reported being either somewhat or very concerned about the sewage crisis. The biggest concern about the sewage contamination was health of household members (81%, n=34,971). Nine percent (8.5%, n=3,663) of households said they were most concerned about a decrease in property value and 7% (n=3,032) reported something else such as environmental effects, infectious disease, or health of pets. Roughly 4% (n=1,504) of households reported "nothing".

90% of households are somewhat or very concerned about the sewage crisis

The main reported drinking water source for households was bottled water (66.6%, n=28,605), followed by tap or city water (21.4%, n=9,201) (Table 4). Twenty-eight percent (28.2%) of households (n=12,108) reported changing their drinking water source since the crisis began. When asked why, most households (77.2%, n=9,345) reported a concern about the quality and/or safety of the water because of the sewage contamination, stating concerns such as "it smells," "want to be sure we have clean water," "do not want to get sick," and "do not trust the tap water."

A third (32.2%, n=13,879) of households reported that they do not feel safe within their homes. In addition, several households (58.6%, n=25,287) stated making changes to daily activities or routines because of the sewage crisis, with 42.9% (n=10,840) of those households making "many changes" and 57.1% (n=14,447) making "some changes" within the past month during which the survey was given.

59% made changes to their activities or routines because of the sewage

Within the past month, more than two-thirds (68.5%, n=29,555) indicated that the sewage crisis has disrupted at least one aspect of their household's life, with 22.5% (n=9,693) reporting five or more disruptions. The most common disruptions noted were exercise (44%, n=18,974), social activities (43.1%, n=18,621), and daily routines (41.1%, n=17,748). Sleep schedule (37.4%, n=16,160), quality time with family (36.8%, n=15,867), and daily community life (33.3%, n=14,363) were also common disruptions noted by households.

Similarly, 75.9% (n=32,775) of households stated that they decreased at least one outdoor activity because of the crisis (Table 5). The most common decrease was visiting beaches (65.9%, n=28,431) followed by time spent outdoors (60.6%, n=26,173).

When asked for their household's greatest need related to the sewage crisis, 64.3% (n=27,778) reported a type of action. Other common responses included requests to improve air quality (38.2%, n=16,509), water quality (27.1%, n=11,709), and quality of life (21.2%, n=9,168) (Table 6).

Household Communications

57% usually get their information via social media

Friends, family, neighbors, and word of mouth (66.9%, n=28,879) were cited as the top way households usually get information about the sewage contamination, followed by television (62.1%, n=26,807), Internet news (58.5%, n=25,254), and Facebook (45.5%, n=19,642) (Table 7). More than half of households (57%, n=24,460) use some type of social media (Facebook, Instagram, X, YouTube, etc.) to get information. When asked about who the households trust the most to give accurate information about the sewage crisis, 55.3% (n=23,865) of households indicated County of San Diego Health Department. This was followed by 43.6% (n=18,834) reporting friends, family, neighbors, and/or coworkers, and 42.8% (n=18,471) reporting a doctor, nurse, and/or health care provider.

Nearly half (47.0%, n=20,280) of households reported at least one member having at least one barrier such as impaired vision (23.4%, n=10,092), difficulty understanding English (22.4%, n=9,652), impaired hearing (18.7%, n=8,062), and difficulty with mobility (18.1%, n=7,808).

Household Opinions & Beliefs

Most households feel that the quality of the Tijuana River water (92.7%, n=40,004), nearby ocean water (90.5%, n=39,079), and air in the area (77.0%, n=33,241) are **not** okay (Table 8).

- **77% believe the air quality is NOT ok**
- **90% believe the crisis is getting worse**
- **80% believe crisis has affected quality of life**

In addition, nearly all households (98.1%, n=41,534) feel like the sewage in the Tijuana River is causing air and water pollution, 96.2% (n=40,960) believe that sewage is causing bad odors in the area, and 89.3% believe that the crisis is getting worse. Few households (12.1%, n=4,949) believe that the cleanup in the area is sufficient.

When it comes to household's quality of life, 80.4% (n=34,318) reported that they believe the sewage has negatively affected their household's quality of life, and 67.3% (n=27,656) reported that the sewage has made their household health worse. Slightly more than half of households (52.8%, n=22,803) feel their community is a safe place to live. Only 22.1% (n=9,551) of households stated that they believe their household tap water is safe to drink.

Household Health

Roughly 49.6% (n=21,415) of households perceive their overall household health to be "good", with 15.2% (n=6,556) reporting "excellent" household health, 29.9% (n=12,920) "fair," and 5.3% (n=2,278) as "poor" (Table 9). In the past month, 44.8% (n=19,337) of households indicated at least one household member had at least one health symptom that they think was caused by the sewage crisis. Of those, the most common symptom stated was headache (80.0%, n=15,452), followed by nausea or upset stomach (71.7%, n=13,873), cough (62.3%, n=12,057), and dry or irritated throat (60.6%, n=11,718). More than three-quarters of households (76%, n=14,700) reported any GI issue (nausea or upset stomach, vomiting, and/or diarrhea) they believe was caused by the crisis in the past month. Of those, several households reported multiple symptoms among household members within the past month, with 19.6% (n = 3,798) reporting 1-3 symptoms, 45.8% (n = 8,853) having 4-7 symptoms, and 34.6% (n = 6,686)

45% reported at least one health symptom in the past month caused by the crisis

reporting eight or more symptoms among members of the household.

More than one-third of households (35.1%, n=15,053) reported having at least one member considered "medically fragile" or had been told by a doctor or healthcare professional they had a chronic medical condition. Approximately 64.5% of households (n=27,701) had at least one member with at least one chronic condition that has worsened in the past month. Excluding households who did not have a member affected by the condition, 75.8% of households with at least one member with allergies reported a worsening of the condition (n=21,943). Similarly, 59.2% of households with migraines (n=12,817), 53.6% of households with chest or lung pain (n=7,759), and 46.4% of households with asthma (n=7,099) reported a worsening of their respective conditions in the past month.

When asked if anyone in the household needed medical care because of the sewage crisis, 18.2% (n=7,819) said "yes." Of those households, 44.7% (n=3,496) went to a clinic, 39.7% (n=3,106) to urgent care, and 25.3% (n=1,979) to the emergency department.

Almost 70% of households (69.0%, n=29,540) have at least one member reporting a sewage-related health issue, and 31% of households (n=13,390) noted that no member of their household has experienced any sewage-related health issue. When asked if health symptoms that any member of the household had from the sewage crisis improved after spending time away from the area, of those who had symptoms, 69.6% of households (n=20,740) reported they got better, while 13.2% (n=3,928) said they did not improve, and 17.2% (n=5,112) stated they did not spend time away from the area.

Household Behavioral Health

Households reported that the sewage crisis has negatively affected their peace of mind (72.6%, n=31,334), health (53.8%, n=23,204), property (35.5%, n=15,320), and finances (21.6%, n=9,309). More than 80% of households (83.5%, n=36,059) reported the crisis negatively affecting at least one of the above, and 15.6% (n=6,751) said yes to all four areas (Table 10). Additionally, 32% of households (n=13,879) reported they felt their home was unsafe in which to live, and an additional 2.8% (n=1,216) did not know.

59% report an increase in stress because of the sewage crisis

Of those with pets, 6.5% (n=1,564) experienced a loss or serious illness to their pet because of the sewage crisis. Most households (58.6%, n=25,141) reported the sewage contamination increased the overall stress level of the household either a lot (24.3%, n=10,414) or a little (34.3%, n=14,727). In addition, because of the sewage crisis, 40.3% (n=17,318) of households reported that they are taking a different route to avoid sewage contaminated areas and 38.2% (n=16,413) said they considered moving. Almost 60% of households (57.3%, n=24,758) reported one or more adaptive changes (e.g., life transitions such as changing jobs or schools, missing work, considered moving, lost employment) because of the sewage water issue.

In addition, 65.9% of households (n=28,443) reported that at least one member experienced one or more signs of emotional distress because of the sewage crisis, including increased anxiety or worry, sadness or depression, lack of energy, physical symptoms (e.g., headache, stomach ache, pain), feelings of isolation, or numbness. The most commonly reported health symptoms included headaches, stomach aches, and body pain (49.0%, n=21,165), followed by anxiety and worry (37.7%, n=16,293), lack of energy (33.5%, n=14,476), and sadness or depression (23.5%, n=10,130).

Additionally, because of the sewage contamination, 65.3% (n=28,045) of households reported at least one member experiencing at least one of the following indicators of potential acute mental health issues in the past month: trouble sleeping or nightmares, difficulty concentrating, agitated behavior, loss of appetite, increased alcohol use, increased drug use, or witnessed serious injury. Trouble sleeping was the most frequently reported indicator at 56.1% (n=24,083), followed by mood changes (34.7%, n=14,949), and difficulty concentrating (32.5%, n=13,948).

When asked if members of the household received services from a counselor, pastor or clergy member, therapist, social worker, or hotline for behavioral health concerns, 88.9% of households (n=37,948) reported no need for services. Five percent (4.9%, n=2,081) received services, and 6.2% (n=2,660) reported they could not get services.

Individual Mental Health

We asked the individual respondents both the Patient Health Questionnaire (PHQ)-2 and Generalized Anxiety Disorder (GAD)-2 screening questions. Both scales have a cut-off score of 3 indicating the probability of depression or anxiety. Fourteen percent (n=14,822) had a score of 3 or more on the PHQ-2 depression scale, and 11.7% (n=12,420) of respondents had a score of 3 or more on the GAD-2 anxiety scale (Table 11). In addition, 15.1% of respondents (n=15,814) reported that their poor physical or mental health kept them from doing their usual activities, such as self-care, work, or recreation, for 14 or more days in the past month, and 11.7% (n=12,420) indicated their mental health, which includes stress, depression, and problems with emotions, was "not good" for 14 or more days in the past month.

- **15% reported 14+ days where poor health kept them from doing usual activities**
- **14% scored 3+ on PHQ-2**
- **12% scored 3+ on GAD-2**
- **12% reported 14+ days "not good" in the past month**

SOURCE: Rawpixel.com

OVERVIEW OF KEY FINDINGS

Household Experiences & Concerns

- 66% of households who took steps to reduce the sewage smell said it does *not* help or only helps *sometimes.*
- 87% of households are somewhat or very concerned about the sewage crisis.
- When it comes to the crisis, 81% of households are MOST concerned about the health of a household member.
- 77% believe the quality of the air in the area is not OK.
- 64% requested some type of action as their greatest need.

Household Life

- 70% had one or more disruptions to their household life because of the crisis.
- 71% do not believe their household tap water is safe to drink.
- 91% of households reported having trusted source(s) to receive accurate information.

Household Health & Behavioral Health

- Of the HHs with at least one member with health symptoms from the sewage crisis, 70% believe their symptoms improved when they left the area.
- 65% have one or more worsening health conditions in the past month.
- 18% needed medical care because of the sewage crisis.
- 59% reported overall stress level has increased because of the sewage crisis.
- 63% reported one or more signs of emotional distress.
- 65% experienced one or more behavioral health indicators of potential acute mental health issues.

Individual Mental Health

- 15% of individuals (~16,000 people) reported that poor physical or mental health kept them from doing their usual activities such as self-care, work, or recreation for 14 or more days over the past 30 days.
- 14% of individuals (~15,000 people) scored a three or more on the Patient Health Questionnaire 2 (PHQ-2), indicating a probability of depression.

Discussion

While the CASPER achieved a completion rate of 90.0%, the cooperation rate of less than 60% indicate several refusals to participate from the community. Although the reasons for refusal were not queried, the refusals could stem from various factors such as general time constraints, survey or issue fatigue because of the ongoing situation, lack of trust or skepticism in how responses will be used, or perceived irrelevance (e.g., results will not lead to any real change). This highlights the need for transparency in sharing results and outlining action items to help continue to build trust within the community.

Five themes formed the basis of this CASPER:

1. **Household experiences**
2. **Communications**
3. **Opinions and beliefs**
4. **Perceived household health**
5. **Behavioral and mental health**

Household Demographics

We compared demographic data from CASPER to the most recent U.S. Census American Community Survey (ACS) 2022 5-year estimates for the surveyed zip codes (91932, 92173, 92154, 92118).[18] The average number of persons per household was comparable with ACS ranging from 2.8-4.2 per household, and the current CASPER reporting an average household size of 3.2 persons.

Additionally, persons 65 years and over make up between 13.6%-19.1% of the area according to the ACS, depending on the zip code of residence. Therefore, the results from this survey show a ***likely overrepresentation of older adults*** as 33.6% of households reported at least one resident 65 years of age or older. The residents of the interviewed households may include older, possibly retired residents more likely to be home and willing to participate when the CASPER was conducted.

Specific to housing, in 2022, 41.3% of the housing in southwest San Diego County (Chula Vista, National Cities, Puma) and 48.4% of south San Diego County (Otay/Mesa, South Bay) were occupied by their owners.[19-20] This is comparable to CASPER results of approximately 40%.

The CASPER results confirmed that language diversity is also significant, with almost 45% of households speaking Spanish as the primary language within their home, representing over 19,000 households, and 2.5%, or approximately 1,100 homes, speaking another language such as Tagalog, Swedish, and Persian. This highlights the ***importance of multilingual communication materials and support services to effectively reach all community members.*** Continued partnership with *promotores* (trusted community health workers in Spanish-speaking communities) and the translation of materials into Spanish are essential. However, it is equally important to engage speakers and trusted leaders of other languages beyond just English and Spanish. Continuing to expand language access ensures that messages are effectively communicated and understood by all members of the community, fostering inclusivity, promoting broader trust, and enhancing community engagement to help address diverse needs more effectively.

Additionally, with over half of households reporting pets, it is essential to consider these factors in messaging and actions so that owners receive adequate support and information about how the crisis may or may not impact their pet and actions they may take to help mitigate any potential negative impact.

Household Experiences

The data reveal a notable level of awareness regarding the sewage crisis, with 85% of households being somewhat or very aware of the issue. This high awareness likely reflects the pervasive nature of the crisis and its impact on daily life. However, a number of households (8%) reported direct contact with contaminated water from the Tijuana River, and 16% have had contact with beach water during closures.

The overwhelming presence of sewage smell, as reported by 94% of households, highlights the impact on daily life. Almost three-quarters of households noticed the smell in all three locations: inside, outside, and in their neighborhood. This indicates the community-wide issue affecting the home and broader environment. ***These data can help validate how the community feels*** by providing evidence to their grievances and requests for assistance.

In response to the odor, a majority of households (89%) have attempted at least one method to mitigate the smell. Closing windows, using air fresheners, and employing cleaning products were common strategies; however, approximately 65% reported that the actions do not, or only sometimes, reduce the smell. This suggests that ***the persistence of the sewage smell, despite individual household mitigation measures, underscores the broader challenges posed by the crisis***. In addition, some actions households are taking to help reduce the smell, such as the use of candles or incense, can pose health risks from the potential for fires or release of harmful pollutants into the air. These substances can exacerbate respiratory issues and negatively impact indoor air quality, ***making it important to message on fire safety as well as safer alternatives for odor management***, such as air purifiers that contain specific filter media (e.g., active carbon impregnated with potassium permanganate).

That households indicated the smell is most potent during evening and night hours could impact quality of life, leading to disruptions in daily routines, such as sleep. These disruptions to daily life are significant, with almost half of households indicating that the sewage crisis has affected at least one aspect of their routine(s). Commonly reported disruptions include decreased physical activity, social engagements, and family time, all of which can have detrimental effects on mental and physical health. The reduction in outdoor activities, especially beach visits, points to a broader social impact, as recreational spaces become less accessible or desirable because of safety, environmental, or nuisance (e.g., odor) concerns. Additionally, anecdotal reports from interview teams and some notes in the "other" field, reported that households responded "no changes" because they had already made changes prior to the last month, indicating that this crisis has had an impact on households for a prolonged period of time.

The community's response to the sewage crisis illustrates a mix of proactive and reactive measures. While 44% of households frequently avoid contaminated areas, 35% reported not taking any precautions at all. This disparity indicates a possible gap between awareness and action, which could stem from various factors such as complacency, perceived urgency, or lack of resources to implement avoidance strategies or precautionary measures.[21-24] However, when considering those who sometimes take steps to avoid certain areas, the impact of the crisis on daily actions is significant, with approximately 65% altering their routines because of the sewage crisis.

When asked about their greatest needs related to the crisis, the demand for action stood out as a clear message from the community. Additionally, improvements in air and water quality, along with better communication regarding the crisis, were highlighted as important needs. ***This illustrates a community ready to seek solutions and emphasizes the necessity for clear, consistent information to inform households of actions they may take as well as steps being taken by the County to address the crisis.***

Household Communications

With regard to receiving information about the sewage contamination, relying on word of mouth was the most common source, cited by over 67% of households. Other top sources included television, internet news, Facebook, Instagram, and work. These modes underscore the importance of community-based communications methods (e.g., word of mouth, social media, places of employment) that should be leveraged for future messaging to ensure that information reaches as many people as possible. An example could be to leverage partnerships with the Department of Education to empower schools to reach the community as a trusted source. While slightly less than 20% of households reported schools as the usual source of information, among households with children 2-17 years of age, the number increases to almost half (45%).

Almost 60% of households engaged in any form of social media to receive their information, which can play an important role in message sharing, including Facebook advertisements, NextDoor posts, and Instagram infographics. This, along with the high percentage reported using internet news, shows that, while traditional methods remain relevant, there is also a shift to digital platforms of information. ***Integrating word-of-mouth strategies with formal communication methods can help create a more robust and comprehensive approach to communication and outreach plans.*** This may include not only written digital messages, but also video shorts potentially featuring local *promotores*, community health workers, and others as trusted sources. Development of these video shorts in multiple languages, combined with tailored algorithms, can help broaden the reach of messages using trusted sources and multi-method modes.

Trust in information sources also plays a critical role in how communities respond to messages. The County of San Diego HHSA is regarded as the most trusted source by over half (55%) of the households. This highlights the importance of official health communications; notably, nearly as many households (43%) trust informal networks of friends, family, and other forms of word of mouth. Also, a number of households trust only themselves, or nobody at all, when it comes to obtaining accurate information about the crisis. This further emphasizes the continued importance of both formal and informal sources to help influence perceptions and behaviors as well as building trust and credibility through the facilitation of two-way communications.

The presence of barriers to communication in nearly half of the households (47%) is important to note, as impaired vision, language difficulties, hearing impairments, and mobility challenges can significantly hinder effective communication. For instance, with almost a quarter of households reporting impaired vision, and 10% reporting difficulty understanding written material, this reinforces the need for accessible information formats. Additionally, with more than 20% of households reporting having difficulty understanding English, this indicates a demand for continued multilingual communication strategies.

Household Opinions & Beliefs

With 93% of households expressing concerns about the quality of the Tijuana River water, and similar levels of apprehension regarding the ocean water and air quality in the area, it is evident that households are deeply concerned by the ongoing crisis. This widespread discontent is compounded by the perception that the situation is worsening, as noted by almost 90% of the households.

The overwhelming consensus among 98% of households that the Tijuana River contributes to air and water pollution, along with 96% reporting that sewage is causing unpleasant odors, reflects the strong concerns and feelings of the community. ***These data can serve to validate their concerns by providing tangible evidence to support their feelings.*** Two-thirds of households believe that their health has worsened because of the crisis, and just under half feel their community is not a safe place to live. This, combined with the perception of inadequate clean-up efforts, emphasizes the strong feelings and desire for action among the community. Given the impact on household daily lives, lack of trust, and desire for action, this is an opportunity to potentially implement new and leverage existing science, technology, engineering, and mathematics (STEM) investments in multiple avenues (e.g., schools, faith-based organizations) to empower the community with air monitoring, local interventions, and broader science education of youth to expand environmental health literacy as previous research has shown positive outcomes.[25]

Importantly, only 22% of households believe their tap water is safe to drink, and 67% of households reported using bottled water as their primary source of drinking water. Tap water consumption among adults in the U.S. from 2007-2014 was approximately 62%.[26] Thus, the percentage of households reporting only drinking bottled water is well above the estimated national average. This survey finding, however, is consistent with some literature suggesting that there is increased intake of bottled water over tap water in certain populations, such as Hispanics, owing to a variety of factors, including distrust in the public water utilities because of pollutants, waterborne diseases, and groundwater contamination.[27] Despite the absence of evidence indicating that the water is unsafe based on previous water quality testing,[28-29] this perception presents a critical opportunity for community engagement in collaboration with the State Water Resource Board. Effective communication continues to be essential in addressing these concerns and building trust. Using video shorts and town halls as a platform and further engaging *promotores* and community health workers, for example, could allow community members to ask questions, share experiences and observations, receive accurate information, and engage directly with local officials. This approach could not only inform residents but foster a sense of community and transparency regarding water safety.

Household Physical Health

While most households (~65%) report their overall household health is either good or excellent, a third of households reported their health as only "fair," and 5% (~2,200 households) said their household health was "poor." The presence of health symptoms perceived to be attributed to the sewage issue is important to note. Almost half of households (~45%) reported that at least one member experienced symptoms they believed were caused by the crisis within the last month, with headaches being the most common. Other prevalent symptoms included gastrointestinal issues, respiratory symptoms, and throat irritation. More than a third of households (35%) reported eight or more symptoms within the past month they attribute to the sewage crisis, indicating the perceived widespread impact on their household health.

At the same time***, few households reported seeking medical care because of the crisis, with the majority (82%) not seeking care within the healthcare system.*** This may be one possible explanation on why hospital and other surveillance systems have not previously recorded increases in these symptoms. However, these data show that the crisis has profoundly impacted perceptions of household health, with many households attributing their symptoms to the crisis. Therefore, a potential course of action could involve collaborating with insurance companies to encourage residents of the South Bay region have access to care when needed, while also promoting key health messages from the County of San Diego HHSA related to the sewage crisis.

Importantly, of the 69% of households who have had at least one member experiencing health issues they attributed to the sewage crisis at any time, the majority (70%) reported that their symptoms improved when they spent time away from the area; less than 15% reported no improvement.

More than a third of households reported having members who are medically fragile or suffer from a chronic condition(s), and nearly two-thirds of those indicated that at least one such chronic condition has worsened in the past month. This highlights the importance for continued support to ensure that those who are at higher risk are aware of and able to access health care services.

Household Behavioral Health

The assessments revealed substantial impacts of the sewage crisis on the behavioral health of households. ***More than 83% of households (~36,000 households) reported negative effects in at least one area between peace of mind, health, property, and finances, with 16% experiencing challenges across all four dimensions.*** In addition, 59% of households reported an increase in stress level because of the sewage crisis. This aligns with existing literature that links environmental crises to psychological distress and further suggest that such crises may have a major impact on overall health, as stress, including financial stress, can adversely affect sleep, self-esteem, energy, and emotional stability.[30-31]

SOURCE: Openclipart

Indicators of potential acute mental health issues were prevalent, with over 65% of households reporting at least one member experiencing issues such as trouble sleeping, mood changes, difficulty concentrating, and agitated behavior. A loss of appetite was noted in more than a quarter of households. ***These data are similar to those captured in CASPERs conducted to support response and recovery efforts related to major natural disasters, such as category 5 hurricanes, and are also comparable to household experiences during the Flint Water Crisis***.[32-33]

These data, along with the previous reported disruptions to daily activities and routines, ***shows that the crisis has created a pervasive sense of distress among the community that extends beyond potential physical health concerns***. The high prevalence of sleep disturbances and mood changes indicates that the sewage crisis is not just a temporary inconvenience, but a source of ongoing anxiety and emotional turmoil among household members. Difficulty concentrating and increased agitation can hinder daily functioning, affecting work, school performance, and interpersonal relationships.

The link between experiencing environmental crises and altered behavioral health was supported by the reported signs of emotional distress experienced because of the sewage crisis, which were prominent among surveyed households. ***Two-thirds of households had at least one member report experiencing signs of emotional distress such as physical complaints, increased anxiety or worry, lack of energy, and more.*** A third of households reported one member experiencing increased anxiety or worry (~38%), lack of energy (~33%), or spending less time with friends and family (~30%).

However, when asked about recent attempts to access counseling services, almost 90% of households overall reported no need for such services. This may suggest some resiliency within the community, poor awareness of the benefits of behavioral health resources, or a potential stigma associated with receiving behavioral health services.[33-36] Some households (~6%) wanted to get services but were not able to; this indicates a need to increase access or awareness of available services. More in-depth data regarding the status of behavioral health in the community, potential barriers to receiving services, and promotion of the benefits of receiving services would be valuable.

These combined behavioral findings emphasize an ***important need for support and community resources to address the psychological and behavioral impacts of the crisis on the community***. Actions could include providing and promoting accessible behavioral health services, including hotlines and support groups, to help households cope with increased anxiety, depression, and other behavioral health concerns. Establishing or enhancing community support systems and outreach programs could also aid in addressing disruptions to daily routines and social connections. Connection to programs offered by partners, such as the Department of Education's Project SERV, could also assist with the potential impact of the crisis on school-aged children.

Regardless, tailored communication efforts continue to be needed to ensure the community is well-informed of resources and services. Promoting community resilience and recovery through support for affected households will also be crucial.

Individual Mental Health

We asked individual respondents both the PHQ-2 and GAD-2 screening questions. Both tools are not meant to establish final diagnosis or to monitor depression or anxiety but serve as a "first step" screening approach. The PHQ-2 is a commonly used and validated depression screening tool for adults and inquiries about the frequency of depressed mood and anhedonia (i.e., the inability to feel pleasure) over the past two weeks. The GAD-2 is a brief screening tool for generalized anxiety and possibly for panic disorder. Around 14% of respondents (~15,000 individuals) scored 3 or more on the PHQ-2 depression scale, indicating a positive predictive value (PPV) of 75.0 for detecting any depressive disorder. Approximately 12% of respondents (~12,500 individuals) scored 3 or more on the GAD-2 anxiety scale, indicating a likelihood ratio of 5.1 for generalized anxiety disorder.[14-15]

We also asked respondents two Behavioral Risk Factor Surveillance System mental health questions. Approximately 15% (~16,000 individuals) reported their mental health prevented them from doing usual activities, and 12% (~12,000 individuals) indicated that their mental health, which includes stress, depression, and problems with emotions, was "not good" for 14 or more days in the past month. As with the household behavioral health results, these data

indicate the continued need for, and promotion of, behavioral health services.

Considerations for Action

Based on the analysis of the rapid needs assessment data, the following are considerations for action:

1. **Continue to rebuild trust through local multiagency and multidisciplinary coordination with trusted sources.** While 55% of households trust the health department to give accurate information on the sewage crisis, 38% trust themselves or their household most, and 9% do not trust anyone. Nearly 43% of households trust doctors or nurses. Roughly 13% of households cited communication as their greatest need. Therefore, there is a need to develop protocols for when air and water concerns arise, especially among groups at higher risk, including those with chronic conditions. Trust could also be built through Live Well San Diego collaboratives and healthcare providers to ensure consistency of communication from leadership and parity of resources and support given to communities affected by environmental hazards. Additionally, trust could be built by acknowledging the disruption the sewage crisis has had to daily life.
2. **Distribute resources and education on health concerns, sewage crisis updates, and water and air exposure in Spanish and English using preferred communication channels, as well as additional languages such as Tagalog**. Consider diverse channels, both formal and informal (e.g., town hall), to reach households within the South region of San Diego County. Roughly 47% of households have one or more barriers to communication, and nearly 60% of households use any form of social media as their usual source of information about the sewage crisis. While Spanish and English are the primary languages, it is important to consider the households (2.5%, n=1.093) who reported speaking another language.
3. **Collaborate with CDC National Center for Environmental Health (NCEH) and California Environmental Protection Agency (CalEPA) on further investigating drinking water sources used by South region households and on developing safety messaging for drinking water quality.** Just over 70% of households do not believe their household tap water is safe to drink, and 67% of households use bottled water as their primary source of drinking water. These findings suggest that there are household concerns within the community that could potentially be addressed through customized communication and active involvement. By understanding the unique needs of the community, targeted messaging can be developed that resonates with affected households. This approach could help alleviate household concerns and foster a sense of trust between the organization and the community.
4. **Collaborate with San Diego Air Pollution Control District on supplying air purifiers that contain filter media (e.g., activated carbon impregnated with potassium permanganate) to reduce hydrogen sulfide in the air of affected households and local community centers.** Roughly 38% of households identified improving air quality as their greatest need. Among the households with one or more health symptoms they attributed to the sewage crisis, most households reported that their health symptoms improved when they spent time away from the area. Therefore, utilizing air purifiers with appropriate filter media may help alleviate health symptoms, reduce the reliance on unsafe mitigation methods that only mask odors (e.g., candles, incense), and foster community trust and partnership.

5. **Promote available hotlines, such as 211 and 988, to connect households to needed services.** The 211 hotline is a free, confidential service available 24/7 that offers information and referrals to essential community resources, including food, housing, utilities, health services, and family support. Also, 988, while known as the suicide prevention hotline, can provide immediate help and connect individuals to relevant services. While many households reported not needing assistance, they also exhibited signs of behavioral health needs; thus, online or phone crisis hotlines may help to bridge the gap in accessing support.
6. **Supplement behavioral health services to address ongoing needs.** A high number of households reported experiencing worry, stress, behavioral health issues, and disruptions to their daily lives. Many also felt that their homes were unsafe and that their quality of life was negatively impacted. In addition, individuals scored high on scales which indicate a likelihood of anxiety and depression. These indicators highlight a need for ongoing availability and promotion of behavioral health services through trusted channels, including the 988 hotline.
7. **Share results with relevant partners and community leaders to promote data-driven efforts and positive change.** Sharing results with partners is important for effective response to this crisis as it ensures that decisions are based on accurate, evidence-based data. This data-driven approach allows for tailored resource allocation, enhances collaboration among organizations, and increases transparency and accountability. Additionally, it helps leverage limited resources, ultimately leading to more efficient and coordinated efforts.
8. **Engage South region veterinarians, County of San Diego One Health Epidemiology Program, and Project Wildlife partners to address ongoing pet and livestock needs and health concerns.** Roughly 7% of households with pets reported a loss or serious illness of their pet they attributed to the sewage crisis. This represents approximately 1,500 homes and highlights an important public health concern. Addressing this issue is crucial not only for the well-being of pets (and livestock) but also for enhancing community trust and ensuring that residents feel supported during this crisis.
9. **Consider a follow-up assessment or study on crisis-related needs to identify and characterize ongoing and long-term health and behavioral health effects in more detail**. An overwhelming consensus of households believe the quality of the Tijuana River water, nearby ocean water, and air in the area are not ok, and nearly 90% of households do not believe the area cleanup is sufficient. While CASPER data provides a high-level outlook and can help determine priorities and needs, a more in-depth approach can provide valuable insight for addressing these concerns.

These suggestions are for County of San Diego HHSA consideration and should continue to be discussed locally for feasibility and prioritization. In addition, they are not all-inclusive; more potential action items are suggested throughout the Discussion section. A key component of all suggestions is to continue to strengthen communications. Effective and tailored communications is essential for building trust, ensuring community engagement, and keeping the community informed about ongoing efforts and resources available to address the crisis. By fostering a diverse range of communication strategies, County of San Diego HHSA can better understand community needs, enhance collaboration among partners, foster inclusivity, and reach a broad audience. Leveraging existing partnerships and platforms (e.g., *promotores*, Facebook ads, websites), along with developing new materials and venues (e.g., video shorts, additional languages, town halls), can help enhance such outreach efforts and improve community engagement. This comprehensive approach will help build trust and facilitate meaningful dialogue about ongoing issues and solutions, as every action necessitates some form of communication efforts for promotion, information sharing, and/or transparency.

These general considerations are based on data from the CASPER conducted between October 17-19, 2024, and it is important to note that this is just the beginning. Specific courses of action for each consideration should be developed, and some considerations may have more than one course of action. Meeting with partners to determine roles and responsibilities for carrying out activities is the next step in turning data into action. Tailored interventions could be developed based on demographic and household data, addressing the needs of different groups such as families with children, older adults, persons with English as a second language, and those with pets. These insights will guide strategic planning and enhance efforts in the continued response to the Tijuana River Valley sewage contamination issue. Therefore, the above suggested actions should be developed locally, with input and support from relevant partners, into specific activities to help ensure the needs of the community identified in this report are met. A follow-up survey can also be conducted yearly to monitor changing needs and gauge potential improvement from any implemented actions.

Limitations

The data generated by the CASPER represent a snapshot in time, which should be considered when interpreting the results. The results are self-reported by one (or more) individual(s) representing an entire household; therefore, bias may occur as the interviewee may not know everything about all household members they are representing. The age distribution of the sample population may be skewed, with a greater proportion of individuals aged 65 years and older represented in the sample than estimated within the 2022 American Community Survey for the area.

Conclusion

The information gathered from households revealed a profound awareness of the Tijuana River sewage crisis, highlighting the pervasive impact on daily life, health concerns, and well-being. While most households are aware of the situation, many continue to risk exposure. The widespread reporting of health symptoms and disruptions to routines underscore the potential impact of the crisis on both physical and behavioral health, particularly among groups more at risk such as those with pre-existing chronic conditions. Community concerns about water and air quality are also compounded by a reported lack of trust in information sources, emphasizing the need for continued transparent and tailored communication and outreach. To address these challenges, a coordinated response involving health education and communication, behavioral health support, and resource distribution is critical. Moving forward, continued engagement with the community in a participatory approach could help foster the rebuilding of trust and strengthening resilience.

References

1. Granados PES, Sant KE, Quintana PJE, Hoh E, et al. Tijuana River contamination from urban runoff and sewage: A public health crisis at the border. San Diego State University School of Public Health. https://www.sdsu.edu/_files/tijuana-sewage-contamination-public-health-crisis-white-paper-021424.pdf
2. Environmental Protection Agency (EPA). USMCA Tijuana River Watershed and Adjacent Coastal Transboundary Wastewater Flows https://www.epa.gov/sustainable-water-infrastructure/usmca-tijuana-river-watershed
3. California Water Boards. Sewage pollution within the Tijuana River Watershed https://www.waterboards.ca.gov/sandiego/water_issues/programs/tijuana_river_valley_strategy/sewage_issue.html
4. Anderson A. Tropical Storm Hilary made South Bay sewage woes worse. https://www.kpbs.org/news/environment/2023/08/23/tropical-storm-hilary-made-south-bay-sewage-woes-worse
5. American Water Works Service Company, Inc: Imperial Beach: Boil Water Advisory. https://alertsdetail.awapps.com/alert/27814
6. Centers for Disease Control and Prevention (CDC). Assessment of Health Risks from Sewage Contamination in the Tijuana River Valley. https://www.cdc.gov/nceh/investigation/tijuana_river.html
7. National Oceanic and Atmospheric Administration (NOAA). Impact of Atmospheric Rivers on San Diego County https://www.noaa.gov/impact-atmospheric-rivers-sd
8. Sisson P. County says it found no evidence of increased illness at South Bay Urgent Care tied to sewage spills https://www.sandiegouniontribune.com/2024/06/01/county-says-it-found-no-evidence-of-increased-illness-at-south-bay-urgent-care-tied-to-sewage-spills/
9. Scott Peters Press Releases. Reps Peters, Vargas, and Senator Padilla announce efforts to address Tijuana River Pollution crisis. https://scottpeters.house.gov/2024/9/reps-peters-vargas-and-senator-padilla-announce-efforts-to-address-tijuana-river-pollution-crisis
10. County, state, formally request epidemiologic assistance from CDC to tackle sewage crisis health impacts. https://www.sandiegouniontribune.com/2024/07/05/county-state-formally-request-epidemiologic-assistance-from-cdc-to-tackle-sewage-crisis-health-impacts/
11. California Water Boards–San Diego R9. Lower Tijuana River indicator bacteria and trash advance restoration plan https://www.waterboards.ca.gov/sandiego/water_issues/programs/tmdls/tijuanarivervalley.html
12. Rios P. San Diegans hold their breath as Newsom defers to Washington D.C. on Tijuana River sewage crisis https://calmatters.org/commentary/2023/11/san-diego-tijuana-river-sewage/
13. Centers for Disease Control and Prevention. Community Assessment for Public Health Emergency Response (CASPER) Toolkit 3.2. https://www.cdc.gov/casper/media/pdfs/CASPER-toolkit-3_508.pdf
14. County Distributing Information to Residents Ahead of CDC Community Health Assessment | News | San Diego County News Center; CDC to survey health effects of Tijuana River Sewage | cbs8.com

15. County of San Diego HHSA. South Region Health Concerns: CDC Health Survey https://www.sandiegocounty.gov/content/sdc/hhsa/programs/phs/community_epidemiology/south-region-health-concerns/casper-study.html
16. Arroll B, Goodyear-Smith F, Crengle S, Gunn J, Kerse N, Fishman T, Falloon K, Hatcher S. Validation of PHQ-2 and PHQ-9 to screen for major depression in the primary care population. *Annals of Family Medicine* 2010, 8(4): 348-353.
17. Kroenke K, Spitzer RL, Williams JB. The 2-item Generalized Anxiety Disorder scale had high sensitivity and specificity for detecting GAD in primary care. Evidence Based Medicine, 2007, 12: 149 http://ebm.bmj.com/content/ebmed/12/5/149.full.pdf
18. United States Census Bureau. Zip Code Profiles https://data.census.gov/advanced?g=040XX00US06
19. DataUSA. San Diego County (South)–San Diego City (South/Otay Mesa & South Bay) https://datausa.io/profile/geo/san-diego-county-south-san-diego-city-southotay-mesa-south-bay-puma-ca#housing
20. DataUSA. San Diego County (Southwest)–Chula Vista. https://datausa.io/profile/geo/san-diego-county-southwest-chula-vista-west-national-city-cities-puma-ca
21. Pahl, S., et al.. The role of urgency in decision-making: How time pressure impacts environmental behavior and risk mitigation strategies. *Journal of Environmental Psychology*, 2023; 86, 101868.
22. Serrano, L., et al.. Barriers to community-level environmental health action: A case study of resource limitations in addressing urban pollution. *Environmental Health Perspectives*, 2022; 130(10), 107004.
23. Bertolote, J. M., et al. (2021). Community responses to health crises: The gap between awareness and preventive action in low-resource settings. *Global Public Health*, 16(3), 387-399.
24. Fitzgerald, L., & Worrall, L. (2020). Addressing the awareness-action gap in public health responses: Case studies in water sanitation crises. *Journal of Public Health*, 42(4), 668-675.
25.Ward F, Lowther-Payne HJ, Halliday EC, Dooley K, Joseph N, Livesey R, Moran P, Kirby S, Cloke J. Engaging communities in addressing air quality: a scoping review. Environmental Health 2022, 21:89 https://pmc.ncbi.nlm.nih.gov/articles/PMC9484248/
26. Rosinger A, Herrick K, Wutich A, et al. Disparities in plain, tap and bottled water consumption among US adults: National Health and Nutrition Examination Survey (NHANES) 2007-2014 - PubMed Public Health Nutrition, 2018, 21(8): 1455-64.
27. Victory K, Wilson A, Cabrera N, et al. Risk perceptions of drinking bottled vs. tap water in a low-income community on the US-Mexico Border, BMC Public health, 2022, 22:1712. https://doi.org/10.1186/s12889-022-14109-5
28. City of San Diego Public Utilities. Water Quality Reports. https://www.sandiego.gov/public-utilities/water-quality/water-quality-reports
29. Project Clean Water. Tijuana. https://projectcleanwater.org/watersheds/tijuana-wma/
30. Ryu S, Fan L. The relationship between financial worries and psychological distress among US adults. *Journal of Family and Economic Issues* 2023, 44(1): 16-33
31. Robinson L, Smith M. Understanding financial stress. *Helpguide.org* https://www.helpguide.org/articles/stress/coping-with-financial-

stress.htm#:~:text=Feeling%20beaten%20down%20by%20money,risk%20of%20depression%20and%20anxiety.
32. Centers for Disease Control and Prevention (CDC). Story: Flint Water Crisis. https://www.cdc.gov/casper/php/publications-links/flint-water-crisis.html
33. Schnall AH, Roth J, Ellis B, Seger K, Davis M, Ellis E. Addressing Community Needs During the Hurricane Response and Recovery Efforts Through Community Assessments for Public Health Emergency Response (CASPER)—United States Virgin Islands, 2017-2018. Prehospital and Disaster Medicine 2019: 53-62.
34. Grieb SM, Platt R, Vazquez MG, Alvarez Ki, Polk S. Mental Health Stigma Among Spanish-Speaking Latinos in Baltimore, Maryland 2023, May 22:1-9. Doi: 10.1007/s10903-023-01488-z
35. Norris FH, Tracy M, Galea S. Looking for resilience: understanding the longitudinal trajectories of responses to stress. Social Science and Medicine. 2009;68(12):2190–2198. doi: 10.1016/j.socscimed.2009.03.043.
36. Bonanno GA, Galea S, Bucciarelli A., Vlahov D. What predicts psychological resilience after disasters? The role of demographics, resources, and life stress. J Consult Clin Psychol. 2007, 75(5): 671-82.

Tables

Contents

Table 1. Survey response rates – Tijuana River Valley, 2024

	CASPER (n=189)	
	Rate	%
Response rates		
Completion[1]	189/210	90.0
Cooperation[2]	189/333	56.8
Contact[3]	189/480	39.4

[1]Percent of surveys completed compared to the goal

[2]Percent of surveys completed compared to total number of households that teams made contact with

[3]Percent of surveys completed compared to all randomly selected households

Table 2. Household (HH) demographics – Tijuana River Valley, 2024

	Tijuana River Valley CASPER (n=189)			
	Frequency	Estimate	% of HH	95% CI
Type of structure				
Multiple unit	94	22,942	53.1	39.1–67.2
Single family home	92	19,543	45.3	30.8–59.7
Mobile home	3	–	–	–
Number of HHs with members in each age category				
Less than 2 years	15	3,294	7.6	3.4–11.8
2-17 years	67	15,245	35.3	26.7–43.9
18-64 years	162	37,469	86.8	81.2–92.2
65 years or older	67	14,489	33.6	25.5–41.6
Household ownership status				
Rent	104	24,987	57.9	46.0–69.9
Own	80	16,944	39.3	27.5–60.0
Occupied w/o ownership/rent	5	1,239	2.9	0.3–5.4
Household animals[1]				
Pets	109	24,191	56.0	49.1–62.9
Livestock	4	–	–	–
Primary language spoken				
English	100	22,748	52.7	40.5–64.8
Spanish	84	19,329	44.8	32.4–57.0
Other[2]	5	1,093	2.5	0.3–4.7

[1]*Households could choose more than one response*
[2]*Other includes Tagalog, Swedish, and Persian*

Table 3. Household (HH) awareness, exposures, and concerns – Tijuana River Valley, 2024

	Tijuana River Valley CASPER (n=189)			
	Frequency	Estimate	% of HH	95% CI
Awareness of sewage contamination				
Very aware	123	27,048	62.7	53.1–72.3
Somewhat aware	38	9,682	22.4	14.1–30.8
A little aware	21	4,998	11.3	6.9–15.8
Not at all aware	7	1,542	3.6	0.6–6.5
Been in contact with water from the river in past month				
No	174	39,867	92.3	88.0–96.7
Yes	15	3,303	7.7	3.3–12.0
Been in contact with beach water while closed in past month				
No	156	36,184	83.8	76.9–90.8
Yes	33	6,986	16.2	9.2–23.1
Taken steps to avoid certain areas				
Frequently	89	19,072	44.2	35.1-53.2
Sometimes	35	9,143	21.2	13.4–29.0
No	65	14,955	34.6	26.0–43.3
Noticed a sewage smell in past month[1]				
In the neighborhood	170	38,754	89.8	84.3–95.3
Outside home	167	38,231	88.6	83.1–94
Inside home	146	31,980	74.1	64.5–83.6
No smell anywhere	11	2,563	5.9	1.9–9.9
Noticed in all three locations	141	30,896	71.6	81.2–61.9
Time of day smell worse (n=177)				
Morning	28	7670	19.0	9.3–28.6
Afternoon	21	4,762	11.8	5.5–18.1
Evening/Night	128	27,980	69.2	59.8–78.7
Products used to reduce sewage smell[1]				
Closed windows	142	31,069	72.0	63.4–80.5
Candles, incense, oil	99	22,582	52.3	41.5–63.2
Air freshener/deodorizer	96	21,236	49.2	39.9–58.5
Portable air purifier, cleaner, or filter	70	15,178	35.2	28.5–41.8
Ammonia/bleach cleaning products	62	13,682	31.7	22.4–41.0
Humidifier/De-humidifier inside the home	34	8,797	20.4	13.1–27.7
Other[2]	31	6,455	15.0	7.2–22.7
Did not use anything	9	2,201	5.1	2.0–8.2
No sewage smell in the home	11	2,563	5.9	2.0–9.9
Actions helped to reduce smell (n=169)				
Yes	54	13,045	34.0	24.7–43.3
Depends/sometimes	75	16,454	42.8	33.8–51.9
No	40	8,906	23.2	16.2–30.2
Concern about sewage contamination				
Very concerned	143	31187	72.2	64.7–79.7
Somewhat concerned	29	6683	15.5	11.4–19.6
A little concerned	10	3,745	8.7	1.5–15.8
Not at all concerned	7	1,555	3.6	0.7–6.5
Biggest concern about sewage contamination				
Health of HH members	158	34,971	81.0	73.4–88.6
Property	17	3,663	8.5	4.8–12.2
Other[3]	8	3,032	7.0	0.0–14.2
Nothing	6	1,504	3.5	0.8–6.2

[1]Households could choose more than one response
[2]Other includes using/purchasing air conditioning, fans, mopping, covering drains, and taping/sealing windows
[3]Other includes environmental affects, infectious disease, health of pets, going to the beach, the smell, impact on Navy Seals, etc.

Table 4. Household (HH) disruptions – Tijuana River Valley, 2024

	Tijuana River Valley CASPER (n=189)			
	Frequency	Estimate	% of HH	95% CI
Usual drinking water source				
Bottle	127	28,605	66.6	57.5–75.8
Tap/city	37	9,201	21.4	13.2–29.7
Other[2]	24	5,124	11.9	6.5–17.4
Changed drinking water source since crisis began				
Yes	53	12,108	28.2	20.1–36.3
No	135	30,822	71.8	63.7–79.9
Household changed daily activities/routines				
Yes	110	25,287	58.6	49.0–68.1
Many changes	*52*	*10,840*	*42.9*	*29.2–56.5*
Some changes	*58*	*14,447*	*57.1*	*43.5–70.8*
No	79	17,833	41.4	31.2–60.0
Disrupted HH live in past month[1]				
Exercise	85	18,974	44.0	34.0–54.0
Social activities	85	18,621	43.1	33.9–52.4
Daily routines	76	17,748	41.1	31.5–50.7
Sleep schedule	74	16,160	37.4	29.3–45.6
Quality time with family	72	15,867	36.8	27.6–45.9
Daily community life	67	14,363	33.3	23.9–42.6
School/work	35	8,862	20.5	12.9–28.1
Eating behaviors/schedules	41	8,819	20.4	14.1–26.7
Childcare/daycare	15	3,371	7.8	3.6–12.0
Church/Place of worship	8	1,881	4.4	1.5–7.2
Other[3]	20	4,317	10.0	5.7–14.3
Number of HH disruptions in past month				
No disruptions	61	13,375	31.5	29.9–37.3
1-4 disruptions	83	19,862	46.0	37.8–54.2
5 or more disruptions	45	9,693	22.5	15.6–29.3

[1]Households could choose more than one response
[2]Other includes entire house filtration systems, filtered water, water fill locations, spring water, and wells
[3]Other includes closing windows (especially at night), gardening, time spent outdoors, surfing, etc.

Table 5. Household (HH) changes in outdoor activities – Tijuana River Valley, 2024

	Tijuana River Valley CASPER (n=189)			
	Frequency	Estimate	% of HH	95% CI
Visiting beaches				
Increased	4	–	–	–
Decreased	128	28,431	65.9	55.0–76.7
No change	57	13,883	32.2	22.4–42.0
Time spent outdoors				
Increased	4	–	–	–
Decreased	119	26,173	60.6	51.5–69.8
No change	66	16,107	37.3	28.3–46.3
Going to parks/playgrounds				
Increased	3	–	–	–
Decreased	96	21,328	49.4	40.2–58.6
No change	90	21,191	49.1	40.6–57.6
Gardening				
Increased	3	–	–	–
Decreased	55	12,110	28.1	20.0–36.1
No change	131	30,409	70.4	62.4–78.5
Other outdoor activitiy[2]				
Increased	2	–	–	–
Decreased	13	2,784	6.4	2.3–10.6
No change	174	39,975	92.6	88.2–97.6
Number of outdoor activities DECREASED				
None	42	10,395	24.1	14.1–34.0
1	27	6,496	15.0	10.4–19.7
2	29	6,155	14.2	8.4–20.2
3	51	11,260	26.1	18.4–33.8
4	40	8,864	20.5	13.9–27.1

[1]*Households could choose more than one response*
[2]*Other includes exercise, kids participation in sports, outdoor dining and entertaining, etc.*

Table 6. Household (HH) greatest need – Tijuana River Valley, 2024

	Tijuana River Valley CASPER (n=189)			
	Frequency	Estimate	% of HH	95% CI
Greatest need because of the crisis[1]				
Actions requested[2]	124	27,778	64.3	55.1–73.6
Improve air quality[3]	76	16,509	38.2	30.5–46.0
Improve water quality[4]	54	11,709	27.1	19.9–34.4
Quality of life[5]	42	9,168	21.2	15.0–27.5
Nothing[6]	24	6,583	15.3	7.1–23.4
Communication needs[7]	25	5,640	13.1	8.7–17.4
Health and safety[8]	26	5,600	13.0	6.7–19.3

[1]*Households could indicate more than one response*
[2]*Actions requested includes air purifiers, filters, clean up, general fixing the problem, fixing the treatment plant and pump station, etc.*
[3]*Improve air quality includes quality of air, addressing odor/smell concerns, etc.*
[4]*Improve water quality includes quality of river and beach water, beaches, drinking water concerns, etc.*
[5]*Quality of life includes needing to adjust normal activities/routines, moving away, housing rates, etc.*
[6]*Nothing includes refused, nothing*
[7]*Communication needs includes request more information, etc.*
[8]*Health and safety includes health symptoms, dangers to health, breathing needs, safety, health effect concerns, mental health, etc.*

Table 7. Household (HH) communications – Tijuana River Valley, 2024

	Tijuana River Valley CASPER (n=189)			
	Frequency	Estimate	% of HH	95% CI
Usual source of information[1]				
Friends, family, neighbor, word of mouth	128	28,879	66.9	56.4–77.4
TV	120	26,807	62.1	52.7–71.4
Internet news	114	25,254	58.5	49.6–67.4
Facebook	83	19,642	45.5	37.8–53.1
Instagram	47	10,059	23.3	17.1–29.5
Work	39	9,809	22.7	13.5–31.9
Public health department	37	8,101	18.8	12.1–25.5
Schools	35	8,081	18.7	12.6–24.8
Radio	38	8,050	18.6	12.3–25.0
Tik Tok	29	7,767	18.0	10.3–25.7
Newspaper	33	6,815	15.8	9.1–22.4
X	20	5,586	12.9	5.9–20.0
Other social media	21	4,660	10.8	5.5–16.1
Church/place of worship	11	2,671	6.2	9.9–2.4
Other[2]	22	4,911	11.4	6.2–16.5
Have not heard any information	2	–	–	–
Most trusted source for accurate information[1]				
County of San Diego HD	103	23,865	55.3	47.0–63.7
Friends, family, neighbor, coworker	80	18,834	43.6	34.5–52.7
Doctor, nurse, healthcare provider	82	18,471	42.8	33.1–52.5
Self/Household	69	16,393	38.0	26.9–49.1
County of San Diego Officials (non-HD)	54	13,020	30.2	20.1–40.2
Mayor	59	13,210	30.6	22.9–38.3
City Officials	57	12,502	29.0	37.6–20.3
Governor	43	9,914	23.0	15.8–30.2
Pastor, priest, spiritual leader	18	4,166	9.7	4.8–14.5
Other[3]	29	7,488	17.3	9.5–25.2
Do not trust anyone	17	3,851	8.9	3.7–14.1
Barriers to communication[1]				
Impaired vision	44	10,092	23.4	16.4–30.4
Difficulty understanding English	43	9,652	22.4	15.2–29.5
Impaired hearing	36	8,062	18.7	13.2–24.7
Difficulty with mobility	36	7,808	18.1	11.8–24.4
Developmental/cognitive disability	20	4,610	10.7	4.6–16.8
Difficulty w/written material	18	4,224	9.8	4.6–15.0
No barriers	98	22,890	53.0	44.8–61.3
1 or more barriers	91	20,280	47.0	38.7–55.2

[1]Households could choose more than one response
[2]Other includes flyers, door hangers, public meetings, lived experiences, mail notices, etc.
[3]Other includes news, CDC, community activist groups for sewage crisis, lifeguards, scientists/environmentalists, professors, etc.

Table 8. Household (HH) opinions and beliefs about the crisis – Tijuana River Valley, 2024

	Tijuana River Valley CASPER (n=189)			
	Frequency	Estimate	% of HH	95% CI
Quality of the Tijuana River water				
Not Ok	175	40,004	92.7	88.4–96.9
Ok	1	–	–	–
Quality of the nearby ocean water				
Not Ok	171	39,079	90.5	85.3–95.8
Ok	4	–	–	–
Quality of air in the area				
Not Ok	145	33,241	77.0	68.8–85.2
Ok	36	8,242	19.1	12.1–26.1
Sewage in Tijuana River causing air and water pollution				
True	182	41,534	98.1	95.8–100.0
False	4	–	–	–
Sewage issue is causing bad odors in area				
True	180	40,960	96.2	92.0–100.0
False	7	1,610	3.8	0.0–8.0
Sewage crisis is getting worse				
True	168	38,553	89.3	85.0–93.6
False	14	2,989	6.9	3.5–10.4
Don't know	7	1,627	3.8	0.7–6.8
Sewage has negatively affected HHs quality of life				
True	156	34,418	80.4	72.3–88.5
False	32	8,392	19.6	11.5–27.7
Sewage made HHs health worse				
True	128	27,656	67.3	57.8–76.8
False	53	13,444	32.7	23.2–42.2
Community feels like a safe place to live				
True	97	22,803	52.8	44.4–61.3
False	87	19,151	44.4	35.9–52.8
Don't know	5	1,216	2.8	0.3–5.3
HH tap water is safe to drink				
False	138	30,753	71.2	62.4–80.1
True	39	9,551	22.1	13.0–31.3
Don't know	12	2,866	6.6	3.1–10.2
Sewage cleanup in area is sufficient				
False	157	35,942	87.9	82.6–93.2
True	22	4,949	12.1	6.8–17.4

Table 9. Household (HH) health status – Tijuana River Valley, 2024

	Tijuana River Valley CASPER (n=189)			
	Frequency	Estimate	% of HH	95% CI
Perceived overall health of HH				
Poor	11	2,278	5.3	2.4–8.2
Fair	58	12,920	29.9	24.3–35.5
Good	90	21,415	49.6	42.0–57.2
Excellent	30	6,556	15.2	9.5–20.9
Experienced symptoms caused by sewage crisis in past month[1]				
Yes	87	19,337	44.8	34.9–54.7
Headache	*68*	*15,452*	*80.0*	*67.9–92.0*
Nausea/upset stomach	*63*	*13,873*	*71.7*	*60.4–83.1*
Cough	*54*	*12,057*	*62.3*	*50.7–73.8*
Dry/irritated throat	*52*	*11,718*	*60.6*	*48.2–72.9*
Dizziness/light-headedness	*45*	*9,917*	*51.3*	*38.9–63.6*
Shortness of breath	*45*	*9,737*	*50.4*	*39.7–61.0*
Fatigue	*43*	*9,497*	*49.1*	*36.3–61.9*
Migraine	*40*	*8,701*	*45.0*	*32.0–58.1*
Diarrhea	*28*	*6,440*	*33.3*	*23.2–43.4*
Vomiting	*27*	*5,929*	*30.7*	*22.0–39.3*
Rash	*26*	*5,794*	*30.0*	*19.3–40.6*
Chest tightness/heaviness	*25*	*5,604*	*29.0*	*20.4–37.5*
Fever	*14*	*3,368*	*17.4*	*4.2–8.8*
Other[2]	*25*	*5,376*	*27.8*	*16.5–39.1*
No	97	22,830	52.9	42.9–62.8
Don't know	5	1,002	2.3	0.3–4.3
Number of symptoms experienced caused by sewage crisis in past month				
1-3 symptoms	17	3,798	19.6	9.9–29.3
4-7 symptoms	40	8,853	45.8	37.3–54.2
8 or more symptoms	30	6,686	34.6	22.9–46.2
Member of HH considered "medically fragile"				
Yes	68	15,053	35.1	26.5–43.6
No	120	27,877	64.9	56.4–73.5
Worsening chronic health in the past month[1]				
Allergies	100	21,943	51.1	41.0–61.2
Migraines	57	12,817	30.0	24.3–35.7
Chest/lung pain	35	7,759	18.1	12.4–23.8
Asthma	33	7,099	16.5	10.7–22.4
Diabetes	18	4,094	9.6	4.1–15.0
Hypertension/heart disease	19	4,077	9.5	5.3–13.7
Previous mental health condition	18	3,962	9.2	4.4–14.0
COPD/emphysema	7	1,627	3.8	0.8–6.9
Other[2]	14	3,286	7.7	2.2–3.2
1+ worsening chronic health condition	125	27,701	64.5	55.5–73.5
Sought medical care because of the crisis[2]				
Yes	36	7,819	18.2	12.4–24.0
Clinic	*16*	*3,496*	*44.7*	*26.0–63.5*
Urgent care	*15*	*3,106*	*39.7*	*20.0–59.4*
Emergency department	*9*	*1,979*	*25.3*	*7.3–43.3*
Other[3]	*6*	*1,216*	*15.6*	*5.0–26.0*
No	152	35,112	81.8	76.0–87.6
Symptoms improved when away from area				
Yes	88	20,740	48.0	38.9–57.1
No	18	3,928	9.1	4.5–13.7
Have not spent time away from area	23	5,112	11.8	6.2–17.5
No sewage-related health issues	60	13,390	31.0	3.6–22.5

[1]*Households could choose more than one response*
[2]*Other includes Lupus, skin conditions, bronchitis, cancer, Autistic behavioral changes, etc.*
[3]*Other includes school nurse, allergist, and other specialist care*

Table 10. Household (HH) behavioral and mental health indicators – Tijuana River Valley, 2024

	Tijuana River Valley CASPER (n=189)			
	Frequency	Estimate	% of HH	95% CI
The sewage crisis negatively affected HHs[1]				
Peace of Mind	135	31,334	72.6	65.1–80.1
Health	105	23,204	53.8	44.8–62.7
Property	64	15,320	35.5	25.5–45.5
Finances	43	9,309	21.6	15.0–28.2
Other[2]	8	1,653	3.8	1.4–6.3
No negative effects	32	7,111	16.5	9.5–23.4
1 or more effects	157	36,059	83.5	76.6–90.5
Feels home is safe in which to live				
Yes	121	28,074	65.0	56.1–73.9
No	62	13,879	32.2	24.0–40.3
Don't know/unsure	6	1,216	2.8	0.3–5.3
Loss or serious illness of pet because of the crisis				
Of HHs w/pets (n=109)	7	1,564	6.5	1.2–11.7
HH stress level since sewage crisis				
No change	73	17,789	41.4	32.6–50.3
Increased a little	67	14,727	34.3	27.5–41.1
Increased a lot	48	10,414	24.3	9.6–18.9
HH adaptive changes (life transitions) because of the crisis				
Take a different route to avoid crisis	73	17,318	40.3	31.1–49.5
Considered moving	74	16,413	38.2	29.6–46.9
Missed school or work	21	4,523	10.5	5.6–15.4
Other[2]	8	1,684	3.9	1.1–6.7
Changed jobs/school	6	1,242	2.9	0.7–5.1
Lost employment	3	–	–	–
1 or more life transition	107	24,758	57.3	47.9–66.8
Experienced behavioral health indicators because of the crisis[1]				
Trouble sleeping/nightmares	109	24,083	56.1	45.1–67.1
Mood change	64	14,949	34.7	25.7–43.9
Difficulty concentrating	65	13,948	32.5	24.9–40.0
Agitated behavior	51	12,100	28.2	19.1–37.3
Loss of appetite	53	11,613	27.1	19.3–34.8
Increased alcohol use	11	2,614	6.1	1.7–2.6
Increased drug use	4	–	–	–
1 or more behavioral health indicator	122	28,045	65.3	55.5–75.2
Experienced signs of emotional distress because of the crisis				
Headaches/stomachaches/body pain	94	21,165	49.0	39.8–58.3
Increased anxiety/worry	76	16,293	37.7	29.2–46.2
Lack of energy	66	14,476	33.5	25.7–41.4
Spending less time with friends/family	59	13,057	30.2	22.4–38.1
Sadness/depression	47	10,130	23.5	16.3–30.6
Feeling alone/isolated	24	5,076	11.8	6.5–17.0
Feeling of numbness	20	4,545	10.5	6.0–15.1
Other	7	1,496	3.5	1.0–5.9
None	60	14,727	34.1	24.9–43.3
1 or more signs	129	28,443	65.9	56.7–75.1
Received behavioral or mental health services in past month				
Yes	10	2,081	4.9	1.5–8.3
Could not get services	13	2,660	6.2	2.3–10.2
No need for services	164	37,948	88.9	82.3–94.8

[1]Households could choose more than one response
[2]Other includes health of pet, quality of life, trust in government action, physical activity, etc.

Table 11. Individual mental health status – Tijuana River Valley, 2024

	Tijuana River Valley CASPER (n=189)			
	Frequency	Estimate	% of HH	95% CI
Over last 2 weeks, had little interest or pleasure doing things				
Not at all	128	74,388	70.9	64.7–77.0
Several days	30	14,924	14.2	8.7–19.8
More than half	19	10,556	10.1	5.0–15.1
Nearly every day	10	5,088	4.8	0.9–8.8
Over last 2 weeks, felt down, depressed, or hopeless				
Not at all	137	79,176	75.4	69.9–81.0
Several days	34	17,335	16.5	11.5–21.5
More than half	13	6,544	6.2	2.2–10.3
Nearly every day	3	--	--	--
Patient Health Questionnaire 2 (PHQ-2) score				
Less than 3	161	91,025	86.0	80.0–92.0
3 or more	28	14,822	14.0	8.0–20.0
Over last 2 weeks, felt nervous, anxious, or on edge				
Not at all	116	66,285	63.2	55.9–70.5
Several days	51	28,102	26.8	20.0–33.5
More than half	12	6,133	5.8	2.3–9.4
Nearly every day	8	4,437	4.2	1.3–7.2
Over last 2 weeks, felt unable to stop or control worrying				
Not at all	130	73,567	70.1	63.0–77.2
Several days	36	19,139	18.2	12.8–23.6
More than half	12	6,923	6.6	2.9–10.3
Nearly every day	9	5,328	5.1	0.6–9.6
Generalized Anxiety Disorder 2 (GAD-2) score				
Less than 3	167	93,427	88.3	82.2–94.3
3 or more	22	12,420	11.7	5.7–17.8
Mental health in past 30 days				
<14 days “not good”	162	92,593	88.2	82.4–94.1
≥14 days “not good”	25	12,363	11.7	5.9–17.6
Mental health keeps from doing usual activities				
<14 days impacting activities	156	89.143	84.9	79.0–90.8
≥14 days impacting activities	31	15,814	15.1	9.2–21.0

Appendix A: Questionnaire

Community Assessment for Public Health Emergency Response (CASPER) – Tijuana River Sewage Crisis, 2024

DK=Don't Know Ref=Refused NA=Not Applicable HH=Household

Date: 10/____/2024 **Cluster Number: _____** **Interview Number: _______** **Team name: ____________________________**

First, we would like to gather some general information about your household – this includes yourself and any other individuals who sleep at your home most nights.

Complete before beginning survey: *Type of structure*
□ Single family □ Multiple unit □ Mobile home □ Other _________

Q1. Including yourself, how many people live in your home? ___#___

Q2. Including yourself, how many people living in your home are
Less than 2 years old? ___#___ 2-17 years old? ___#___
18-64 years old? ___#___ 65 years or older? ___#___ □ DK □ Ref

Q3. Is your home… □ Owned by you or somebody in your home
□ Rented □ Occupied without ownership or rent □ DK □ Ref

Q4. Does your household have any…pets? □ Yes □ No □ DK □ Ref
…livestock? □ Yes □ No □ DK □ Ref

Q5. What is the primary language spoken in your HH? *(Check ONE)*
□ English □ Spanish □ Other__________ □ DK □ Ref

Now we would like to know more about you your household's experience with air and water exposures related to the sewage crisis

Q6. How **aware** is your HH about the Tijuana River Valley sewage crisis? □ Very □ Somewhat □ A little □ Not at all □ DK □ Ref

Q7. In the past month, have you or a member of your HH been in direct contact with water from the Tijuana River?
□ Yes □ No □ DK □ Ref

Q8. In the past month, have you or a member of your HH been in direct contact with the beach water from Imperial Beach, Tijuana Slough, or Silver Strand shorelines while these beaches have been closed? □ Yes □ No □ DK □ Ref

Q9. Has your HH taken any extra steps to avoid certain areas because of the sewage contamination?
□ Yes - frequently □ Yes – sometimes □ No □ DK □ Ref

Q10. In the past month, have you or a member of your HH noticed a sewage smell…
- inside your home □ Yes (Q10a) □ No □ DK □ Ref
- outside your home □ Yes (Q10a) □ No □ DK □ Ref
- in the neighborhood? □ Yes (Q10a) □ No □ DK □ Ref

Q10a. IF YES, what time of day has your HH noticed the smell is the strongest? *(Check ONE)*
□ Morning □ Afternoon □ Evening/Night □ DK □ Ref

Q11. Have you or a member of your HH used any of the following to *reduce the sewage smell* inside your home? *(Check ALL)*
□ Portable air purifier, cleaner, or filter □ Air freshener/Deodorizer
□ Humidifier or de-humidifier inside your home □ Closed windows
□ Candles, incense, or oil □ Ammonia/Bleach cleaning products
□ Other ______________________________
□ None - Did not use anything
□ No sewage smell in the home □ DK □ Ref

Q11a. *If YES to any* above, did it help to remove the smell?
□ Yes □ No □ Depends/Sometimes □ DK □ Ref

Q12. How **concerned** is your HH about the sewage crisis?
□ Very □ Somewhat □ A little □ Not at all □ DK □ Ref

Q13. Does your HH feel your home is safe to live in?
□ Yes □ No □ DK □ Ref

Q14. Has your HH changed any daily activities or routines because of the sewage crisis? *(Check ONE)*
□ Yes – many changes □ Yes – some □ No changes □ DK □ Ref

Q15. In the past month, has the sewage crisis disrupted any of the following aspects of your HH's life? *(Check ALL)*
□ Daily routines □ Social activities □ Exercise □ Sleep schedule
□ School/work □ Childcare/daycare □ Church/place of worship
□ Daily community life □ Quality time with family
□ Eating behaviors/schedule □ Other ____________________
□ No disruptions □ DK □ Ref

Q16. In the past month, has the sewage crisis affected any of your HH's outdoor activities? *(Check ALL)*
- Time outdoors □ Increased □ Decreased □ No change □ DK □ Ref
- Gardening □ Increased □ Decreased □ No change □ DK □ Ref
- Visiting beaches □ Increased □ Decreased □ No change □ DK □ Ref
- Parks/playgrounds □ Increased □ Decreased □ No change □ DK □ Ref
- Other _________ □ Increased □ Decreased □ No change □ DK □ Ref

Q17. What is your HH **MOST** concerned about when it comes to the sewage crisis? *(Check ONE)* □ Health of HH members
□ Health of pets/livestock □ Decrease in property value
□ Other ________________________ □ Nothing □ DK □ Ref

Q18. Where do you get **most** of your drinking water? *(Check ONE)*
□ Tap/city □ Bottle □ Well □ Other ____________ □ DK □ Ref

Q19. Has your HH changed where you get drinking water since the crisis began? □ Yes (Q19a) □ No □ DK □ Ref

Q19a. If YES, why? ______________________________ □ DK □ Ref

Now we would like to know a little more about your household's communication preferences

Q20. Do you or does anyone in your household have any of the following? *(Check ALL)* □ Impaired hearing □ Impaired vision
□ Developmental/cognitive disability □ Difficulty understanding English □ Difficulty understanding written material
□ Difficulty with mobility □ None of the above □ DK □ Ref

Q21. Where does your household **usually** get information about the sewage crisis? *(Check ALL)* □ TV □ Radio □ Newspaper
□ Internet news □ Instagram □ Facebook □ Tik Tok □ X
□ Other social media □ Church/Place of worship
□ Schools □ Work □ Public Health Department
□ Friends/Family/Neighbor/Word of Mouth
□ Other ______________________________
□ Have not heard any information □ DK □ Ref

Q22. Who does your household **trust most** to give accurate information about the sewage crisis? *(Check ALL)*
□ County of San Diego non-HD officials □ City officials
□ County of San Diego Health Department (HD)
□ Doctor, nurse, healthcare provider
□ Pastor, priest, spiritual leader □ Friend/Family/Neighbor/Coworker
□ Mayor □ Governor □ Other ____________________
□ Ourselves/household □ Do not trust anyone □ DK □ Ref

Now we would like to know a little more about your household's thoughts about the sewage crisis.

Q23. Please tell us if your HH believes the following have been **OK** or **Not OK** in the past month
- a. Quality of the air in the area □ OK □ Not OK □ DK □ Ref
- b. Quality of the nearby ocean water □ OK □ Not OK □ DK □ Ref
- c. Quality of the Tijuana River water □ OK □ Not OK □ DK □ Ref

Q24. Please tell us if your HH believes the following are **TRUE (T)** or **FALSE (F)**

The sewage crisis is getting worse	□ T □ F □ DK □ R	The sewage issue is causing bad odors in the area	□ T □ F □ DK □ R
Our HH tap water is safe to drink	□ T □ F □ DK □ R	The sewage has negatively affected our HHs quality of life	□ T □ F □ DK □ R
The sewage cleanup in the area is sufficient	□ T □ F □ DK □ R	The sewage has made our HH's health worse	□ T □ F □ DK □ R
Our community feels like a safe place to live	□ T □ F □ DK □ R	Sewage in the Tijuana River is causing air & water pollution	□ T □ F □ DK □ R

The next questions are about the health of you and members of your household

Q25. Has the sewage crisis negatively affected your HH's...
(Check ALL) □ Property □ Finances □ Health □ Peace of Mind
□ Other______________________ □ No negative effects □ DK □ Ref

Q26. How would you rate the overall health of your HH? *(Check ONE)*
□ Excellent □ Good □ Fair □ Poor □ DK □ Ref

Q27. Has your HH experienced a loss or serious illness because of the sewage crisis to.... a pet □ Yes □ No □ No pet □ DK □ Ref
... livestock □ Yes □ No □ No livestock □ DK □ Ref

Q28. In the past month, have you or a member of your HH had any health symptoms that they think were *caused by* the sewage crisis?
□ Yes (Q28a) □ No □ DK □ Ref

Q28a. *IF YES,* which symptoms? *(Check ALL)* □ Dry/Irritated throat
□ Cough □ Rash □ Fever □ Shortness of breath
□ Chest tightness/heaviness □ Headache □ Migraine
□ Nausea/Upset stomach □ Vomiting □ Diarrhea
□ Fatigue □ Dizziness/Light-headedness
□ Other ________________________________ □ DK □ Ref

Q29. Have health symptoms you or a member of your HH had from the sewage crisis gotten better when they spent time away from the area? □ Yes □ No □ N/A – no sewage-related health issues
□ N/A – have not spent time away from the area □ DK □ Ref

Q30. Is anyone in your HH considered "medically fragile", or been told by a doctor or healthcare professional they have a chronic medical condition? □ Yes □ No □ DK □ Ref

Q31. In the past month, have you or any members of your HH experienced **worsening** of...

Allergies	□ Yes □ No □ N/A □ DK □ Ref
Asthma	□ Yes □ No □ N/A □ DK □ Ref
Chest/lung pain	□ Yes □ No □ N/A □ DK □ Ref
COPD/Emphysema	□ Yes □ No □ N/A □ DK □ Ref
Diabetes	□ Yes □ No □ N/A □ DK □ Ref
Hypertension/heart disease	□ Yes □ No □ N/A □ DK □ Ref
Migraines	□ Yes □ No □ N/A □ DK □ Ref
Previous MH condition	□ Yes □ No □ N/A □ DK □ Ref
Other ________________	□ Yes □ No □ N/A □ DK □ Ref

Q33. How has the sewage crisis affected the overall stress level of your HH? *(Check ONE)*
□ Increased a lot □ Increased a little □ No change □ DK □ Ref

Q34. Because of the sewage crisis, have you or a member of your HH...

Lost employment	□ Yes □ No □ N/A □ DK □ Ref
Changed jobs	□ Yes □ No □ N/A □ DK □ Ref
Change schools	□ Yes □ No □ N/A □ DK □ Ref
Changed day care	□ Yes □ No □ N/A □ DK □ Ref
Missed school or work	□ Yes □ No □ N/A □ DK □ Ref
Considered moving	□ Yes □ No □ N/A □ DK □ Ref
Take a different route to avoid sewage-contaminated areas	□ Yes □ No □ N/A □ DK □ Ref
Other________________	□ Yes □ No □ N/A □ DK □ Ref

Q35. In the past month, have you or a member of your HH had any of the following *because of the sewage crisis?*

Difficulty concentrating	□ Yes □ No □ DK □ Ref
Trouble sleeping/nightmares	□ Yes □ No □ DK □ Ref
Loss of appetite	□ Yes □ No □ DK □ Ref
Agitated behavior	□ Yes □ No □ DK □ Ref
Mood changes (e.g., irritable, sad)	□ Yes □ No □ DK □ Ref
Increased alcohol consumption	□ Yes □ No □ DK □ Ref
Increased drug use, including marijuana	□ Yes □ No □ DK □ Ref

Q36. Have you or members of your household experienced any of the following because of the sewage crisis? *(Check ALL)*
□ Lack of energy □ Feelings of numbness
□ Sadness/depression □ Increased anxiety/worry
□ Headaches/stomachaches/body pain □ Feeling alone/isolated
□ Spending less time with friends/family
□ Other ________________________________
□ None □ DK □ Ref

Q37. In the past month**,** have you or members of your HH received services from a counselor, pastor/clergy member, therapist, social worker, or hotline (e.g., 988) for behavioral health concerns as a result of the sewage crisis?
□ Yes □ No – couldn't get services □ No – no need □ DK □ Ref

Q32. Have you or anyone in your household needed medical care because of the sewage crisis? □ Yes (Q32a) □ No □ DK □ Ref

Q32a. *IF YES,* where did you/they go? *(Check ALL)* □ Clinic □ Emergency Dept □ Urgent Care □ School nurse
□ Other ______________________________ □ DK □ Ref

Now we are going to ask about YOU as an INDIVIDUAL. Please remember your responses are confidential and private

Q38. Thinking about your mental health, which includes stress, depression, and problems with emotions, for how many days during the **past 30 days** was your mental health not good? __#__ □ DK □ Ref

Q39. During the **past 30 days**, for about how many days did poor physical or mental health keep you from doing your usual activities, such as self-care, work, or recreation? __#__ □ DK □ Ref

Q40. Over the last __**2 weeks**__, how often have you...
Had little interest or pleasure in doing things? □ Not at all □ Several days □ More than half the days □ Nearly every day □ DK □ Ref
Felt down, depressed or hopeless? □ Not at all □ Several days □ More than half the days. □ Nearly every day □ DK □ Ref

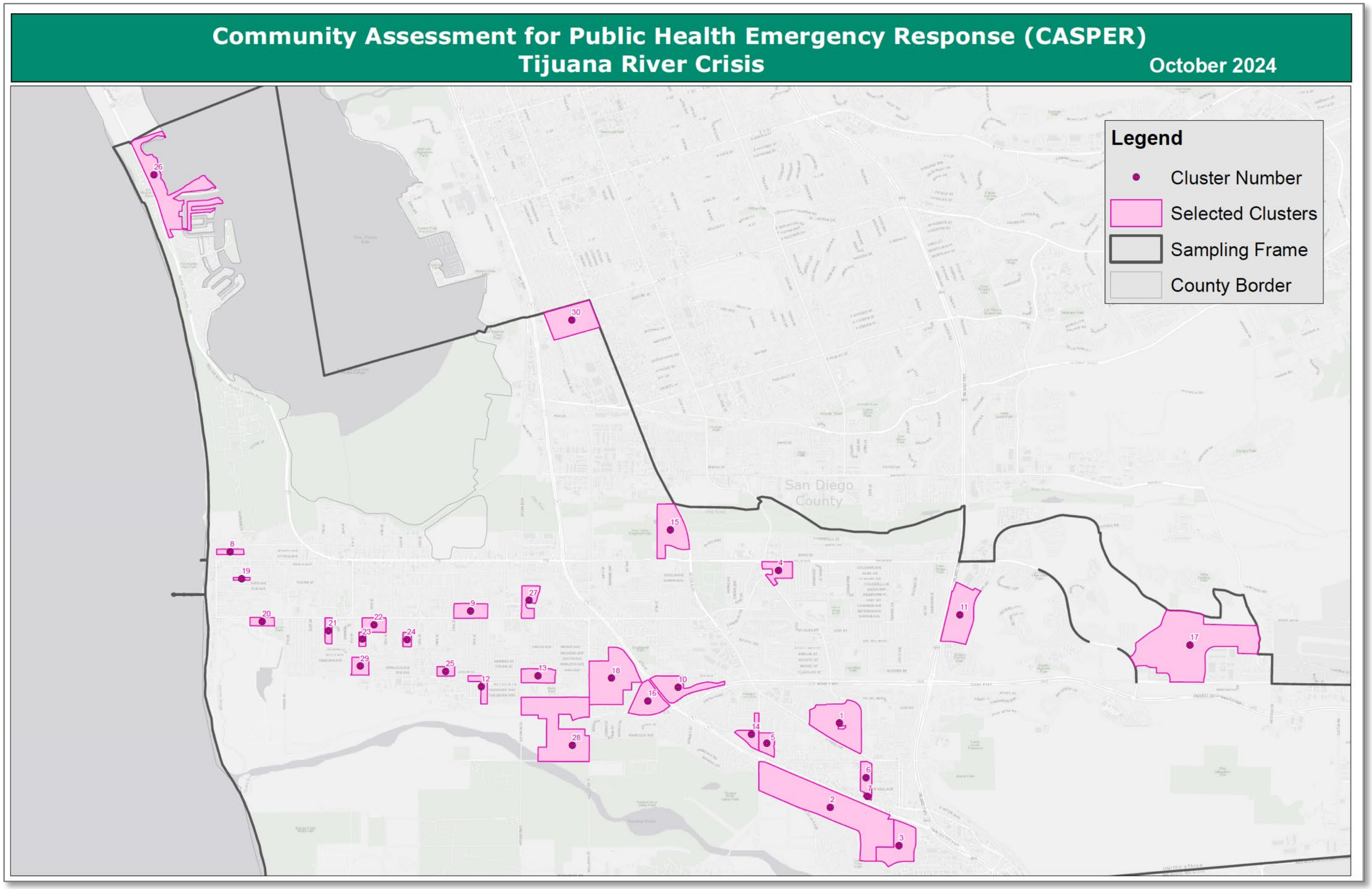
Q41. Over the last __**2 weeks**__, how often have you...
Felt nervous, anxious, or on edge? □ Not at all □ Several days □ More than half the days □ Nearly every day □ DK □ Ref
Been unable to stop or control worrying? □ Not at all □ Several days □ More than half the days □ Nearly every day □ DK □ Ref

Q42. Last question, what is your HHs greatest need as result of the Tijuana River sewage crisis at this time?

□ Nothing □ DK □ Ref

NOTE: Questionnaire was also translated into Spanish

Appendix B: Selected Clusters



Appendix C: Consent Script

Tijuana River Crisis

Community Assessment for Public Health Emergency Response (CASPER)

We are part of the field team with representatives from County of San Diego and Centers for Disease Control and Prevention (CDC). We are talking to randomly chosen households for a Community Health Assessment in the Tijuana River Valley.

- We are talking to people who live in the Tijuana River Valley about the problems with sewage.
- We want to find out if your household noticed any issues with the air or water, how it may be affecting health, what resources your family may need, and how your household prefers to get updates and information about the situation
- We are trying to figure out how to better help your community
- Your house was randomly chosen for this survey
- If you agree to take part, we will not ask any personal questions like about education or where your household members were born. The questions are about your ENTIRE household
- The survey will take about 20 minutes. Your answers will be kept private, and you do not have to answer anything you do not want to.
- We also have some information that may be useful for you and your household

If you have any questions about this survey, you may email the County of San Diego at phs.southregionhealth.hhsa@sdcounty.ca.gov

NOTE: Consent was also available in Spanish

Appendix D: Confidential Referral Form

Community Assessment for Public Health Emergency Response

Confidential Referral Form

Date: __/__/____ Time: __:__
Cluster No.: _____
Interviewer's Initials: _____

Name: ____

Address: ____

Contact Information:

Home telephone: ______ - _____ - _______

Cell phone: _____ - ____ - _______

E-mail: ____________________________

Summary of Need:

____
____
____
____
____
____
____

Referral Made: Yes ☐ No ☐

Referred to: _____________________________________

Appendix E: Public Health Materials

SOUTH REGION CDC HEALTH SURVEY

*The Centers for Disease Control and Prevention (CDC) is working with the County of San Diego to learn more about **health concerns and impacts from sewage and pollution in the Tijuana River Valley**. This will be done through a survey called a Community Assessment for Public Health Emergency Response, or CASPER.*

WHAT IS A CASPER?

CASPER stands for Community Assessment for Public Health Emergency Respon[…] type of household survey developed by the CDC.

- It is a way to quickly gather information about the needs of an affected com[…]
- It is a point-in-time survey.

HOW IS A CASPER DONE?

CASPER is done by interviewing people face-to-face in their community.

- A CASPER uses a two-stage sampling method designed to pick just the righ[…] of households to interview. First, 30 blocks (clusters) are selected, then 7 households are selected in each block. A total of 210 interviews will be con[…]
- Representatives from the County and CDC will visit randomly selected hom[…] South Region. They will ask about health concerns, experiences, and impac[…] sewage and pollution in the Tijuana River Valley.
- If your home is randomly selected, the in-person survey will take about 15 […] of your time. Participation is voluntary and anonymous.

WHAT WILL THE DATA BE USED FOR?

There has been a long history of cross-border flows containing untreated sewa[…] sediment, and trash entering the Tijuana River Valley. This impacts local recrea[…] damages sensitive habitats, threatens public health, and causes beach water co[…] closures.

Your input will help us better understand the health status, experiences, and ne[…] the South region of […] River Valley.

To lea[…] sandi[…]
For q[…] phs.s[…]

LIVE WELL SAN DIEGO

Sewage Safety

Sewage can run out into the yard or land from wastewater backing up from underground sewer pipes, or septic tank build up, or heavy rains.

PROTECT YOURSELF AND OTHERS FROM SEWAGE

Avoid Direct Contact

- Stay away from areas with visible sewage spills.
- Do not allow children to play in areas where visible sewage is present.

Wear Protective Gear

- Use gloves, masks, and boots when cleaning or handling items contaminated with sewage.

Proper Cleaning

- Disinfect all surfaces with a bleach solution.
- Wash clothes and fabrics that have come into contact with sewage separately in hot water.

Personal Hygiene

- Wash hands well with water and soap.
- Do not touch your nose, mouth, eyes, or ears with your hands, unless your hands have been washed.

Seek Help

- Talk to your doctor or nurse if you are sick after being exposed to sewage.

Scan QR code for more resources and updates, or visit South Region Illness Concerns.

Scan QR code to see if water areas are monitored, under advisory, or have been closed for health or safety reasons, or visit the Beach & Bay Water Quality Program.

LIVE WELL SAN DIEGO
PHAB
07/22/2024

ENVIRONMENTAL & YOUR HEALTH

WHAT'S THAT SMELL?

Hydrogen sulfide is a colorless gas. At low le[…] eggs. Hydrogen sulfide occurs naturally in so[…] organic decomposition (breakdown), such as […] with large amounts of decaying seaweed.

STEPS TO TAKE

Smelling hydrogen sulfide does not always m[…] the smell is strong, or you are concerned, the[…]

Reduce Exposure

- Limit outdoor activity.
- Keep windows and doors closed.
- Air out your home, or business, when odors are not present.

Improve Air Quality in Your Home or Business

- Use air conditioning, or portable indoor air purifiers. Look into whether filters need to be replaced.
- Use certified HEPA filters with activated charcoal.
- If possible, run your air conditioner at your business for 1-2 hours before opening.

Call Your Doctor

- If you are experiencing persistent, worrisome, or worsening symptoms from strong odors, call your doctor, especially if you have chronic health conditions.
- If you do not have a doctor, contact 2-1-1 San Diego.

MORE INFORMATION

Scan this QR code, or visit sandiegocounty.gov/southregionhealth.

LIVE WELL SAN DIEGO
PHAB
9/13/2024

Appendix F: Interview Team Quotes from the Field (selected list)

"*When we were interviewing a husband and wife, they spoke about how their kids' class had to be cancelled because of the quality of air and how they are very concerned about the future of their children's health and now they don't want the lives of their kids to be more affected than they already are.*" – Interview Team

"*One of the residents we interviewed has been aware of the Tijuana River Crisis for decades. Since the boil water advisories, she has stopped drinking tap water. Her and her family only drink bottled water. They have also moved parts of town because of the smell and pollution.*" – Interview Team

"*A resident has been surfing since he was 13 years old and now has to leave his community/local beach to drive up the coast to safer beaches. He is now experiencing worsening health conditions related to respiratory illnesses (i.e., asthma, allergies).*" – Interview Team

"*Our one interview was super happy to speak with us as she has directly felt the impacts of the sewage crisis. She remembers when it began 35+ years ago and had to move after retiring from being a preschool teacher in IB. When she leaves the area her allergy-like symptoms go away, making her feel worse when she gets back…*" – Interview Team

"*One resident was so passionate about this, ... He said if this was happening in La Jolla, it would've been fixed years ago.*" – Interview Team

"*I visited 2 homes, each home included a woman in her 60's who gardens and developed a rash on their elbows and backs. The rashes seems to go away when the garden less frequently. Residents have no where to "hide" because the stench is outside and in their homes. One couple takes 4-6 hour drives at night to get away from the neighborhood when it stinks. This is affecting their sleep and ability to work. The stench is commonly smelled between 6pm-5am. A man is concerned that the sewage is causing respiratory infections and edema in his children, and they had gone to the hospital for these symptoms multiple times. Another woman said that if she had young children, she would move.*" – Interview Team

"*One resident told us that they use multiple filtration systems for drinking water for themselves and their pets, and they installed a filter in their shower because of their sensitive skin.*" - Interview Team

"*Households we spoke to today really seemed to have their neighborhood social activities affected. No one wants be outside in the evening so the kids do not play or hang out with each other. One woman said her daughter's friends don't want to come to her house because of the smell.*" – Interview Team

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- Heidi Aiem, Assistant Branch Chief
- Jeffrey Johnson, Branch Chief/Assistant Medical Services Administrator
- Mark Beatty, Assistant Medical Director
- Robert Sills, Chief/Assistant Medical Services Administrator
- Seema Shah, Interim Deputy Public Health Officer

Centers for Disease Control and Prevention

- Amy Helene Schnall, Chief, Disaster Epidemiology Unit, Emerging Environmental Hazards & Health Effects Branch, NCEH
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- DaJuandra Eugene, Epidemic Intelligence Service Officer (EISO)
- Danielle Brown, Epidemic Intelligence Service Officer (EISO)
- Fhallon Ware-Gilmore, Epidemic Intelligence Service Officer (EISO)
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- CDR James Gooch, Lead, All-Hazards Team
- CDR Michelle Dittrich, Region 2

Interview Team Members & Survey Respondents!

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the Centers for Disease Control and Prevention and the Agency of Toxic Substances and Disease Registry

County of San Diego

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BRIAN ALBRIGHT
INTERIM DEPUTY CHIEF ADMINISTRATIVE OFFICER

January 19, 2024

TO: Supervisor Nora Vargas, Chairwoman
Supervisor Terra Lawson-Remer, Vice Chair
Supervisor Joel Anderson
Supervisor Monica Montgomery Steppe
Supervisor Jim Desmond

FROM: Brian Albright, Interim Deputy Chief Administrative Officer

ECONOMIC IMPACTS OF TRANSBOUNDARY POLLUTION

On June 27, 2023 (16) the Board of Supervisors proclaimed a local emergency for U.S-Mexico Transboundary Pollution Environmental Crisis. Recommendation 3 directed the Chief Administrative Officer to evaluate the scope of economic impacts resulting from that crisis and report back to the Board.

County staff from multiple departments engaged with the affected municipalities, business associations, and the South County Economic Development Council (SCEDC) to disseminate a Transboundary Pollution Economic Impact Survey to local businesses in south county. The Office of Emergency Services (OES), the Department of Parks and Recreation (DPR), the Office of Economic Development and Government Affairs (EDGA), the Department of Environmental Health and Quality (DEHQ), and the County Communications Office (CCO) all worked diligently to share both the survey and relevant background information to interested parties, via a variety of outreach efforts including email, social media, and direct outreach and contact.

Economic Impacts of Transboundary Pollution

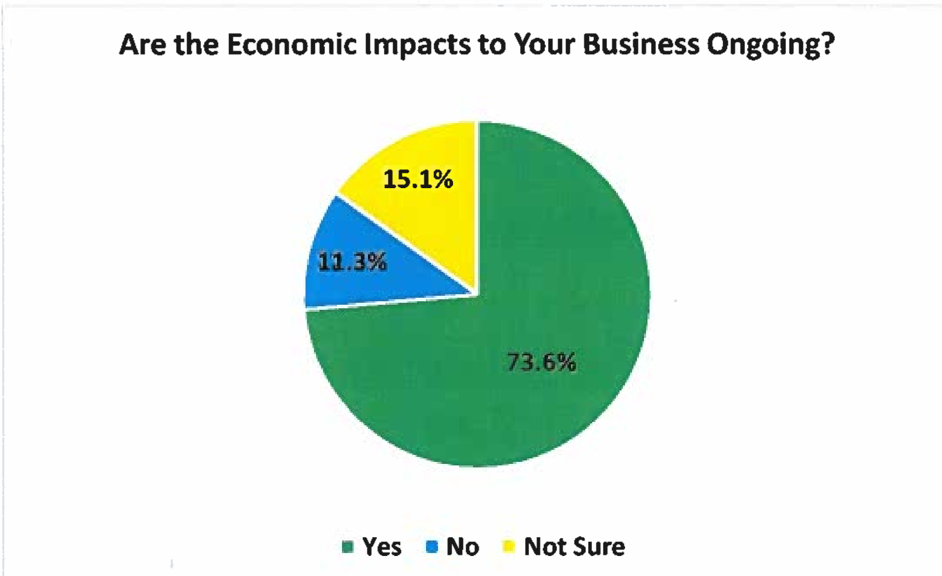
San Diego's south county beaches help create jobs, attract tourism, and provide economic opportunity to local businesses and communities. When ocean waters at the beaches are closed due to sewage impacts or under advisory or warning due to high bacteria levels, there are negative impacts to small businesses and the local economy. The full scope of economic impacts resulting from the transboundary pollution is difficult to quantify without a dedicated study.

Information gathered through a small business survey and outreach to affected business communities indicate long-standing negative economic impact that is expected to continue and become progressively worse if this situation continues. The following pages present a summary of survey questions that were directed to business in the impacted area and their responses, along with a summary of the findings and associated response data.

Question 1: Are the economic impacts to your business ongoing?

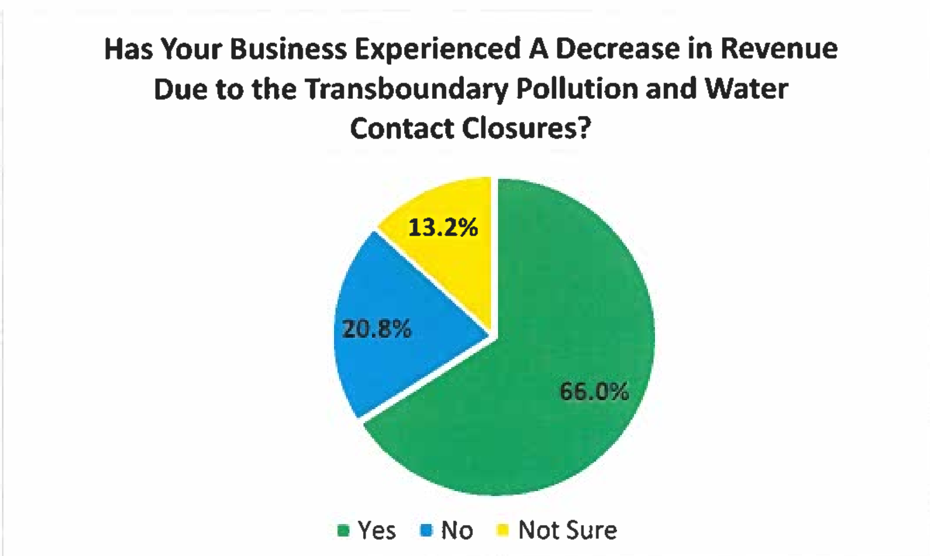
A total of 63 businesses responded to the survey via the online portal. The survey indicated that 74% of business respondents have been, and continue to be, negatively impacted by the transboundary pollution.

Looking at revenue, 66% of the respondent businesses reported a decrease in revenue due to the pollution and recent water contact closures. Exact figures cannot be independently verified, but of those respondents who provided an estimate of total economic losses, 47% indicate they have lost at least $100,000 in business revenue due to the pollution. Several respondents indicated they have lost over $100,000 in just the last fiscal year.



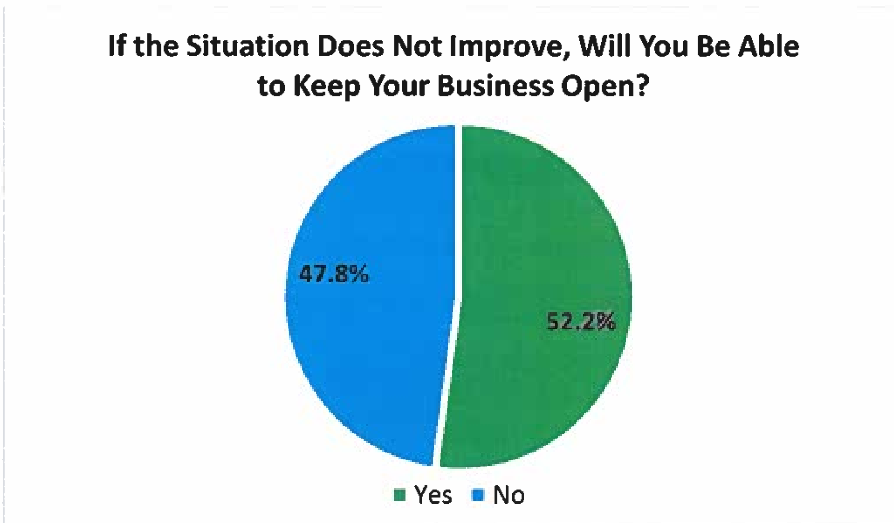
Question 2: Has your business experienced a decrease in revenue due to the transboundary pollution and water contact closures?

A majority of businesses reported a continued decline in customer "foot traffic" due to the sewage impacts resulting in beach water closures. With many of these businesses reliant on the tourism industry and visitors coming to the beach, anytime beach access is restricted or closed, local businesses lose customers. This is true for businesses that are both near the sewage affected beaches and on the traffic corridors to the beach. Nearly 30% of respondents shared that they have been forced to lay off employees (this percentage could be misleading, as many small businesses employ only a handful of employees, with many operated by the business owner themselves, therefore, this 30% figure might not fully capture the staffing difficulty of local small businesses). When asked about the future should the transboundary pollution situation not improve, a majority of business respondents report they will have trouble keeping their doors open, and several reported they plan on moving or closing. One business, Coronado Brewing Company, issued a Worker Adjustment and Retraining Notification (WARN) in September, 2023 and closed their location in Imperial Beach, laid off 27 workers in November 2023, They indicated that this closure was a direct result of the transboundary pollution issue.



Question 3: If the situation does not improve, will you be able to keep your business open?

According to the recently released report by the San Diego Tourism Authority, "Elevating Opportunities: San Diego Tourism Jobs Create Economic and Social Mobility", visitors to the region spent a record $13.6 billion in 2022, with many coming here for the beaches. When south county ocean waters are impacted by sewage and closed, local businesses, many of them small and locally owned businesses, suffer economically, as tourist move to beaches further up the coast. If there is a continued reduction in tourism due to beach water closures there will be a corresponding reduction in profitable and operating businesses, which will result in lost wages for employees and lost revenue for business owners. Affected municipalities, already having to expend funds on cleanup, disposal, and maintenance due to the transborder pollution, will likely face future budgetary restrictions due to reductions in property and sales tax revenue.



In addition to local businesses, transboundary pollution and the resulting beach water closures have resulted in the loss of recreational activities for locals and tourists alike, along with an increase in health concerns for residents. The local YMCA has had to reduce its programs, train lifeguards off-site and away from the ocean, and transport camp participants to off-site beaches. From 2005 to 2019 Imperial Beach hosted an annual surf contest held by WILDCOAST, drawing approximately 1,000 participants a year. The organization stopped hosting the event due to the number of times the beach water was impacted by sewage and closed, and in 2021 relocated its business operation to Del Mar, partly due to staff reportedly getting sick from the pollution.

To highlight examples of the responses received, below are two questions asked in the survey, with three selected answers:

Question 18: Please provide a brief explanation of the economic impacts the transboundary pollution and water contact closures have had on your business.

Answer: "The current situation had significantly decreased tourism, visitors, event's organizers, investments resulting in a significant loss for a restaurant business like ours. We opened in May 2022 and decided to invest in this area and we are now really suffering from the current pollution situation that keep people and revenue away from IB."

Answer: "We are a nonprofit that runs youth and family outdoor education and recreation programs with a focus on the county's disadvantaged communities. We typically run our programs at Imperial Beach and Silver Strand State Beach and have experienced increased staff and transportation costs associated with having to go to more distant beaches to run programs. Other times we have been unable to gain permits to run programs at other beaches and have had to cancel programs."

Answer: "My main business (for almost 30 years now) is rentals and sales of products for use at the beach and in the ocean (surfboards, boogie boards, skim boards, wetsuits, beach chairs, umbrellas). I can't rent these items nor sell them with the ocean closed. I also sell towels, beach games, sunscreen, etc. I have lost $30,000 over the past 7-8 months."

Question 21: Do you foresee any continued economic impacts if the situation does not improve?

Answer: "Most definitely. My business relies on people going to the beach and into the ocean. Tourists are appalled when I tell them that they can't go into the water."

Answer: "Yes. Continued loss of tourism revenue. Drop in property values. Continued health impacts."

Answer: "Constant water closures will lessen beach town's attractiveness to tourists resulting in general losses of all business segments."

In conclusion, there are both quantitative and anecdotal indicators that the transboundary pollution situation has had, and will continue to have, a negative economic impact on the businesses of the south county region. County staff will continue to stay in communication with the affected business community, business associations, and SCEDC to monitor the economic impacts, and any changes that may occur.

The federal landscape that influences this issue is evolving, and our advocacy efforts have increased and expanded. In the Board's recently adopted 2024 Legislative Program, additional language was added to the Priority Issues section specific to the Tijuana River Valley. Specific advocacy is focused on the Federal Appropriations Process and needed funds for the region, such as the continued push for $310 million that is supported by our Congressional Delegation. While we continue to focus efforts on essential infrastructure needs and regulatory amendments to remedy the root cause, we also are working to identify funding streams and grant opportunities that could be of use in the short term based off of the needs identified in the information contained in this memo.

If your office has any question regarding staff evaluation of the scope of economic impacts resulting from the transboundary sewage crisis, please contact Caroline Smith, Director of the Office of Economic Development and Government Affairs at (619) 531-5198 or Caroline.Smith@sdcounty.ca.gov.

Respectfully submitted,

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SAN DIEGO STATE UNIVERSITY
SCHOOL OF PUBLIC HEALTH

SDSU
College of Health and Human Services
School of Public Health

Tijuana River Contamination from Urban Runoff and Sewage:
A Public Health Crisis at the Border

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Introduction

The Tijuana River flows north from Tijuana into the Tijuana River and Estuary (TJRE) in the US, emptying into the Pacific Ocean at Imperial Beach, CA (Figure 1). The TJRE is severely contaminated by untreated sewage, industrial waste, and urban run-off due to inadequate infrastructure and urbanization and the watershed is classified as an impaired water body according to the U.S. Clean Water Act. [1-7] This contamination is a persistent environmental and **public health threat** with major economic, legal, social, and **health implications** for the nearby California communities such as San Ysidro and Imperial Beach, who have long been concerned about this devastating problem. Threats to public health include known concerns posed by any exposure to untreated sewage in the U.S., but of special concern and specific to this watershed are the unusual threats to health from pollutants arising in Mexico, including human and livestock diseases eradicated in California, pathogens carrying antibiotic-resistant genes, and industrial and municipal chemicals not permitted to be discharged into the environment in California, among others. Heavy rainfall events, including the recent Hurricane Hilary, have caused further damage to the aging infrastructure and continue to overwhelm the systems on both sides of the border, exacerbating concerns. [8] Extreme events related to climate change are only anticipated to become more frequent and intense, increasing the urgency for a solution to this crisis. [9-11] Contaminated water is flowing into the ocean year-round, and, especially after rain events, has forced beach closures in the region for several years (Figure 2) [12,13]; however, this problem does not just adversely affect beachgoers and surfers exposed to contaminated seawater. Exposures impact the health of people who live and work nearby like children, seniors, lifeguards, military personnel, border patrol officers and other at-risk populations.[14] Current regulation and monitoring measures are inadequate in relation to known contaminants yet the potential health risks to surrounding communities from **harmful viruses, bacteria and parasites as well as toxic chemicals in water and air**, presenting a pressing **public health crisis.**[15-18]

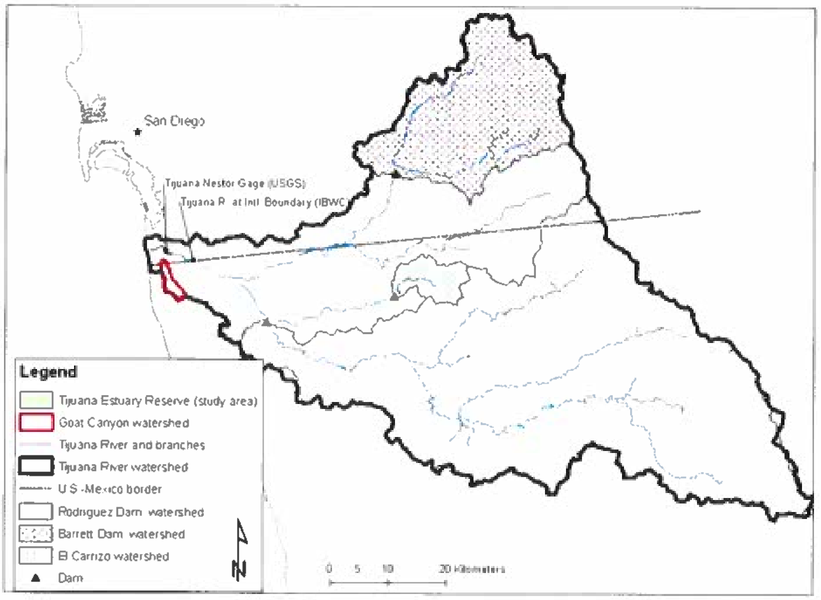

Figure1. Map of the Tijuana River Watershed, from Biggs, et.al. [19]

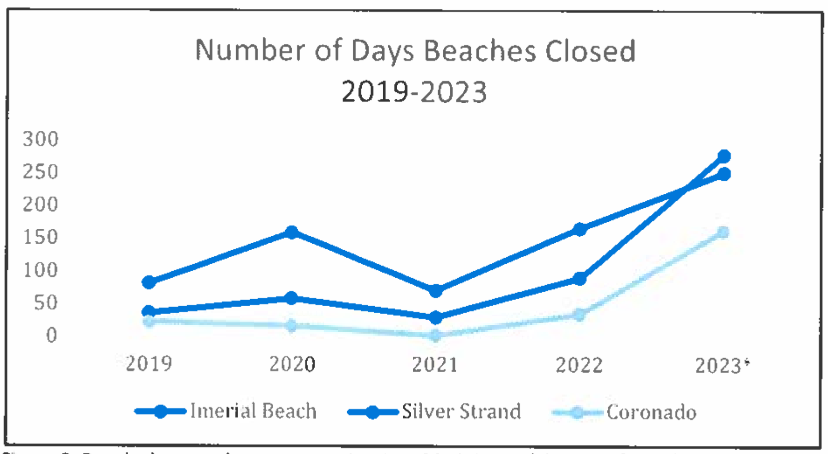

Figure 2. Beach closures due to contamination, 2019-2023, *data as of October 20,2023 from San Diego County Department of Environmental Health and Quality

What's in the soil, water, and the air?

Water Contamination

Multiple studies over the last decade done by our team at SDSU and other regional experts have shown the presence of **serious pathogens** such as viruses and bacteria, including SARS-CoV-2 and Hepatitis in the water sampled from the TJRE.[2,5,13,20-25] These pathogens pose a serious health risk to both humans and aquatic species.[26-29] One recent example of an emerging zoonotic pathogen of concern impacting our local aquatic system was documented in bottle nosed dolphins found stranded in San Diego. The animals were found to have died from sepsis caused by a bacterium called *Erysipelothrix rhusiopathiae,* which is generally transmitted through contact with feces or urine in contaminated water, food or soil.[27] The authors of the study also noted an increase in the number of stranded dolphins in the region, indicating that changes in their environment or exposures to contaminated water could be causing illness and subsequent death. These dolphins serve as sentinels for the risk of possible human exposures to dangerous bacteria such as *E. rhusiopathiae* by both recreational water users and through occupational health exposures.[30]

Research into the extent of **chemical contamination** has been sporadic, however studies by local government agencies have reported high levels of metals, pesticides, herbicides, volatile organic carbons (VOCs), and semi-volatile organic compounds (SVOCs).[13,20,31] Additionally, researchers have found highly concentrated toxicants such as acetone, methanol, xylene, plasticizers, hormones, and flame retardants.[32,33] Another recent study by SDSU experts identified 392 organic chemical contaminants in the border water by applying a novel analytical approach, mass spectrometry based nontargeted analysis. Out of the 392 identified compounds, 224 appeared on a regulatory list, and 175 appeared in the U.S. Environmental Protection Agencies Toxic Substance Control Act. A substantial number of **contaminants of emerging concern** were detected in the water for the first time.[3]

Another developing threat recently found through the application of metagenomic analysis by SDSU researchers is the significantly elevated levels of microbes carrying antibiotic-resistant genes (ARG), including beta-lactamases (resistant to antibiotics including penicillin), and resistant strains of *E. coli* and *Legionella,* which are of considerable public health concern.[23,34] This study also revealed the presence of microbial species that are not routinely monitored but are potential pathogens such as *Acrobacter cryaerophilus*, which can cause severe gastrointestinal illness, and was the most common species of bacteria found.[34-37] Other pathogens that can cause significant illness were identified and included bacteria such as *Salmonella enterica, Vibrio parahaemolyticus*, *Streptococcus pneumoniae*, *Mycobacterium tuberculosis and Listeria monocytogenes,* parasites like *Trichomonas vaginalis*, and viruses such as *HIV-1*, *Hepatitis B and C*.[23] These findings indicate the **potential for community exposure to harmful pathogens including antibiotic resistant varieties** due to cross-border sewage contamination and illustrate the need for increased surveillance of a broader range of contaminants.

Air Contamination

Air contamination originating from nearby impaired water bodies and contaminated ocean water is a concern and is a pathway of exposure that has hardly been studied.[15,16,38-41] A recent study examining air over the coastal waters near TJRE documented airborne microbes and chemicals related to the sewage and runoff over the ocean.[15] However, no studies have been conducted inside communities where people live, work and play. Contaminated air from the nearby Tijuana River outflows can possibly diffuse across the community of San Ysidro and Imperial Beach and enter homes, childcare centers, schools, and potentially **increase the health risks of local community members without any direct water contact.** Community concerns about strong odors and pollution within San Ysidro from the Tijuana River have been frequently reported.[42,43] Air mass transport patterns that can potentially transfer pollutants to border communities are not well characterized. While long-range transport of persistent chemicals transferring from water to air has a strong theoretical basis [18,44-46], and is a well-known cause of global chemical contamination, pollution transfer to air basins inside communities next to or near impaired water bodies has not been thoroughly explored and poses a potentially serious health threat to already at-risk communities.[40,47-49] This is an area of urgent need for increased monitoring and surveillance.

Soil Contamination

Analysis conducted on soil sediments in and around the Tijuana River and Estuary by the authors and others have detected over 170 organic chemicals and inorganic elements including toxic polycyclic aromatic hydrocarbons (PAHs), banned pesticides such as chlordane and DDT, polychlorinated biphenyls (PCBs), heavy metals, and phthalates.[4,49-53] Many of the detected contaminants are a direct result of the transboundary sewage flows and are known to be **persistent, bio-accumulative, carcinogenic, toxic** and can be **resuspended in water and air** during weather events in both the wet and dry seasons, exposing nearby communities.[4,53] San SDSU experts found significant levels of harmful chemical contaminants in the soil from Los Laureles-Goat Canyon, a sub watershed located within the Tijuana River Watershed. Arsenic and cadmium concentrations were higher than the EPA recommended levels (0.07 ppm for arsenic and 1.7 ppm for cadmium) in soil samples taken from Los Laureles Canyon and TJRE (Figure 3). [54] Bisphenol A (BPA) and triclosan were also high and comparable to concentrations found in sewage sludge and soils amended with sewage sludge.[54] The results of this study indicate that the heavy metals and organic contaminants in the soil are not just coming from solid waste disposal sources but are also from wastewater flows and pose a health risk to residents in the area. Exposure to these contaminants may come from ingestion, respiration or/and dermal contact and are known to have significant harmful effects on humans and wildlife.[55-58]

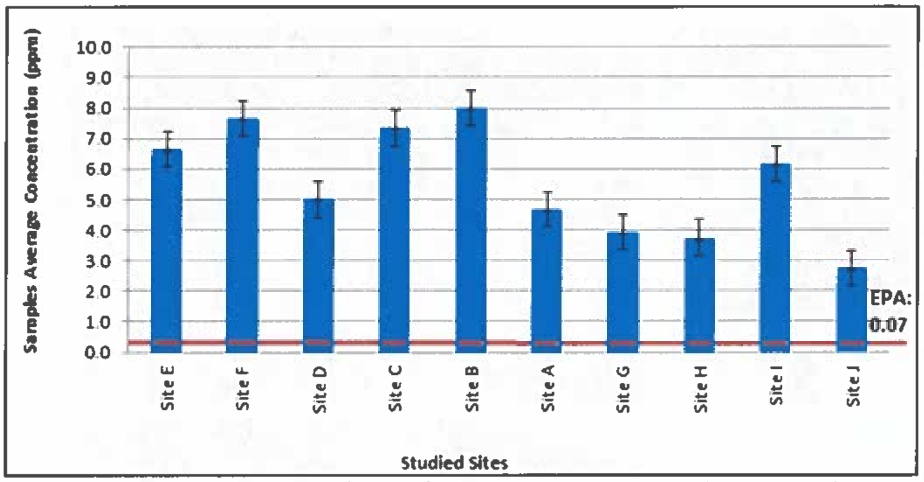

Figure 3. Average concentrations of arsenic found at study sites in Los Laureles Canyon and TJRE, A-F are sites in Mexico and G-J are sites in the U.S., n=22 [54]

Exposures Pathways and Risks

Dangerous pathogens and chemicals in contaminated waters pose a spectrum of short and long-term health risks, spanning gastrointestinal illnesses to neurological disorders.[26,59] Sewage and runoff are reservoirs for diverse and prevalent pathogenic bacteria (including antibiotic resistant), viruses, harmful chemicals, and pollutants that can cause both acute and long-term health consequences, especially when being chronically exposed.[34,60] Contaminated soils from years of transborder flows of polluted waters are laden with dangerous and toxic legacy chemicals, and when they enter the waterways or become airborne during dry weather seasons, they present major health concerns for residents and workers. Exposure pathways include contact/touching, leading to ingestion, either through contaminated soil, water or house dust, and this pathway may be especially significant for infants and toddlers. Inhalation is also a pathway of exposure, as these dangerous contaminants can also be airborne.[15,40,61] Contaminated aerosols can be transported over land and deposited through various mechanisms, exposing residents and workers by inhalation.[61]

Figure 4. Photos taken of the TJRE during sampling events by SDSU researchers, courtesy of Dr. Kari Sant

Public Health Significance

Community concerns and the documented presence in the Tijuana River and Estuary of toxic chemicals and human and animal pathogens, especially antibiotic resistant pathogens, demands urgent attention. Monitoring for a wide suite of chemicals and microbes in water and air is necessary to characterize the risks and geographic extent of the contamination to our region. In addition, special populations within this area may be at heightened risk, including workers such as lifeguards, other outdoor workers and border patrol agents, pregnant women, with their increased risk from exposure to chemical and microbial pollutants, and children, who are both highly susceptible and at increased risk of exposures due to hand-to-mouth behaviors. The possibility for a **heightened incidence of illnesses** linked to the influx and constant exposure to wastewater into California communities along the U.S.-Mexico border should be investigated. New analytical tools (e.g. non-targeted analysis of chemicals and microbial genomes) that allow characterization of a wide range of chemical and microbial pollutants much beyond the contaminants currently measured should be used to help paint a better picture of the magnitude of the problem. Especially, **poorly understood pathways of exposure should be carefully and explicitly studied**, such as exposures through breathing community air and through particulate matter and dust deposited on

surfaces touched by children. The potential for acute infectious diseases as well as long-term health impacts in both humans and animals necessitates comprehensive monitoring and more research. Health data collection for environmental epidemiology, a robust monitoring program assessing chemicals and pathogens correlated to toxicity and a broad suite of microbial risks should be considered. A multidisciplinary approach such as this is critical for understanding the current ecological and human health risks prevalent in the region and to determine best solutions for reducing the flow of sewage and improving public health.

Environmental Justice

The U.S. border communities of San Ysidro and Imperial Beach are located directly adjacent to the border and are both within the boundaries of the Tijuana River Watershed. Both cities are characterized as having a majority of residents who are resource limited and economically marginalized with an overall elevated risk of chronic diseases compared to surrounding cities in San Diego county.[62] Increased exposure to soil, air and waterborne contaminants from the pollution in the region could be one potential factor for the increased risk of disease. Also, despite being on the coast, both cities are designated as being "park poor".[63] By definition this means that there is less than three acres of green space per 1,000 residents, and there is inequitable access to these green spaces and their quality is subpar.[64] A qualitative study looking at community perceptions of their environment and the sewage contamination issues demonstrated that the majority of youth living in or near Imperial Beach are "disgusted" with the environmental issues and feel the beaches and water are unsafe.[65] This environmental injustice has created both real and perceived barriers for these communities to access outdoor spaces and healthy environments. These current environmental health challenges faced in the region may have lasting effects that will be difficult to mitigate if urgent action is not taken.

Next Steps

To better understand the human and environmental risks both short term and long term imposed by this public health crisis and environmental disaster, activities focused on **monitoring of environmental contaminants** and **investigating nearby community exposures and health effects** are urgently needed, especially exposures to at-risk individuals. Collaborations among healthcare professionals, public health departments, researchers, local organizations, and government agencies are necessary to ensure adequate data access and collection to provide evidence-based solutions and allocate appropriate resources. Investments by Congress and federal and state agencies are desperately needed to not only slow and prevent the ongoing and egregious contamination but to also assess the health and environmental harm that has occurred as a result. Strategic planning amongst partners in both Mexico and the U.S. to prioritize infrastructure investments and find a reliable funding stream to implement improvements is of utmost urgency and should be prioritized to prevent further harm to the residents, visitors, workers and wildlife in our region.[66]

References

1. Cooper JM. Same As It Ever Was: The Tijuana River Sewage Crisis, Non-State Actors, and the State. *Cardozo Int'l & Comp L Rev.* 2021;5:501.
2. Gersberg RM, Daft D, Yorkey D. Temporal pattern of toxicity in runoff from the Tijuana River Watershed. *Water Research.* 2004;38(3):559-568.
3. Espinoza J. *Identification and Assessment of Constituents of Emerging Concern in the Tijuana River Stormwater*: Masters Thesis, San Diego State University; 2023.
4. McLamb F, Feng Z, Shea D, et al. Evidence of transboundary movement of chemicals from Mexico to the US in Tijuana River estuary sediments. *Chemosphere.* 2023:140749.
5. Villaverde GA. *A study of international wastewater challenges and policy in the Tijuana River Watershed.* The University of Texas at El Paso; 2012.
6. Ayad M, Li J, Holt B, Lee C. Analysis and classification of stormwater and wastewater runoff from the Tijuana River using remote sensing imagery. *Frontiers in Environmental Science.* 2020;8:599030.
7. California Water Boards. *Sewage Pollution within the Tijuana River Watershed.* 2023.
8. Leggate J. San Diego Wastewater Plant Damaged By Tropical Storm Hilary Needs $8M in Repairs. *Engineering News Related* Septmeber 15, 2023, 2023.
9. Swain DL, Langenbrunner B, Neelin JD, Hall A. Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change.* 2018;8(5):427-433.
10. Rosa M, Haines K, Cruz T, Forman F. A binational social vulnerability index (BSVI) for the San Diego-Tijuana region: mapping trans-boundary exposure to climate change for just and equitable adaptation planning. *Mitigation and Adaptation Strategies for Global Change.* 2023;28(2):12.
11. Schwarz L. *Climate knows no borders: Assessing the role of extreme weather events in driving adverse health outcomes in a binational United States-Mexico border region*: Doctoral Dissertation, San Diego State University; 2023.
12. University of San Diego Non Profit Insitute. Beach and Coastal Health. 2023; https://www.sandiego.edu/soles/centers-and-institutes/nonprofit-institute/signature-programs/dashboard/water-quality.php. Accessed December 10, 2023.
13. U.S. Border Patrol San Diego. *Tijuana Wastewater FlowsImpact on CBP Operations.* U.S. Customs and Border Protection;2019.
14. Stahl L. Raw sewage flowing into the Tijuana River brings toxic sludge to California. In: 60 Minutes Nature; 2020.
15. Pendergraft MA, Belda-Ferre P, Petras D, et al. Bacterial and Chemical Evidence of Coastal Water Pollution from the Tijuana River in Sea Spray Aerosol. *Environmental Science & Technology.* 2023;57(10):4071-4081.
16. Dueker ME, O'Mullan GD, Juhl AR, Weathers KC, Uriarte M. Local environmental pollution strongly influences culturable bacterial aerosols at an urban aquatic superfund site. *Environmental science & technology.* 2012;46(20):10926-10933.

17. Hurtado L, Rodríguez G, López J, et al. Characterization of atmospheric bioaerosols at 9 sites in Tijuana, Mexico. *Atmospheric Environment.* 2014;96:430-436.
18. Dachs J, Van Ry DA, Eisenreich SJ. Occurrence of estrogenic nonylphenols in the urban and coastal atmosphere of the lower Hudson River estuary. *Environmental Science & Technology.* 1999;33(15):2676-2679.
19. Biggs TW, Atkinson E, Powell R, Ojeda-Revah L. Land cover following rapid urbanization on the US–Mexico border: Implications for conceptual models of urban watershed processes. *Landscape and Urban Planning.* 2010;96(2):78-87.
20. Fox AN. *Assessment of Bacterial Contamination in the US Portion of the Tijuana River and Tijuana River Estuary*, San Diego State University; 2021.
21. Gersberg R, Brooks H. *A Human Health Risk Assessment for Enteroviruses and Hepatits A in Runoff from the Tijuana River and in Bathing Waters of Nearby Imperial Beach, Project Number: W-02-03.*
22. Johnsen C. *Countries Divided, Shared Pollution: Whose Mess is it? A Case Study on the issue of Transnational Border Sewage in the Tijuana River Valley Watershed*: Masters Thesis, Lund University; 2018.
23. Allsing N, Kelley ST, Fox AN, Sant KE. Metagenomic Analysis of Microbial Contamination in the US Portion of the Tijuana River Watershed. *International Journal of Environmental Research and Public Health.* 2022;20(1):600.
24. Steele JA, Blackwood AD, Griffith JF, Noble RT, Schiff KC. Quantification of pathogens and markers of fecal contamination during storm events along popular surfing beaches in San Diego, California. *Water research.* 2018;136:137-149.
25. Rocha AY, Verbyla ME, Sant KE, Mladenov N. Detection, quantification, and simplified wastewater surveillance model of SARS-CoV-2 RNA in the tijuana river. *ACS Es&t Water.* 2022;2(11):2134-2143.
26. Feddersen F, Boehm AB, Giddings SN, Wu X, Liden D. Modeling Untreated Wastewater Evolution and Swimmer Illness for Four Wastewater Infrastructure Scenarios in the San Diego-Tijuana (US/MX) Border Region. *GeoHealth.* 2021;5(11):e2021GH000490.
27. Danil K, Colegrove KM, Delaney MA, Mena A, Stedman N, Wurster E. Systemic Erysipelas Outbreak among Free-Ranging Bottlenose Dolphins, San Diego, California, USA, 2022. *Emerging Infectious Diseases.* 2023;29(12):2561.
28. Shuval H. Estimating the global burden of thalassogenic diseases: human infectious diseases caused by wastewater pollution of the marine environment. *Journal of water and health.* 2003;1(2):53-64.
29. Arnold BF, Schiff KC, Ercumen A, et al. Acute illness among surfers after exposure to seawater in dry-and wet-weather conditions. *American Journal of Epidemiology.* 2017;186(7):866-875.
30. Ugochukwu IC, Samuel F, Orakpoghenor O, et al. Erysipelas, the opportunistic zoonotic disease: history, epidemiology, pathology, and diagnosis—a review. *Comparative Clinical Pathology.* 2019;28:853-859.
31. Venn MA. *Mitigation of Contaminated Transboundary Flows in the Tijuana River: Public Health Considerations for Remediation Strategies*: Masters Thesis, San Diego State University; 2021.
32. Árnason ÁV. *The determining legal, political, and social factors that need to be taken into account when trying to solve binational water pollution: The case of Tijuana, Mexico* Masters Thesis, Lund University Sweden; 2007.

33. García J, García-Galán MJ, Day JW, et al. A review of emerging organic contaminants (EOCs), antibiotic resistant bacteria (ARB), and antibiotic resistance genes (ARGs) in the environment: Increasing removal with wetlands and reducing environmental impacts. *Bioresource technology.* 2020;307:123228.
34. Shahar SA. *Metagenomic Analysis of Microbial Communities in the Tijuana River, Antibiotic Resistance Genes, and Potential Sources*: Masters Thesis, San Diego State University; 2023.
35. Barboza K, Cubillo Z, Castro E, Redondo-Solano M, Fernández-Jaramillo H, Echandi MLA. First isolation report of Arcobacter cryaerophilus from a human diarrhea sample in Costa Rica. *Revista do Instituto de Medicina Tropical de São Paulo.* 2017;59:e72.
36. Figueras M, Levican A, Pujol I, Ballester F, Quilez MR, Gomez-Bertomeu F. A severe case of persistent diarrhoea associated with Arcobacter cryaerophilus but attributed to Campylobacter sp. and a review of the clinical incidence of Arcobacter spp. *New microbes and new infections.* 2014;2(2):31-37.
37. Hsueh P-R, Teng L-J, Yang P-C, et al. Bacteremia caused by Arcobacter cryaerophilus 1B. *Journal of Clinical Microbiology.* 1997;35(2):489-491.
38. Dueker ME, O'Mullan GD. Aeration remediation of a polluted waterway increases near-surface coarse and culturable microbial aerosols. *Science of the Total Environment.* 2014;478:184-189.
39. Maqbool A. *Investigating Distribution of Legionella Pneumophila in Urban and Suburban Watersheds*: Masters Thesis, Queens College; 2021.
40. Pendergraft MA, Grimes DJ, Giddings SN, et al. Airborne transmission pathway for coastal water pollution. *PeerJ.* 2021;9:e11358.
41. Weagle CL, Saint-Louis R, Dumas-Lefebvre É, Chavanne C, Dumont D, Chang RY-W. Sea-air transfer of a tracer dye observed during the Tracer Release Experiment with implications for airborne contaminant exposure. *Marine Pollution Bulletin.* 2022;182:113945.
42. California Air Resources Board. *International Border Community Steering Committee Meeting, AB617.* January 18, 2023.
43. San Diego Air Pollution Control District. *International Border Committee Meeting.* July 18,2023.
44. Achman DR, Hornbuckle KC, Eisenreich SJ. Volatilization of polychlorinated biphenyls from Green Bay, Lake Michigan. *Environmental science & technology.* 1993;27(1):75-87.
45. Finizio A, Mackay D, Bidleman T, Harner T. Octanol-air partition coefficient as a predictor of partitioning of semi-volatile organic chemicals to aerosols. *Atmospheric Environment.* 1997;31(15):2289-2296.
46. Miller MM, Wasik SP, Huang GL, Shiu WY, Mackay D. Relationships between octanol-water partition coefficient and aqueous solubility. *Environmental science & technology.* 1985;19(6):522-529.
47. Beyer A, Mackay D, Matthies M, Wania F, Webster E. Assessing long-range transport potential of persistent organic pollutants. *Environmental Science & Technology.* 2000;34(4):699-703.
48. Gouin T, Mackay D, Jones KC, Harner T, Meijer SN. Evidence for the "grasshopper" effect and fractionation during long-range atmospheric transport of organic contaminants. *Environmental pollution.* 2004;128(1-2):139-148.

49. Shen L, Wania F, Lei YD, Teixeira C, Muir DC, Bidleman TF. Atmospheric distribution and long-range transport behavior of organochlorine pesticides in North America. *Environmental science & technology.* 2005;39(2):409-420.
50. Wang Y, Qian H. Phthalates and their impacts on human health. Paper presented at: Healthcare; 2021.
51. Agency for Toxic Substances and Disease Registry. Polycyclic Aromatic Hydrocarbons (PAHs). In: 2023.
52. Science Direct. Organochlorine Pesticide. https://www.sciencedirect.com/topics/earth-and-planetary-sciences/organochlorine-pesticide. Accessed December 9, 2023.
53. US Environmental Protection Agency. Polychlorinated Biphenals. 2023; https://www.epa.gov/pcbs/learn-about-polychlorinated-biphenyls. Accessed December 9, 2023.
54. Galvez NIL. *Soil analysis of organic and inorganic contaminants in Goat Canyon (Cañon De Los Laureles), at the US-Mexico border*: Masters Thesis, San Diego State University; 2014.
55. Agency for Toxic Substances and Disease Registry [ATSDR]. *Toxicological profile for cadmium.* Atlanta, GA: U.S. Department of Health and Human Services,;1997.
56. Agency for Toxic Substances and Disease Registry [ATSDR]. *Toxicological profile for arsenic (update).* Atlanta, GA: U.S. Department of Health and Human Services,;2007.
57. İyigündoğdu İ, Üstündağ A, Duydu Y. Toxicological evaluation of bisphenol A and its analogues. *Turkish Journal of Pharmaceutical Sciences.* 2020;17(4):457.
58. Milanović M, Đurić L, Milošević N, Milić N. Comprehensive insight into triclosan—from widespread occurrence to health outcomes. *Environmental Science and Pollution Research.* 2023;30(10):25119-25140.
59. Boehm AB, Soller JA. Recreational water risk: pathogens and fecal indicators. In: *Environmental Toxicology: Selected Entries from the Encyclopedia of Sustainability Science and Technology.* Springer; 2012:441-459.
60. Gaffield SJ, Goo RL, Richards LA, Jackson RJ. Public health effects of inadequately managed stormwater runoff. *American Journal of Public Health.* 2003;93(9):1527-1533.
61. Huang Z, Yu X, Liu Q, et al. Bioaerosols in the atmosphere: A comprehensive review on detection methods, concentration and influencing factors. *Science of The Total Environment.* 2023:168818.
62. Agency CoSDHHS. *Disease Deaths in San Diego County—South Region, 2000–2018;.* 2020.
63. Wolch J, Wilson, J., P., Fehrenbach, J. . *Parks and Park Funding in Los Angeles: An Equity Mapping Analysis.* Los Angeles, CA; 2002.
64. The San Diego Foundation. *Parks for Everyone* San Diego, CA; 2020.
65. Holliday E. *Place-Based Environmental Education and Environmental Justice in Imperial Beach, California*, San Diego State University; 2020.
66. Ganster P, I. Coronado, J. McNeece, W. M. Micklin, K. S. Becker, J. K. Nierman, J. L. Palacios, E. Moderow, L. Fleet, J. Rizk, J. M. Heyman, F. Lara, A. Sweedler, R. DeLeon, M. Jordan, J. Collert, C. Helmer, J. Payne, C. Suarez, S. Mumme, P. Aguirre, A. R. Barcenas, K. Collins, E. A. Cruz, M. E. Gonzales-Roses, J. Hinojosa, M. D. Hollis, J. P. King, E. Lee, M. Lopez, J. Maruffo, J. Murrieta-Saldivar, P. L. Vandervoet, M. E. Giner, and T. R. Pohlman. *Water and Wastewater in the U.S.–Mexico Border Region* Washington, D.C; 2023.

ATTACHMENT E

ATTACHMENT E

Heavily Polluted Tijuana River Drives Regional Air Quality Crisis

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Abstract

Toxic industrial chemicals and untreated sewage have polluted the Tijuana River for decades, recently causing over 1,000 consecutive days of California beach closures. In the summer of 2024, wastewater flows surged to millions of gallons per day despite no rain, enhancing water-to-air hydrogen sulfide (H_2S) transfer at a turbulent hotspot. High wastewater flows and low winds led to nighttime H_2S peaks, reaching 4,500 parts-per-billion (ppb)—exceeding typical urban levels of 1 ppb. H_2S levels and community malodor reports were strongly correlated ($r = 0.92$), validating long-dismissed community voices and highlighting an environmental injustice issue. This study demonstrates that poor water quality can significantly impact air quality—though rarely included in air quality models and health assessments—with widespread implications as polluted waterways increase globally.

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The 4,532-km² Tijuana River Valley, spanning the western U.S.-Mexico border, has been the epicenter of a worsening environmental and public health crisis over many decades. The heavily polluted Tijuana River, containing untreated sewage, industrial waste, and stormwater runoff, crosses the border and flows through the Tijuana River Estuary before emptying into the Pacific Ocean at the southern edge of San Diego County(*1, 2*). The Tijuana Watershed has been classified as an impaired water body under the U.S. Clean Water Act, with over 1,000 days of recent beach closures and significant impacts on public health, the environment, and the region's economy(*3*). During the rainy season, November-March, river flows can reach billions of gallons per day. Until recently, dry season flows (June-September) have been negligible except after rare summer rain events. The ongoing water pollution crisis in the Tijuana River Watershed has been exacerbated by the winter arrival of record high numbers of intense Atmospheric Rivers in 2023 and 2024, damaging already aging and inadequate wastewater infrastructure on both sides of the border (*4*, *5*). Additionally, coastal discharge of treated and untreated sewage coming from Punta Bandera—a major wastewater outfall located 10 km south of the border—often flows northward during the summer swell, adding to the polluted coastline from Imperial Beach north to other coastal San Diego communities (*5*-*9*).

Health concerns regarding pollution in the Tijuana River Watershed have primarily focused on direct exposure to contaminated water—either by drinking polluted water or by entering the ocean for recreational activities (*10*-*12*). However, many processes transfer water pollutants to air including bursting bubbles in waterfalls, turbulence in rivers, aeration in wastewater treatment plants, toilet flushing, and breaking waves in coastal surf zones which form aerosols in a process known as aerosolization(*13-16*). Studies have shown that water pollutants, bacteria, viruses, pathogens, and fungal spores can become enriched in the aerosolization process (*17*-*24*). In addition to aerosolization, gaseous pollutants can partition from water-to-air (*25*, *26*). Airborne pollutants can then be dispersed by winds over distances of miles, increasing the number of people exposed to these contaminants beyond just those in direct contact with the polluted water. Further, humans inhale 11,000 L of air per day compared to drinking 2 L per day of often filtered water, potentially rendering inhalation the largest exposure pathway to many of these water-derived pollutants(*27, 28*). The nature and magnitude of heavily contaminated river and ocean water on air quality and human health have long been overlooked while water pollution, anthropogenic runoff, and local flooding are increasing due to population growth, aging infrastructure, and climate change(*29*).

This study presents a compelling example of how water pollution does not always stay within the banks of a polluted river or waterway. The health impacts of pollutants and pathogens transferred from heavily polluted waters into the atmosphere represent a major gap in our knowledge (*30, 31*). Since more than half of the world's population lives near rivers, lakes, and oceans(*32*), better understanding and monitoring are needed to address the ways that pollution moves from water bodies to surrounding air masses and, ultimately, neighborhoods and beyond. More broadly, the impact of water pollution on air quality, including emerging air contaminants of concern, represents a critical yet under-explored public health issue with significant implications for a large portion of humanity(*33*).

Identifying the Tijuana River H_2S and Malodor Hotspot

In a previous winter season study at Imperial Beach, we used genomic sequencing to show that up to 76% of airborne bacteria could be directly traced to the contaminated Tijuana River(*34*). This study extends our focus to include gases and aerosols in the same region during summer when negligible flows in the Tijuana River were expected.

Air quality measurements initially commenced at a coastal site near the U.S.-Mexico border, specifically at Border Field State Park (indicated by the blue square in **Fig. 1**), which can be impacted by pollution in the summer from Punta Bandera (*8*). However, input from residents in inland communities—including reports of malodors and health symptoms—helped us identify a turbulent and foamy site along the Tijuana River that was visible in satellite imagery (**Fig. 1 and S1-2**). Based on findings in previous wastewater management flow studies, we hypothesized that turbulence at this riverine hotspot was leading to enhanced H_2S emissions, and other gases, aerosols, and associated malodors (*35*-*39*). Consequently, we moved our mobile air quality laboratory approximately 5 km inland to the community of Nestor, the closest neighborhood to the river hotspot (red triangle in **Fig. 1**) and near a high density of K-12 schools (**Fig. S3**). Nestor air measurements began on September 1, 2024, and included the criteria pollutants ozone, carbon monoxide (CO), nitric oxide (NO), particulate matter (PM_1, $PM_{2.5}$), as well as hydrogen sulfide (H_2S).

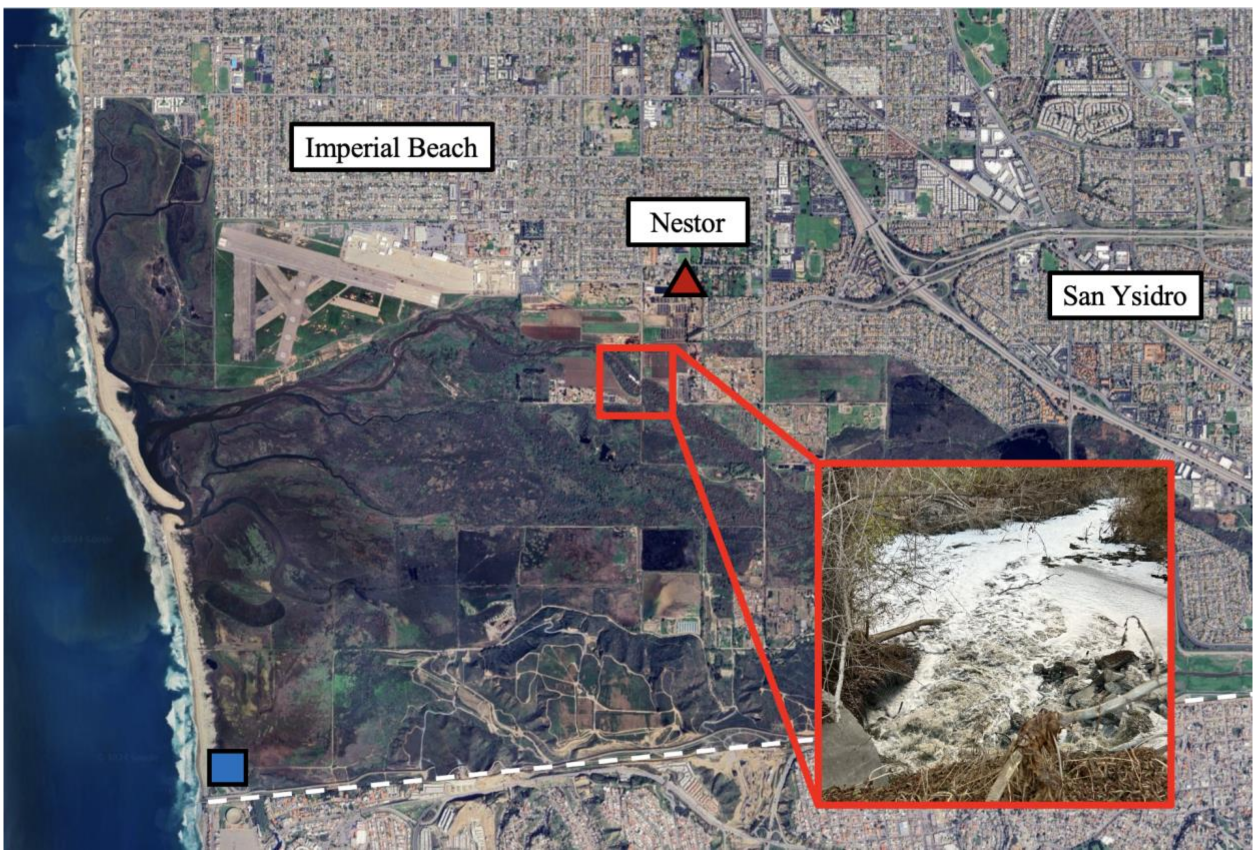

Fig. 1. Map of Coastal and Inland Air Sampling Sites. The blue square represents the coastal sampling site at Border Field State Park; the red triangle marks the inland sampling site in Nestor; and the red box shows the river crossing at Saturn Boulevard, identified with community

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input as the major source of malodors. The inset highlights the region where turbulent flow produces extensive surface foam (September 5, 2024).

H_2S: A Toxic Sewage Gas and Airborne Tracer of Water Pollution

For decades, communities near the Tijuana River Valley have reported malodors and health symptoms. Despite overwhelming community concerns, quantitative air quality measurements have never been conducted with sufficient resolution to identify the specific air pollutants causing the malodors and address the adverse health effects in this region. H_2S, known for its distinctive "rotten egg" smell and low odor threshold (*40*), is the most common gaseous tracer of sewage. In this study, we used H_2S as a general marker to trace malodors and other airborne contaminants produced from sewage-laden waters. Produced by the anaerobic decomposition of organic matter, H_2S can be toxic even at relatively low levels(*41*). The CDC's Agency for Toxic Substances and Disease Registry (ATSDR) reports that urban ambient H_2S levels are typically below 1 part-per-billion (ppb)(*42, 43*). Respiratory irritation and neurological effects can occur at higher exposure levels(*44*). California Air Resources Board (CARB) set a 1-hr average California Air Quality Standard (CAAQS) of 30 ppb for the purpose of odor control. The South Coast Air Quality Management District (SCAQMD) uses this same 30 ppb for acute exposure. The California Office of Health Hazard Assessment (OEHHA) and SCAQMD use a chronic exposure limit of 7.3 ppb for chronic exposure levels, particularly for vulnerable populations (e.g., pregnant women, children, older adults, immunocompromised).

One-hour average H_2S levels at the Border Field coastal site (top panel), as well as the Nestor neighborhood site (bottom panel), are shown in **Fig. 2**. Measured levels are shown relative to the 30 ppb 1-hr average CAAQS for H_2S. During the August 24-25 sampling period at Border Field, H_2S levels remained below the CAAQS (**Fig. 2 A-D**). From September 7-8 at the Nestor site, H_2S levels routinely exceeded the CAAQS. The polar plots clearly demonstrate that the proximity of Nestor to the riverine hotspot led to much higher H_2S levels than Border Field, particularly during low-wind and stagnant-air nighttime conditions (**Fig. 2 E-F**).

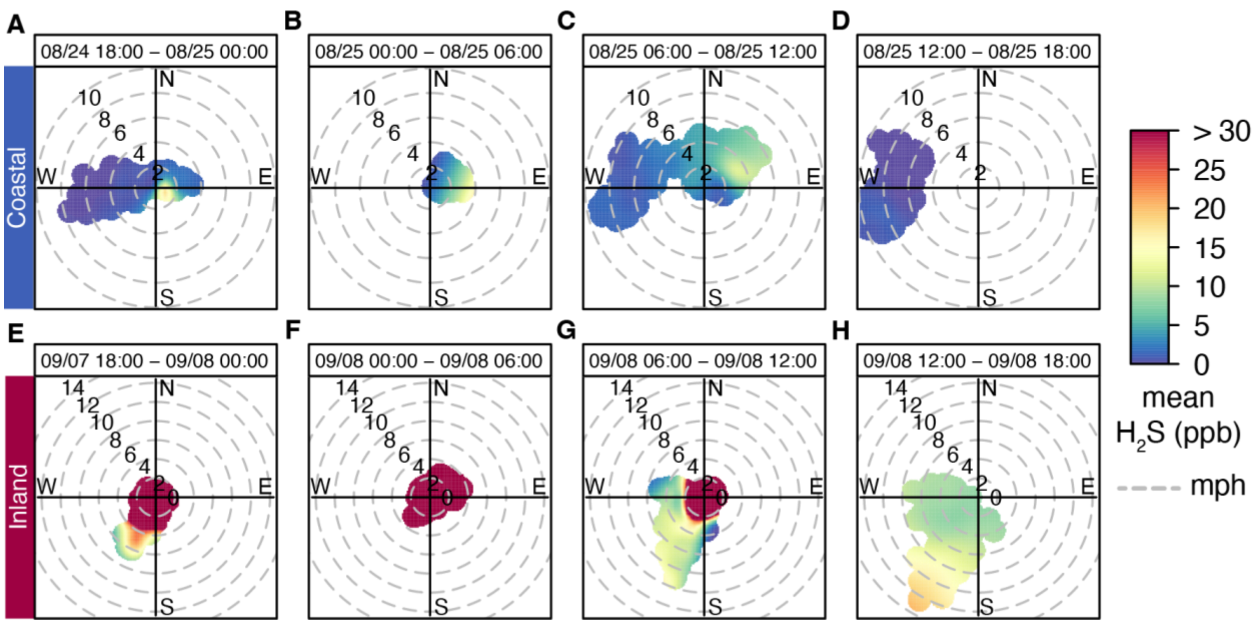

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Fig. 2. Polar heat maps of H_2S levels at coastal and inland sampling sites segmented into four six-hour periods. (A, B, C, D) H_2S polar heat maps at the Border Field State Park coastal site, spanning August 24-25, 2024. **(E, F, G, H)** H_2S polar heat maps at the inland site of Nestor, spanning September 7-8, 2024. Color bar denotes 1-hr average H_2S levels with a maximum scale value of 30 ppb, corresponding to the CAAQS. Windspeeds shown in miles per hour (mph).

Unprecedented Dry Summer Season Flows in 2024

In the past two rainy seasons, unusually high numbers of winter storms with intense rainfall resulted in record transboundary annual flows of 44 billion gallons in 2023 and 35 billion gallons (to date) in 2024 (**Fig. 3A and S4**). The two corresponding dry seasons also had higher annual flows than previous years (**Fig. 3B-F**). The impact of Hurricane Hillary in the summer of 2023 resulted in higher than normal August flows (**Fig. 3E**). The reason for the unprecedented high dry season flows in summer of 2024, in the absence of rain, is not known. While high rainy season flows are diluted by rainfall, dry season flows are typically low due to minimal rainfall(*45*). As shown in **Fig. 3F**, unprecedented high river flows were recorded throughout most of the 2024 dry season, ranging between 40-80 million gallons per day. On September 10, pump stations in Mexico were suddenly activated. This diversion of wastewater effectively reduced transboundary flows, with daytime flows dropping to nearly zero and nighttime flows diminishing to less than 5 million gallons per day (**Fig. 3F inset and S5**). High-resolution, 15-min flow data show after this abrupt wastewater management decision on September 10, wastewater discharge to the river occurred only during nighttime hours (6 p.m. to 4 a.m.) for the remainder of the 2024 dry season (**Fig. 3F inset and S5**).

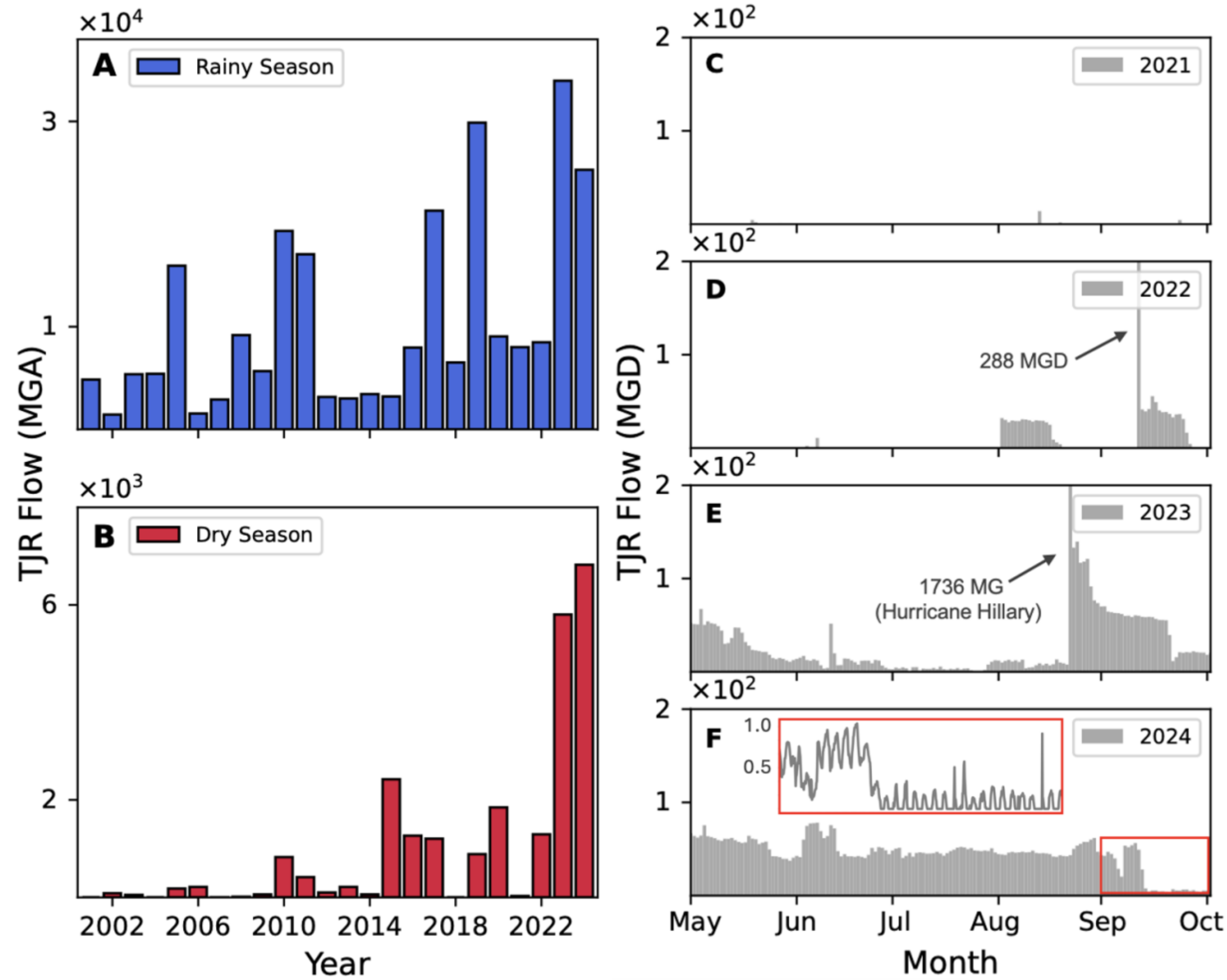

Fig. 3. Historical annual transboundary river flow. (A) Tijuana River flow during the San Diego rainy season (November-March) between January 2001- October 2024 in millions of gallons annually (MGA). **(B)** Tijuana River flows during the San Diego dry season (May-September) between January 2001- October 2024. **(C,D,E,F)** Annual dry season river flow between 2021-2024. Inset in **F** shows normalized TJR flow (15-min averaged) between September 1-30, 2024. Data was downloaded from IBWC (*46*).

Record High Dry Season Flows Drive Toxic H_2S Levels and Community Malodor Reports

Measurements in the Nestor community were conducted to quantify community airborne exposure to the identified local Tijuana River H_2S hotspot. See **Fig. S6** for the full timeline of events related to this study. Time series of H_2S levels measured at Nestor from September 1-22 are shown in **Fig. 4**. During the period with the highest river flows (September 5-9), 1-min averaged H_2S levels surged at night to 4,500 times typical urban ambient levels (**Fig. 4A**). Following the September 10 wastewater diversion, H_2S levels dropped by roughly 95%. However, H_2S levels still peaked at night when river flows were highest due to controlled nighttime releases when wind speeds and temperatures were at their lowest (**Fig. S7-9**).

Meteorological conditions led to reduced dispersion and atmospheric dilution of H_2S, trapping the gas (which is heavier than air) near the ground in nearby communities between ~6 pm each night and ~8 am the next morning (**Fig. S10-11**).

Residents living in south San Diego and Imperial Beach communities reported increasing and ultimately record-high numbers of daily malodor reports (**Fig. 4B**) and health symptoms (e.g., respiratory problems, headaches, anxiety, and fatigue) to the San Diego Air Pollution Control District (SDAPCD). These malodor reports were typically made during the nighttime or early morning hours. The sudden wastewater diversion and corresponding decrease in H_2S levels on September 10 were directly reflected in malodor reports, which decreased from 233 daily reports on September 9 to fewer than 10 by September 12. Linear regression analysis revealed a strong positive correlation ($r = 0.92$) between H_2S levels and community malodor reports (**Fig. S12**). The strong temporal correlation between the polluted Tijuana River flow and ambient H_2S levels in Nestor supports the hypothesis that the turbulent hotspot was the primary source of malodors and H_2S emissions.

Framing the H_2S measurements in a regulatory context, 1-hr average H_2S levels reached 2,100 ppb (**Fig. 4B**), nearly 70 times the 1-hr CAAQS of 30 ppb. **Fig. 4C** illustrates the number of hours in a 24-hr period that residents in Nestor were exposed to H_2S levels above the CAAQS. Before the intentional wastewater diversion, residents experienced between 5 to 14 hours of exposure above the CAAQS, largely at night, with 1-hr average H_2S levels ranging from 30 to 2,100 ppb. As shown in the inset in **Fig. 4B** and in **Fig. 4C**, after the wastewater was diverted, while H_2S levels decreased significantly, residents still experienced up to five hours of exposure above the CAAQS on most nights. While the duration of this study allows direct comparison with acute exposure standards, assessing chronic exposure would be appropriate only if these three weeks of measurements were representative of the typical air quality conditions over months to years. The OEHHA/SCAQMD chronic exposure limit of 7.3 ppb is also included in **Fig. 4B** for reference.

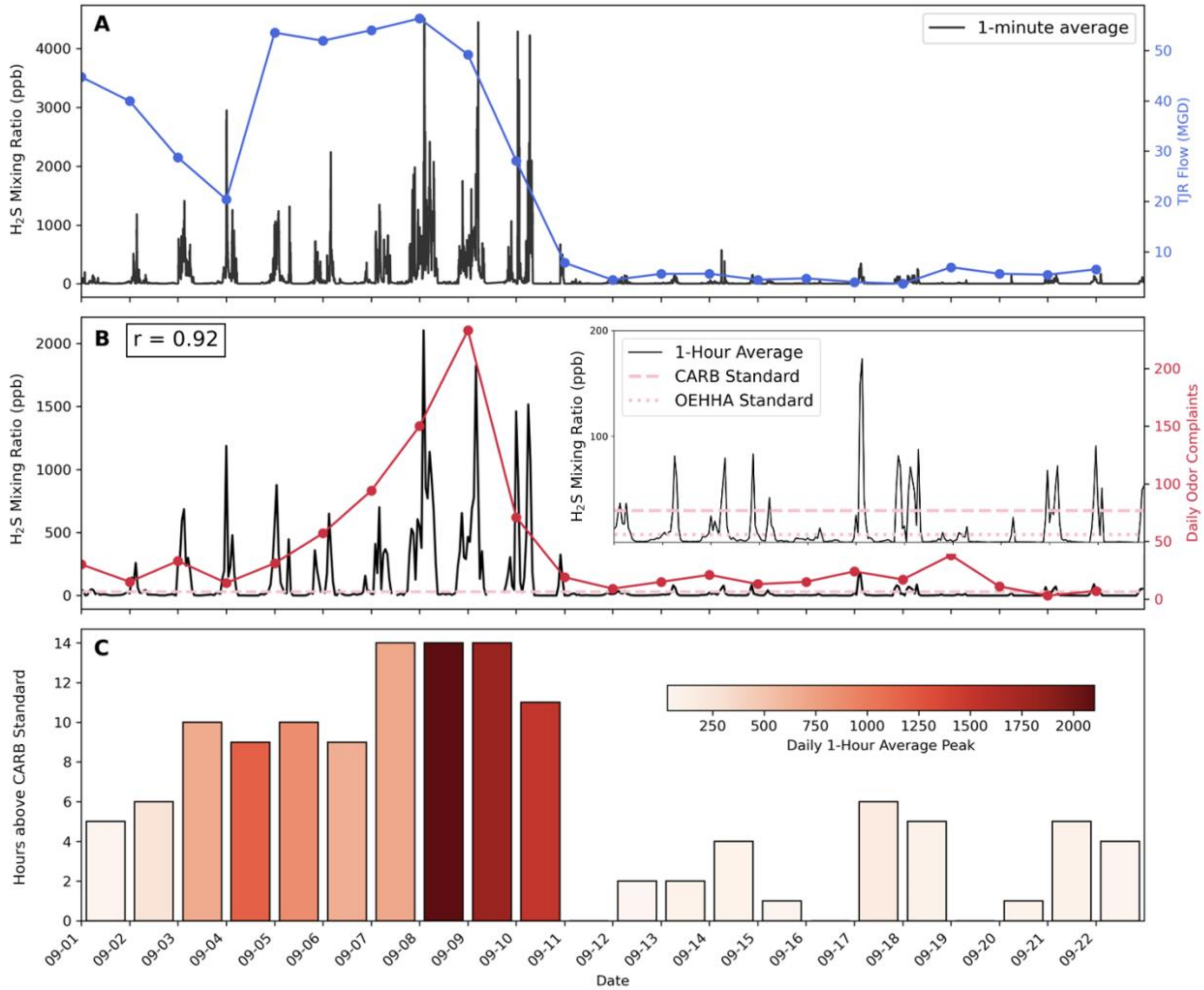

Fig. 4. Time Series plots, H_2S and malodor reports correlation, and comparison to CARB Ambient Air Quality Standard. (A) H_2S levels (1-min average) and daily river flow in millions of gallons per day (MGD). **(B)** H_2S levels (1-hr average) and daily malodor reports received by the SDAPCD. Correlation (r = 0.92). Dashed light-red line shows the CAAQS of 30 ppb. Dotted light-red line shows OEHHA standard for chronic exposure of 7.3 ppb. **(C)** Bar plot of the number of hours per day ambient H_2S levels exceeded the 1-hr average CAAQS. The color bar indicated daily peak H_2S levels in ppb (1-hr average).

Air Dispersion of Pollutants Broadens Tijuana River Impact to Regional Scale

High temporal resolution measurements in this study capture the impact of the Tijuana River pollution on Nestor, a local community closest to the turbulent river hotspot. Therefore, to investigate the extent to which pollution from the Tijuana River can impact air quality in neighboring communities and beyond, HYSPLIT (*47*) trajectory and dispersion modeling was used. The 1-hr average Tijuana River flow rates were used to estimate H_2S emissions, capturing the effect of increased flow on source strength, as well as turbulence at the river hotspot.

Dispersion modeling allows further study of the factors affecting the spatial distribution of airborne pollutants emanating from the river hotspot, including river source strength and meteorology. **Fig. 5** illustrates the regional impact of H_2S emissions from the Tijuana River crossing at Saturn Boulevard. Relative levels of potentially degraded air masses were binned into three time periods with distinct flow and meteorological conditions: high river flow during moderate-temperature conditions from September 1 through September 5 (Period 1); high river flow during atmospherically stagnant conditions from September 6 through 12:00 pm on September 10 (Period 2); and reduced river flow with westerly winds over the remainder of the study from 12:01 pm September 10 through September 22 (Period 3). The cutoff between periods 2 and 3 was set to noon on September 10, since the wastewater diversion occurred that morning.

As shown in **Fig. 5**, high river flow periods at the beginning of September resulted in higher airborne pollutant levels near the hotspot river source region (shown as a black point in all panels). Compared to Period 1, Period 2 nighttime boundary layer winds were weaker, resulting in the highest H_2S buildup in and around Nestor and surrounding communities (**Fig. 5A**, **5B**). Higher river flows starting in the evening hours reproduced the nightly increases of H_2S in Nestor, showing earlier and higher levels in Period 2 (**Fig. 5D**, **5E**). Reduced flows occurring after the wastewater diversion led to reduction in H_2S emissions during Period 3. Along with more consistent westerly winds, reduced river flow contributed to a greatly reduced density of weighted trajectories over the study region, with nighttime peaks only a fraction of those seen during high river flow conditions (**Fig. 5C**, **5F**). It is important to note that weighting summed trajectories by the 1-hr average river flows was necessary to reproduce these measured trends at Nestor across the three time periods (i.e., meteorology alone without flow-based weighting did not reproduce the trends), further confirming the Saturn Boulevard riverine hotspot as the major source region driving local emissions of H_2S and other airborne pollutants.

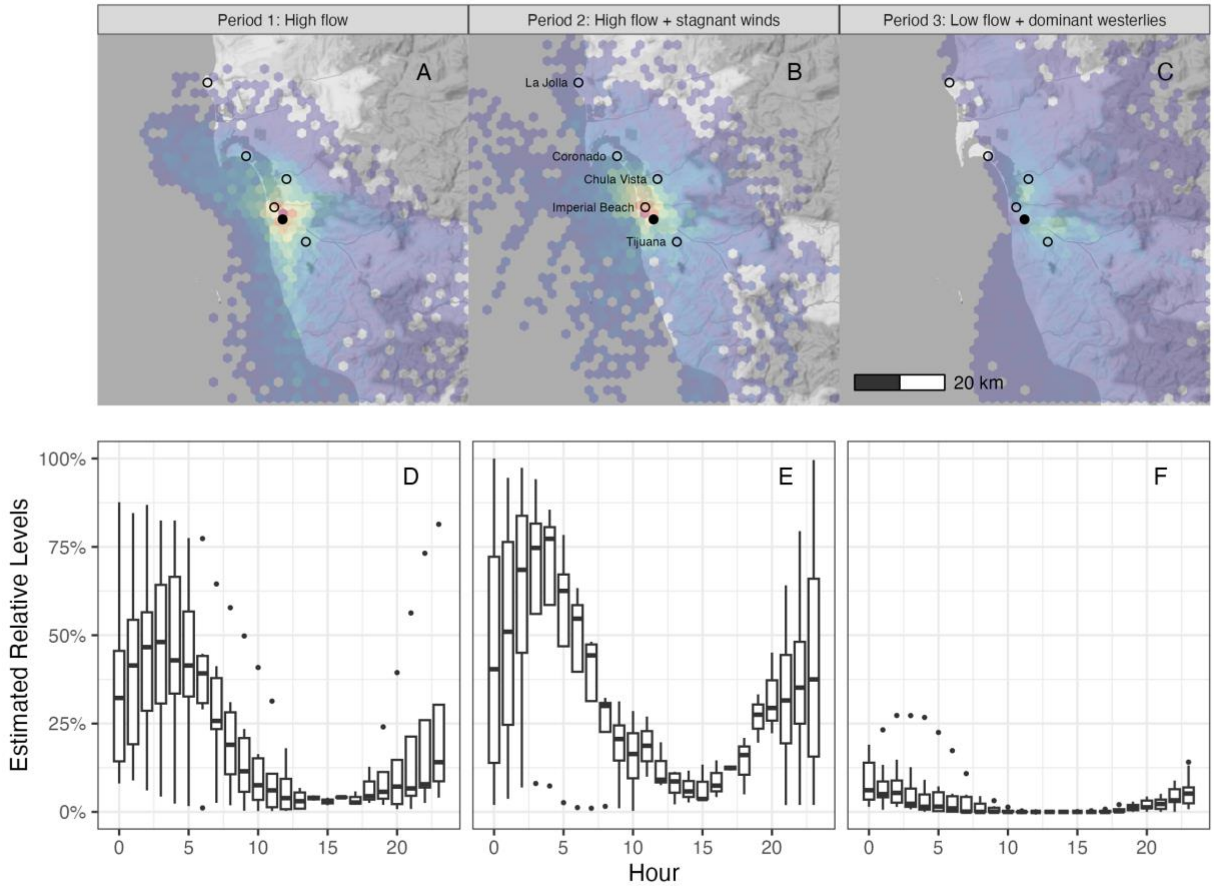

Fig. 5. Dispersion modeling showing spatial and diurnal patterns for trajectories starting at the Saturn Boulevard river crossing H_2S hotspot. Relative dispersion and spatial intensities across Tijuana River Valley and surrounding area are shown for **(A)** Period 1 (September 1-5), **(B)** Period 2 (September 6-10), and **(C)** Period 3 (September 10-23). The cutoff between period 2 and 3 was set at 12:00 on September 10, 2024. **(D,E,F)** Hourly sums across San Diego and Imperial Beach communities are shown for Period 1, Period 2, and Period 3, respectively.

Polluted Water Bodies as Emission Sources for Air Quality Modeling

This study demonstrates the major impact a turbulent portion of a polluted river can have on regional air quality—a finding with global implications as many countries grapple with waterways contaminated by increasing levels of untreated sewage and industrial waste.

The severity of water pollution in the Tijuana River was visibly marked by foam accumulating on the river surface, starting at the Saturn Boulevard hotspot and extending miles through the Tijuana Estuary, peaking each morning and often persisting throughout the day (**Figs. S1-2**). Another global example of similar persistent foam layers has been reported in the Yamuna River in New Delhi, which has been attributed to a similar combination of industrial pollutants and raw wastewater(*48*, *49*). These surface foams have been shown to contain untreated waste, industrial chemicals, metals, and surfactants that accumulate on the water's surface(*48*, *49*). Similar foaming phenomena have also been documented in gravity sewer networks, where dry weather flows and turbulence have been shown to amplify H_2S emissions (*35*-*39*).

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Air trajectory modeling supports the impact of polluted transboundary river flow—serving as a proxy for source strength of water-derived pollutants. Specifically an increase in volume levels and enhanced turbulence-driven partitioning—coupled with meteorological conditions, on the observed H_2S levels. It is important to note that H_2S is only one of potentially thousands of other pollutants emitted from the Tijuana River and impacting regional health across San Diego County and beyond(*50*). Both measurements and models demonstrate that fluctuations in wind speed and direction, on timescales of hours to days, influenced the variability of H_2S and likely other co-emitted pollutants. Therefore, routine air quality measurements that capture these spatial and temporal variations, especially near turbulent zones with waterfalls and sewer drop-offs, are needed to serve as inputs for air quality models, assess neighborhood-scale air quality, and address public health concerns. Such measurements are critical for advancing current estimates of the effects of public health consequences of water pollution, which do not consider inhalation pathways and degradation of air quality.

This study underscores the pressing need to enhance our understanding of how pollutants move between environmental reservoirs, in this case polluted water and air. Current air quality models do not include gaseous emissions from polluted rivers, estuaries, and coastal systems—areas increasingly impacted by anthropogenic pollution. Incorporating emissions from polluted water bodies will be essential for accurate predictions of health impacts of environmental pollution and developing effective mitigation strategies. As human population growth continues to drive pollution to levels that strain and exceed Earth's natural capacity for processing, understanding these transfer mechanisms has become essential for addressing pollution impacts both locally and globally.

Addressing Environmental Justice and Protecting Public Health

Residents living near the Tijuana River Valley have endured the impacts of environmental water pollution since the 1930s, with escalating impacts in recent years(*51*). The H_2S levels measured in this study support the decades of concerns raised by the residents living near the Tijuana River Valley, who have had less attention and slower acknowledgment than other communities experiencing similar levels of H_2S exposure. A parallel can be drawn with the air quality crisis in Carson, California in 2021(*44, 52, 53*), where residents were subjected to malodors related to high H_2S levels. In that emergency, the SCAQMD investigated and responded rapidly providing air filtration units, while local authorities moved to investigate to rapidly identify and eliminate the H_2S source. In order to respond to community exposure to toxic air pollutants, SCAQMD has implemented a community air monitoring program (CAMP) as part of Rule 1180 at multiple sites across Los Angeles county with real-time publicly accessible display and rapid response communication to warn communities when high levels multiple toxic gases, including H2S, are reached to reduce community exposure(*54*).

Chronic exposure to hydrogen sulfide (H_2S) and other air pollutants released from untreated wastewater can help explain many of the longstanding health symptoms reported in the South Bay San Diego and Imperial Beach region, including respiratory and gastrointestinal issues, headaches, fatigue, skin infections, nausea, and anxiety. However, limited research exists on the long-term effects of inhaling H_2S and the complex mixture of airborne pollutants originating from polluted water sources. Research has shown similar health effects experienced by wastewater treatment plant workers and people living in communities near wastewater treatment plants(*55-57*). The demographics of Imperial Beach, and the San Diego communities of Nestor and San Ysidro, align with the definition of environmental justice communities (*58*). These areas have high Hispanic/Latino populations ranging from 53% to 93%, and, additionally, a significant portion of residents live below the poverty line (*59, 60*). Besides the social stressors that the community endures, environmental pollution leads to cumulative impacts (*61*) on the local economy, health, and overall quality-of-life. Such prolonged exposure without adequate protection or timely intervention highlights a clear environmental injustice that would not be tolerated in more affluent or less marginalized communities.

Given that H_2S levels peak at night, providing effective indoor air filtration represents a practical short-term solution. For the filters to be effective, they must include activated carbon with potassium permanganate to reduce H_2S and other toxic gases, along with particulate filters to reduce exposure to aerosolized pollutants including viruses, bacteria, and fungal spores. In addition to filtration, implementing a community air monitoring program—similar to CAMP established by the SCAQMD—is essential for protecting public health. Such measures are fundamental to safeguarding community health by providing real-time data on air quality and enabling timely responses to unacceptable pollution events (*54, 62*).

Providing readily accessible air quality data with educational support empowers residents to make informed decisions. Still, comprehensive water quality improvements—including infrastructure upgrades and stricter water pollution controls enforced by both the U.S. and Mexico—are essential. This study demonstrates that water pollution does not stop at the river's edge; therefore, the benefits of water quality management and repairing polluted waterways extend beyond the immediate water users—both human and ecological—themselves. While the ultimate solution for affected residents involves eliminating the contamination, regardless of the original source of pollution, building the infrastructure to support this will take years and substantial resources. In the meantime, a relatively quick remedy is to eliminate the turbulence at the Saturn Boulevard H_2S hotspot, where this study shows significant emissions are occurring. Without critical interventions, residents living on both sides of the border will continue to suffer unacceptable health impacts due to poor air quality. Continuous monitoring and coordinated action among public agencies are imperative and must include community engaged solutions to be effective. Sustained commitment and collaboration are necessary to protect the communities suffering from this increasing environmental pollution by providing the resources they urgently need and deserve.

References

1. S. Y. Kim, E. J. Terrill, B. D. Cornuelle, Assessing coastal plumes in a region of multiple discharges: The U.S.−Mexico Border. *Environmental Science & Technology* **43**, 7450-7457 (2009).
2. G. McMahon, "Tijuana River diversion study: Flow analysis, infrastructure diagnostic and alternatives development" (2019); https://www.nadb.org/uploads/files/tijuana_river_diversion_study_final_report_full_sm.pdf.
3. C. Helmer, "Tijuana – Project Clean Water" (2022); https://projectcleanwater.org/watersheds/tijuana-wma/.
4. R. Aguilera, A. Gershunov, T. Benmarhnia, Atmospheric rivers impact california's coastal water quality via extreme precipitation. *Science of the Total Environment* **671**, 488-494 (2019).
5. C. Hecht, "Epic snow from all those atmospheric rivers in the west is starting to melt, and the flood danger is rising" (The Conversation, 2023); https://theconversation.com/epic-snow-from-all-those-atmospheric-rivers-in-the-west-is-starting-to-melt-and-the-flood-danger-is-rising-203874
6. M. V. Orozco-Borbón *et al.*, Bacteriological water quality along the Tijuana–Ensenada, Baja California, México shoreline. *Marine Pollution Bulletin* **52**, 1190-1196 (2006).
7. S. Dedina, The political ecology of transboundary development: Land use, flood control and politics in the Tijuana river valley. *Journal of Borderlands Studies* **10**, 89-110 (1995).
8. L. M. Sassoubre, D. C. Love, A. I. Silverman, K. L. Nelson, A. B. Boehm, Comparison of enterovirus and adenovirus concentration and enumeration methods in seawater from Southern California, USA and Baja Malibu, Mexico. *J Water Health* **10**, 419-430 (2012).
9. A. G. Zimmer-Faust *et al.*, A Combined digital PCR and next generation DNA-sequencing based approach for tracking nearshore pollutant dynamics along the southwest United States/Mexico Border. *Frontiers in Microbiology* **12**, (2021).
10. F. Feddersen, A. B. Boehm, S. N. Giddings, X. Wu, D. Liden, Modeling untreated wastewater evolution and swimmer illness for four wastewater infrastructure scenarios in the San Diego-Tijuana (US/MX) border region. *Geohealth* **5**, e2021GH000490 (2021).
11. K. Hally-Rosendahl, F. Feddersen, D. B. Clark, R. T. Guza, Surfzone to inner-shelf exchange estimated from dye tracer balances. *Journal of Geophysical Research: Oceans* **120**, 6289-6308 (2015).
12. J. A. Warrick *et al.*, River plume patterns and dynamics within the Southern California Bight. *Continental Shelf Research* **27**, 2427-2448 (2007).
13. M. A. Pendergraft *et al.*, Airborne transmission pathway for coastal water pollution. *Peerj* **9**, (2021).
14. M. Lou *et al.*, The bioaerosols emitted from toilet and wastewater treatment plant: a literature review. *Environmental Science and Pollution Research* **28**, 2509-2521 (2021).
15. M. E. Dueker, G. D. O'Mullan, Aeration remediation of a polluted waterway increases near-surface coarse and culturable microbial aerosols. *Sci Total Environ* **478**, 184-189 (2014).
16. S. Kataki *et al.*, Bioaerosolization and pathogen transmission in wastewater treatment plants: Microbial composition, emission rate, factors affecting and control measures. *Chemosphere* **287**, 132180 (2022).

17. E. R. Baylor, Virus transfer from surf to wind. *Science* **198**, 575-580 (1977).
18. D. Blanchard, Mechanism for the water-to-air transfer and concentration of bacteria. *Science* **170**, 626-628 (1970).
19. E. B. Franklin *et al.*, Atmospheric benzothiazoles in a coastal marine environment. *Environmental Science & Technology* **55**, 15705-15714 (2021).
20. E. B. Franklin *et al.*, Anthropogenic and biogenic contributions to the organic composition of coastal submicron sea spray aerosol. *Environmental Science & Technology* **56**, 16633-16642 (2022).
21. J. Brahney *et al.*, Constraining the atmospheric limb of the plastic cycle. *Proceedings of the National Academy of Sciences of the United States of America* **118**, (2021).
22. J. M. Michaud *et al.*, Taxon-specific aerosolization of bacteria and viruses in an experimental ocean-atmosphere mesocosm. *Nature Communications* **9**, (2018).
23. J. H. Tian *et al.*, Detection and characterization of bioaerosol emissions from wastewater treatment plants: Challenges and opportunities. *Frontiers in Microbiology* **13**, (2022).
24. N. N. Zang, H. Y. Tian, X. Y. Kang, J. W. Liu, Bioaerosolization behaviour of potential pathogenic microorganisms from wastewater treatment plants: Occurrence profile, social function and health risks. *Science of the Total Environment* **923**, (2024).
25. A. Zavarsky, L. Goddijn-Murphy, T. Steinhoff, C. A. Marandino, Bubble-mediated gas transfer and gas transfer suppression of DMS and CO2. *Journal of Geophysical Research: Atmospheres* **123**, 6624-6647 (2018).
26. P. K. Farsoiya, S. Popinet, L. Deike, Bubble-mediated transfer of dilute gas in turbulence. *Journal of Fluid Mechanics* **920**, A34 (2021).
27. L. Lin, H. R. Yang, X. C. Xu, Effects of water pollution on human health and disease heterogeneity: A Review. *Frontiers in Environmental Science* **10**, (2022).
28. P. J. Landrigan *et al.*, Human health and ocean pollution. *Annals of Global Health* **86**, (2020).
29. A. Boretti, L. Rosa, Reassessing the projections of the World Water Development Report. *npj Clean Water* **2**, 15 (2019).
30. A. Gershunov *et al.*, Precipitation regime change in Western North America: The role of atmospheric rivers. *Scientific Reports* **9**, (2019).
31. S. D. Polade, A. Gershunov, D. R. Cayan, M. D. Dettinger, D. W. Pierce, Precipitation in a warming world: Assessing projected hydro-climate changes in California and other Mediterranean climate regions. *Scientific Reports* **7**, (2017).
32. M. Kummu, H. de Moel, P. J. Ward, O. Varis, How close do we live to water? A global analysis of population distance to freshwater bodies. *PLoS One* **6**, e20578 (2011).
33. F. Wang *et al.*, Emerging contaminants: A One Health perspective. *Innovation (Camb)* **5**, 100612 (2024).
34. M. A. Pendergraft *et al.*, Bacterial and chemical evidence of coastal water pollution from the Tijuana River in sea spray aerosol. *Environmental Science & Technology* **57**, 4071-4081 (2023).
35. K. Park *et al.*, Mitigation strategies of hydrogen sulphide emission in sewer networks - A review. *International Biodeterioration & Biodegradation* **95**, 251-261 (2014).
36. L. Carrera, F. Springer, G. Lipeme-Kouyi, P. Buffiere, A review of sulfide emissions in sewer networks: Overall approach and systemic modelling. *Water Science and Technology* **73**, 1231-1242 (2016).

37. N. F. Hamad *et al.*, Case study of hydrogen sulfide release in the sulfate-rich sewage drop structure. *Journal of Water and Climate Change* **14**, 3713-3725 (2023).
38. N. M. Matias, J. S. Matos, F. Ferreira, Hydrogen sulfide gas emission under turbulent conditions - an experimental approach for free-fall drops. *Water Sci Technol* **69**, 262-268 (2014).
39. L. Sun, W. Zhang, Z. Zhu David, Mass transfer of hydrogen sulfide at turbulent water surface by falling drops or a single Jet. *Journal of Environmental Engineering* **149**, 04023021 (2023).
40. G. M. Woodall Jr, R. L. Smith, G. C. Granville, Proceedings of the hydrogen sulfide health research and risk assessment symposium October 31-November 2, 2000. *Inhalation Toxicology* **17**, 593-639 (2005).
41. R. Wang, Physiological implications of hydrogen sulfide: A whiff exploration that blossomed. *Physiological Reviews* **92**, 791-896 (2012).
42. O. J. Chou S, Pohl HR, Scinicariello F, Ingerman L, Barber L, et al., "Toxicological profile for hydrogen sulfide and carbonyl sulfide," (Division of Toxicology and Human Health Sciences, Atlanta, GA: ATSDR, 2016).
43. S. L. Malone Rubright, L. L. Pearce, J. Peterson, Environmental toxicology of hydrogen sulfide. *Nitric Oxide* **71**, 1-13 (2017).
44. A. J. L. Quist, J. E. Johnston, Respiratory and nervous system effects of a hydrogen sulfide crisis in Carson, California. *Science of the Total Environment* **906**, (2024).
45. NOAA National Weather Service (2024); https://www.weather.gov/wrh/Climate?wfo=sgx
46. Internation Boundary and Water Commisson Data Portal (2024); https://www.ibwc.gov/water-data/
47. A. F. Stein *et al.*, NOAA's HYSPLIT atmospheric transport and dispersion modeling system. *Bulletin of the American Meteorological Society* **96**, 2059-2077 (2015).
48. P. Joshi, A. Chauhan, P. Dua, S. Malik, Y.-A. Liou, Physicochemical and biological analysis of river Yamuna at Palla station from 2009 to 2019. *Scientific Reports* **12**, 2870 (2022).
49. G. Sejwal, S. K. Singh, Perspective: The unexplored dimensions behind the foam formation in River Yamuna, India. *Environmental Science and Pollution Research* **30**, 90458-90470 (2023).
50. K. Pochwat, M. Kida, S. Ziembowicz, P. Koszelnik, Odours in sewerage—A description of emissions and of technical abatement measures. *Environments* **6**, 89 (2019).
51. S. Schoenherr, "Tijuana River Valley" (South Bay Historical Society, 2015); http://sunnycv.com/history/exhibits/trv.html.
52. A. J. L. Quist, A. Hovav, A. D. Silverman, B. Shamasunder, J. E. Johnston, Residents' experiences during a hydrogen sulfide crisis in Carson, California. *Environmental Health* **23**, (2024).
53. A. J. L. Quist, J. E. Johnston, Malodors as environmental injustice: health symptoms in the aftermath of a hydrogen sulfide emergency in Carson, California, USA. *Journal of Exposure Science & Environmental Epidemiology*, (2023).
54. South Coast Air Quality Management District – Community Air Monitoring Program (2023); https://www.aqmd.gov/nav/about/initiatives/environmental-justice/ab617-134/ab-617-community-air-monitoring

55. J. Thorn, E. Kerekes, Health effects among employees in sewage treatment plants: A literature survey. *American Journal of Industrial Medicine* **40**, 170-179 (2001).
56. A. Vantarakis *et al.*, Impact on the quality of life when living close to a municipal wastewater treatment plant. *Journal of Environmental and Public Health* **2016**, 8467023 (2016).
57. J. Thorn, L. Beijer, R. Rylander, Work related symptoms among sewage workers: A nationwide survey in Sweden. *Occupational and Environmental Medicine* **59**, 562-566 (2002).
58. D. Rowangould, A. Karner, J. London, Identifying environmental justice communities for transportation analysis. *Transportation Research Part A: Policy and Practice* **88**, 151-162 (2016).
59. U.S. Census Bureau (2022). *American Community Survey 5-year estimates*. Retrieved from *Census Reporter Profile page for Census Tract 101.12, San Diego, CA* http://censusreporter.org/profiles/14000US06073010112-census-tract-10112-san-diego-ca/
60. U.S. Census Bureau (2022). *American Community Survey 5-year estimates*. Retrieved from *Census Reporter Profile page for Census Tract 100.13, San Diego, CA* http://censusreporter.org/profiles/14000US06073010013-census-tract-10013-san-diego-ca/
61. Tulve, N.S., Guiseppi-Elie, A., Geller, A.M. *et al.* Redefining exposure science to advance research supporting cumulative impacts, environmental justice, and decision-making. *J Expo Sci Environ Epidemiol* **33**, 843–845 (2023).
62. SCAQMD, "Rule 1180" (2017); https://www.aqmd.gov/home/rules-compliance/rules/support-documents/rule-1180-refinery-fenceline-monitoring-plans

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ATTACHMENT E

White Paper -Health Impacts in Residents Exposed to Tijuana River Pollution

A Community-Based Assessment of Environmental and Public Health Risks

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Disclaimer

This white paper presents preliminary results from a community health survey conducted between October 2024 and July 2025. These findings are shared for community engagement and policy planning purposes. A peer-reviewed publication with expanded data analysis is in development.

Executive Summary

The Tijuana River Valley, in San Diego County just north of the border with Mexico, represents one of the most severe public health and infrastructure crises in the United States. Millions of gallons of untreated sewage along with urban and industrial runoff flow daily into the United States, which is exacerbated by failing cross-border infrastructure to treat the wastewater. Severely impacted communities in San Diego County, especially San Ysidro, Imperial Beach, and other South Bay neighborhoods, have long reported health effects from exposure to the contaminated water and the gases emanating from the pollution. In addition, there is a strong economic impact as the contaminated water flows into the ocean and affect recreation and tourism dollars for these communities.

This white paper presents preliminary findings from a bilingual community health survey of 340 residents and 140 workers (some participants lived and worked in the region) in environmentally impacted areas, conducted from October 2024 through July 2025. This survey is still ongoing however preliminary results show serious health concerns that need to be addressed urgently. These results show high rates of the following reported health symptoms among participants taking the survey, including:

- Upper respiratory issues (76%)
- Headaches (84%)
- Sleep disturbances (70%)
- Gastrointestinal illness (68%)
- Allergic reactions (69%)
- Cognitive symptoms like difficulty concentrating (51%)

The survey asked about participants perception of their environment. Residents reporting exposure to poor or very poor air quality were significantly more likely to report sleep disturbance (4 times), gastrointestinal symptoms (3.4 times), and allergic reactions (1.9 times). Those reporting being exposed to very strong odors five or more times per week were up to 5.3 times more likely to experience appetite loss than those exposed less often.

These findings are consistent with results from the County of San Diego and CDC's CASPER assessment, conducted in October 2024 [18]. The study found similar rates of respiratory symptoms, headaches, and sleep problems [18]. The CASPER study also documented significant behavioral health impacts: over 65% of households reported mental health distress such as anxiety, insomnia, and appetite loss, and 12–14% of individuals screened positive for anxiety or depression. Together, these complementary survey results confirm what residents have long reported: that the sewage pollution crisis is not only a persistent environmental hazard but a daily public health emergency.

When asked in our survey about how participants think their environment has changed over time, 91% of respondents report being more concerned about pollution in their community this year when compared to one year ago. Many (81%) also report making changes in response to poor air quality, such as spending less time outdoors, keeping windows closed, and inviting people over less often, after experiencing or being informed of the conditions. Despite recent actions, such as air filter distribution programs, expanded hourly hydrogen sulfide monitoring in three community locations, and the allocation of over $650 million in federal and state infrastructure funding, major

gaps remain. Frontline workers and vulnerable families continue to live and work in hazardous conditions without consistent protection, recognition, or relief.

This white paper calls for **urgent and coordinated local, state and federal action**, including:

- Immediate emergency response measures to reduce sewage discharges
- Long-term binational infrastructure solutions
- Ongoing environmental monitoring using advanced technologies, including people's exposure where they live and work
- Culturally responsive healthcare access and education
- Longitudinal epidemiologic surveillance to measure impacts and progress over time

The crisis in the Tijuana River Valley is impacting the entire region. The communities bearing the brunt of this pollution deserve the same urgency and investment that would be expected in any other part of the country. This is a public health and environmental emergency.

The Crisis at the Border: What's Happening and Why It Matters

The Tijuana River flows from Mexico into the United States, discharging into the Pacific Ocean via the Tijuana River Estuary. Decades of inadequate binational wastewater infrastructure and unchecked sewage, urban runoff and industrial discharges have led to chronic contamination of water, soil, and air in the region. Heavy rains and aging infrastructure have exacerbated the situation, resulting in beach closures, degraded air quality, and increasing health complaints from surrounding communities [1-4].

Scientific studies conducted in the region have documented widespread environmental contamination. Water sources contain viruses such as SARS-CoV-2 and Hepatitis B/C, antibiotic resistant bacteria and hundreds of chemicals including pesticides, solvents, and flame retardants [1, 5-8]. Air contamination studies have shown aerosolized pathogens and hydrogen sulfide gases that are measured at concentrations far above urban norms [3,9-11]. Soil analysis has found over 170 hazardous compounds including arsenic, cadmium, PAHs, PCBs, and banned pesticides like DDT [12, 13]. These exposures potentially present major health risks for communities, particularly given recent understanding of the transfer of bacteria and chemicals from contaminated water to air [1, 14,15].

Community Health Findings: What Residents Are Experiencing

To better understand the public health implications of this crisis, a bilingual, cross-sectional (participants take only one time) community survey was conducted from October 2024 through July 2025. Eligibility was restricted to individuals over 18 years of age and who lived or worked in southern San Diego County near the Tijuana River Valley or potentially impacted coastal waters, including San Ysidro, Imperial Beach, National City, Coronado and other surrounding neighborhoods (see Figure 1).

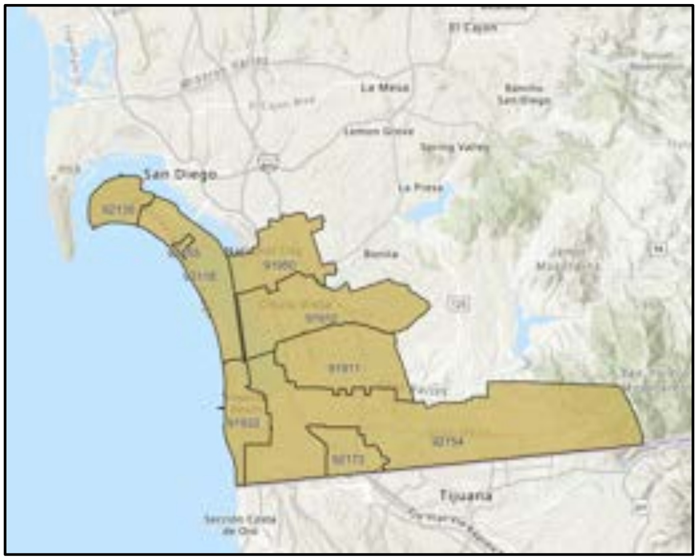

Figure 1: Map of zip codes in San Diego County where survey is being conducted

Participants were recruited through partnerships with community organizations, flyer distribution, social media outreach, website (tjriver.sdsu.edu) and door-to-door engagement. The online survey is collecting information on socio-demographics, environmental perceptions, and health symptoms participants have experienced over the previous 2 weeks from when they took the survey.

Survey Findings

The sample at the time of this paper included 405 respondents. Approximately 36% of participants identified as Hispanic or Latino and represented a range of ages and occupations. Reported symptoms over the previous two weeks from when taking the survey included upper respiratory issues (76%), headaches (84%), allergic reactions (69%), sleep disturbances (70%), gastrointestinal illness (68%), and cognitive complaints such as trouble concentrating (51%). Environmental concerns were also prevalent: 90% rated air quality as unhealthy, very unhealthy, or hazardous, 97% perceived the water quality as poor or very poor, and 25% experienced daily strong odors consistent with sewage or chemicals.

Deeper Look: How Pollution Affects Health

Statistical analysis revealed significantly positive associations between some of the health symptoms and higher levels of perceived pollution and odors (Figure 1) (adjusted for age, gender, race/ethnicity, insurance, education, and working/residence status). People exposed to perceived poor air quality were over 3 times more likely to report sleep problems and more than 3 times as likely to report diarrhea in the past two weeks. Perceived poor air quality was also linked to 1.5 times respiratory issues and almost 2 times reports of allergic reactions. Those who reported smelling strong chemical or sewage-like odors five or more times a week were up to 5 times more likely to report losing their appetite and about 1.5 times more likely to suffer from headaches.

Figure 1: Prevalence ratios of reported health symptoms for unhealthy air quality (top) and higher frequency of environmental odors (bottom). Controlled for age, gender, race, ethnicity, education, insurance coverage, and residence/working status. A value greater than 1 on the y-axis means that the symptoms were more frequent than reported by residents who reported more moderate air quality concerns and fewer odors.

This analysis shows a clear and consistent connection between perceived poor environmental conditions and community health. The high rates of reported symptoms, especially respiratory, sleep, and digestive issues, were strongly linked to perceived poor air and water quality, as well as frequent exposure to strong chemical or sewage-like odors. These findings track with reports of levels of hydrogen sulfide frequently exceeding acceptable levels and logs of community reports to the local air district. These results offer community-level evidence of what many residents already know from lived experience: the Tijuana River pollution crisis is not just an environmental issue, but a public health emergency [3]. The data confirm that community perceptions of risk are grounded in real and measurable health impacts [14-17].

Longitudinal Follow-Up (Surveying Participants Monthly)

We now have a longitudinal version of the survey underway, where we give the same survey to a group of participants every month. This will allow us to assess trends in exposure perception and health status over time and compare these results to environmental monitoring. Results will be released in future reporting.

Economic & Worker Impacts: How Pollution Affects Daily Life

The environmental and public health crisis in the Tijuana River Valley is imposing a significant economic burden on residents, workers, and the broader regional economy. Our survey data reveal that 22% of residents living and/or working in the affected areas reported missing work due to illness attributed to pollution-related symptoms such as gastrointestinal distress. These absences reflect lost wages, job insecurity, and reduced productivity, particularly for hourly or gig workers without paid leave or health insurance. The economic toll extends beyond individual households. Businesses in Imperial Beach and South San Diego, especially those dependent on coastal tourism, have experienced downturns due to prolonged beach closures, malodor complaints, and negative media coverage surrounding the sewage crisis [19]. Anecdotal stories of real estate values being negatively affected in areas where environmental degradation is widely heard, further reducing the wealth of families already facing structural disadvantages.

Occupational Health Risks and Effects on the Military

Outdoor and frontline workers face elevated occupational health risks. Lifeguards, border patrol agents, military personnel, and construction workers who operate near the river or coastline are frequently exposed to airborne and waterborne contaminants [20]. These workers have reported symptoms consistent with hydrogen sulfide exposure, including headaches, nausea, and respiratory irritation [3].

Most notably, recent national media coverage has spotlighted reports that Navy SEALs training off the San Diego coast became ill from exposure to raw sewage discharges. Multiple military service members reported vomiting, fever, and gastrointestinal distress after waterborne training exercises near Imperial Beach, further illustrating the severity of the pollution problem and its reach into federal operations [21, 22]. The Department of Defense has acknowledged these cases, and public health officials have called for urgent remediation to prevent further military exposure. This is another example of how this crisis is far reaching and is even impacting our national security.

Comparison with San Diego County CASPER Survey Findings

Our survey findings closely align with results from the *Community Assessment for Public Health Emergency Response (CASPER)* conducted by the County of San Diego and the CDC over two days in October 2024 [18]. That assessment surveyed 189 households near the Tijuana River Valley using door-to-door outreach and found widespread concern about health and environmental conditions related to sewage contamination.
Both our study and CASPER found high rates of reported health symptoms, especially:

- Respiratory issues (76% in our survey; 62% in CASPER)
- Headaches (84% vs. 80%)
- Sleep disturbances (63% vs. 56%)
- Cognitive symptoms like difficulty concentrating (51% in our survey; 33% reported lack of energy or difficulty concentrating in CASPER)

Community concern about their environment was also nearly universal. In both surveys, over 90% of respondents reported poor air and water quality, and many described strong sewage odors and changes to daily routines. About three-quarters of participants in each study reported reducing outdoor activity due to pollution. Together, these two assessments provide complementary evidence of the ongoing public health impacts of sewage contamination in the Tijuana River Valley and reinforce the urgent need for action. There was another survey done by the CDC and the Agency for Toxic Substances and Disease Registry (ATSDR) called the Aces survey that has recently released results. Our team will be comparing results in the near future.

Interventions Underway

In response to worsening environmental conditions and rising community health concerns, several interventions have been initiated. The San Diego Air Pollution Control District (SDAPCD) launched the *Air Improvement Relief Effort (AIRE) Program* to help residents reduce indoor air pollution exposure. This initiative provides free air purifiers and replacement filters to households in the most heavily impacted neighborhoods, particularly in San Ysidro and Imperial Beach. The program aims to create cleaner indoor environments, especially during high-pollution events when outdoor air becomes hazardous.

To further support public health, SDAPCD also expanded its environmental monitoring efforts in late 2024 with the release of an hourly hydrogen sulfide monitoring dashboard. This publicly accessible tool delivers near real-time air quality data at three locations for people living and working in or near the Tijuana River Valley, empowering them with timely information about exposure risks. While the dashboard represents a significant advancement in transparency and awareness, there are currently no binding regulatory thresholds or automatic enforcement actions tied to hydrogen sulfide concentrations, limiting its practical protections.

On a broader scale, long-overdue investment in cross-border infrastructure is finally underway. In early 2025, nearly $650 million in federal and state funding was secured to modernize the failing binational wastewater systems through the International Boundary and Water Commission (IBWC). This funding will support major upgrades to pump stations, sewage diversion systems, and wastewater treatment capacity, aiming to reduce the chronic overflows that send raw sewage from Tijuana into the United States. However, these infrastructure projects are still in planning or early implementation phases, and the health consequences for residents remain ongoing.

The San Diego County Board of Supervisors have also recently voted to approve a 5-point Sewage Action Plan authored by the newly elected Supervisor Paloma Aguirre (district 1). The plan proposes to eliminate toxic hot spots along the river, enhance filtration and ventilation in schools and childcare facilities, conduct a large scale epidemiological study, assess economic impacts and establish a committee to coordinate cross-agency actions to stop the contaminated flows.

Community Health Disparities & Gaps

The communities most affected by the Tijuana River Valley pollution, particularly San Ysidro, Imperial Beach, and parts of South San Diego, are predominantly low income and working middle class. These areas face entrenched social, economic, and infrastructure inequities that compound the effects of chronic exposure to pollutants. Historically under-resourced and overlooked in resource planning these neighborhoods lack the protective infrastructure, healthcare access, and environmental enforcement that wealthier regions often take for granted.

This environmental crisis limits opportunities for outdoor recreation for many residents. Even when outdoor spaces are technically accessible, the persistent presence of sewage odors, beach closures, and poor air quality makes them unsafe or undesirable for children and families. Approximately 64% of survey participants reported reducing outdoor activities for elderly family members and/or children due to environmental concerns. Community members describe feeling “disgusted,” “ignored,” and “abandoned,” citing unsafe beaches, contaminated air, and strong chemical smells as reasons for keeping children indoors and avoiding physical activity [23]. These psychosocial impacts are deeply intertwined with physical health consequences and economic hardship, including missed work, increased medical visits, and chronic stress. The scale and persistence of contamination in the Tijuana River Valley would likely prompt immediate federal intervention if it occurred in a more affluent community. The lack of proportional attention, funding, and regulatory enforcement reflects systemic infrastructure neglect in underserved communities. In this context, the Tijuana River Valley crisis is not only a public health and environmental issue, but also a matter of national public health and infrastructure responsibility. Continued failure to act exposes communities to disproportionate and preventable risks due to long-standing infrastructure failures.

What Needs to Be Done Now: Recommendations for Action

Addressing this crisis requires bold, sustained, and coordinated action across federal, state, and local agencies. First and foremost, the **federal and state governments could declare a public health and environmental emergency in the Tijuana River Valley**. Such a designation would unlock emergency resources, facilitate cross-agency coordination, and signal the national urgency of this binational pollution crisis. In the short term, emergency measures must be implemented to reduce the immediate flow of untreated sewage into neighborhoods and coastal waters. These include expanding sewage diversion capacity, reinforcing stormwater control systems, and installing temporary physical barriers at known overflow points. Such interventions are especially critical during extreme weather events when overwhelmed infrastructure allows large volumes of contaminated water to enter the coastal zone.

Longer-term solutions require robust investment to replace and modernize the aging binational wastewater infrastructure. Transboundary pollution cannot be resolved without joint United States-Mexico infrastructure solutions and a shared commitment to long-term operation and maintenance. Federal funding secured in 2025 is an essential step forward, but it must be matched by effective implementation, maintenance and binational oversight. Comprehensive environmental monitoring must also be institutionalized, with year-round sampling of air, water, and soil for pathogens and chemical contaminants. This includes use of advanced technologies such as metagenomic sequencing and non-targeted chemical analysis to identify emerging contaminants not captured by traditional testing methods. San Diego State University and the University of California San Diego are currently conducting these types of studies for research purposes, but the appropriate government agencies should be conducting these measurements and/or coordinating with local academic scientists on these efforts. The expansion of air quality monitoring tools, like the hydrogen sulfide dashboard launched by SDAPCD, should be scaled to include more communities and standardized across the region with appropriate warning systems in place for exceedances that may impact health.

To protect public health, impacted communities must be provided with no-cost medical screenings, improved access to culturally competent care, and environmental health education tailored to community needs. Special attention should be given to high-risk populations, including children, elders, and outdoor workers, who face heightened vulnerability to both acute and chronic exposures. Binational coordination is essential. The United States must work closely with Mexican authorities to reduce raw sewage discharges and industrial runoff at their sources. This effort will require transparent data sharing, joint accountability frameworks, and continued diplomatic pressure to ensure compliance and sustained progress. Occupational health protections remain inadequate. There are still no standardized safety guidelines or compensation mechanisms for workers such as lifeguards or border patrol agents exposed to pollution-related hazards in the Tijuana River Valley. The lack of formal recognition of exposure-related illnesses in affected workers, including military personnel, delays treatment and denies justice. Moreover, the burden on residents accessing local healthcare systems, especially in San Ysidro and South Bay, continues to strain resources, with many symptoms such as “difficulty concentrating” or “fatigue” going unrecognized or untreated. Without further policy, occupational safety, and healthcare investment, the cycle of exposure, illness, lost work, and financial strain will persist. Targeted relief from these chronic exposures and environmental enforcement are essential to reversing this trend and protecting the health and livelihoods of the region’s residents and workers.

Finally, environmental restoration must be matched by longitudinal health surveillance. Chronic long-term exposure to environmental contaminants carries long-term health consequences, and without a sustained public health monitoring system, new threats may go undetected and mitigation efforts unmeasured. Establishing this surveillance will allow communities and policymakers to track improvements, identify emerging risks, and hold systems accountable over time.

Conclusion

These health effects reported in the white paper and other studies do not occur in a vacuum. They intersect with economic insecurity, occupational exposure, and systemic inequities that compound the burden on already vulnerable populations. Survey findings show that illness from pollution is interfering with people’s ability to work, care for their families, and participate in daily life. The crisis is affecting local economies, workers, our military and the healthcare system, underscoring the multifaceted nature of the harm and the urgent need for comprehensive, equity-centered solutions.

The Tijuana River Valley crisis is a pressing environmental emergency in the United States today. The ongoing convergence of contaminated water, polluted air, and toxic soil in the region presents a clear and present danger to public health, community well-being, national security and ecological resilience. This white paper provides robust, community-driven evidence of the health harms experienced by residents, backed by scientific data and real-world testimony. Without decisive and sustained intervention, the human, economic, and environmental toll will only deepen, disproportionately affecting the region. The time for action is now. Federal and State leadership, strategic investment, and sustained binational collaboration are essential to restoring safety and dignity to the communities of the Tijuana River Valley.

References

1. Stigler Granados PE, Sant KE, Quintana PJE, et al. Tijuana River Contamination from Urban Runoff and Sewage: A Public Health Crisis at the Border. San Diego State University; 2024. Available at: https://www.sdsu.edu/_files/tijuana-sewage-contamination-public-health-crisis-white-paper-021424.pdf.
2. California Water Boards. Sewage Pollution within the Tijuana River Watershed. Published 2023.
3. Rico B, Barsanti K, Porter W, Granados PS, Prather K. Heavily polluted Tijuana River drives regional air quality crisis. ChemRxiv. Pre-print https://chemrxiv.org/engage/chemrxiv/article-details/67525c1b5a82cea2fa2227b7 Published online 2024. Accepted in Science - estimated publication August 2025.
4. Leggate J. San Diego Wastewater Plant Damaged By Tropical Storm Hilary Needs $8M in Repairs. *Engineering News Related* September 15, 2023.
5. Gersberg RM, Daft D, Yorkey D. Temporal pattern of toxicity in runoff from the Tijuana River Watershed. *Water Research.* 2004;38(3):559-568.
6. Espinoza J. *Identification and Assessment of Constituents of Emerging Concern in the Tijuana River Stormwater*: Masters Thesis, San Diego State University; 2023.
7. Allsing N, Kelley ST, Fox AN, Sant KE. Metagenomic analysis of microbial contamination in the U.S. portion of the Tijuana River Watershed. Int J Environ Res Public Health. 2022;20(1):600.
8. Steele, Joshua A., et al. "Quantification of pathogens and markers of fecal contamination during storm events along popular surfing beaches in San Diego, California." *Water research* 136 (2018): 137-149.
9. Adam Cooper *et al.* ,Identifying wastewater chemicals in coastal aerosols.*Sci. Adv.***11**,eads9476(2025).
10. Pendergraft, Matthew A., Pedro Belda-Ferre, Daniel Petras, Clare K. Morris, Brock A. Mitts, Allegra T. Aron, MacKenzie Bryant et al. "Bacterial and chemical evidence of coastal water pollution from the Tijuana River in sea spray aerosol." *Environmental science & technology* 57, no. 10 (2023): 4071-4081.
11. Hurtado, Lilia, et al. "Characterization of atmospheric bioaerosols at 9 sites in Tijuana, Mexico." *Atmospheric Environment* 96 (2014): 430-436.
12. McLamb F, Feng Z, Shea D, et al. Evidence of transboundary movement of chemicals from Mexico to the US in Tijuana River estuary sediments. *Chemosphere.* 2023:140749.
13. Lopez -Galvez N. Soil Analysis of Organic and Inorganic Contaminants in Goat Canyon (Cañon De Los Laureles), at the US-Mexico Border [Master's Thesis]. San Diego State University; 2014.
14. Arnold BF, Schiff KC, Ercumen A, et al. Acute illness among surfers after exposure to seawater in dry- and wet-weather conditions. Am J Epidemiol. 2017;186(7):866–875
15. Venn, Marissa Ann. *Mitigation of Contaminated Transboundary Flows in the Tijuana River: Public Health Considerations for Remediation Strategies*. MS thesis. San Diego State University, 2021.
16. Calderón-Villarreal, Alhelí, et al. "Deported, homeless, and into the canal: Environmental structural violence in the binational Tijuana River." *Social Science & Medicine* 305 (2022): 115044.
17. Fox, Alexandra Nicole. *Assessment of Bacterial Contamination in the US Portion of the Tijuana River and Tijuana River Estuary*. MS thesis. San Diego State University, 2021.
18. County of San Diego, Health and Human Services Agency. CASPER Study: South Region Health Concerns. October 2024. Available at: https://www.sandiegocounty.gov/content/sdc/hhsa/programs/phs/community_epidemiology/south-region-health-concerns/casper-study.html
19. Murtaugh T. Sewage crisis in South Bay puts businesses on the brink of bankruptcy. *FOX 5 San Diego*. Published March 20, 2024. Accessed May 30, 2025. https://fox5sandiego.com/news/business/sewage-crisis-in-south-bay-puts-businesses-on-the-brink-of-bankruptcy/
20. U.S. Border Patrol San Diego. *Tijuana Wastewater FlowsImpact on CBP Operations.* U.S. Customs and Border Protection; 2019.
21. Murtaugh T. Navy SEALs face health risks from toxic sewage exposure, report finds. *FOX 5 San Diego*. Published February 14, 2025. Accessed May 30, 2025. https://fox5sandiego.com/news/local-news/navy-seals-face-health-risks-from-toxic-sewage-exposure-report-finds/

22. Garrison N. Report confirms Navy SEALs sickened while training in polluted waters off San Diego. *The San Diego Union-Tribune*. Published February 15, 2025. Accessed May 30, 2025. https://www.sandiegouniontribune.com/2025/02/15/report-confirms-navy-seals-sickened-while-training-in-polluted-waters-off-san-diego/
23. Holliday E. Place-Based Environmental Education and Environmental Justice in Imperial Beach, California [Master's Thesis]. San Diego State University; 2020.

Disclaimer: This white paper presents preliminary results from a community health survey conducted between October 2024 and July 2025. These findings are shared for community engagement and policy planning purposes. A peer-reviewed publication with expanded data analysis is in development.

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Low Level Exposure to Hydrogen Sulfide: A Review of Emissions, Community Exposure, Health Effects, and Exposure Guidelines

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Abstract

Hydrogen sulfide (H_2S) is a toxic gas that is well-known for its acute health risks in occupational settings, but less is known about effects of chronic and low-level exposures. This critical review investigates toxicological and experimental studies, exposure sources, standards, and epidemiological studies pertaining to chronic exposure to H_2S from both natural and anthropogenic sources. H_2S releases, while poorly documented, appear to have increased in recent years from oil and gas and possibly other facilities. Chronic exposures below 10 ppm have long been associated with odor aversion, ocular, nasal, respiratory and neurological effects. However, exposure to much lower levels, below 0.03 ppm (30 ppb), has been associated with increased prevalence of neurological effects, and increments below 0.001 ppm (1 ppb) in H_2S concentrations have been associated with ocular, nasal and respiratory effects. Many of the studies in the epidemiological literature are limited by exposure measurement error, co-pollutant exposures and potential confounding, small sample size, and concerns of representativeness, and studies have yet to consider vulnerable populations. Long-term community-based studies are needed to confirm the low concentration findings and to refine exposure guidelines. Revised guidelines that incorporate both short- and long-term limits are needed to protect communities, especially sensitive populations living near H_2S sources.

Keywords

hydrogen sulfide; chronic; environmental; epidemiology; occupational

1 Introduction

1.1 Background

Hydrogen sulfide (H_2S) is a toxic gas also known as dihydrogen monosulfide, dihydrogen sulfide, hydrosulfuric acid, sewer gas, stink damp, sulfur hydride, and sulfureted hydrogen.

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Declaration of Interest

The authors declare that they have no known competing financial interests or relationships. The authors have not participated in and do not anticipate participation in any legal, regulatory, or advocacy proceedings related to the contents of the paper.

Exposure to high concentrations of H_2S has been considered a serious risk in occupational settings for hundreds of years (e.g., Fuller and Suruda 2000; Guidotti 2010, 1996; Lambert et al. 2006; NIOSH 1978), and is the second most common cause of fatal gas inhalation exposure in the workplace, second only to carbon monoxide (Guidotti 2010). A recent and disturbing trend is deliberate H_2S poisoning, which in Japan caused 208 fatalities in 220 suicide attempts over a 100 day period in 2008 using "homemade" H_2S gas and information disseminated by social media (Morii et al. 2010).

The dose-response relationship for mortality from acute, high-level exposure of H_2S is reasonably well understood. Less is known about the health impacts of chronic, low-level exposures and exposure-response relationships for morbidity, the focus of this review. Community exposure to H_2S and other reduced sulfur compounds, which is common around industrial, agricultural and natural sources that emit these gases, mostly occurs concentrations below 0.1 ppm, much lower than in occupational settings. Community exposure has long been considered a nuisance issue. Because people living near H_2S-emitting facilities can experience long-term exposures and frequently have health, racial, socioeconomic, and other disparities that can increase their vulnerability and susceptibility to pollutants, H_2S exposures and health impacts are an environmental justice issue.

1.2 H_2S sources

H_2S is emitted at numerous locations from a variety of sources. These include naturally occurring geothermal and volcanic sources where emissions cannot be altered, and anthropogenic sources such as confined animal feeding operations (CAFOs), oil and gas facilities, paper mills, and wastewater plants where emissions can be controlled using standards, operation practices, and administrative and engineering controls. Geothermal and volcanic sources produce H_2S by hydrolysis of sulfide minerals (Ma et al., 2019). Industrial source such as petroleum refineries release H_2S present in the feedstock (e.g., sour gas) and from the hydrodesulfurization process which generates H_2S prior to removing sulfur from the petroleum product by partial combustion via the Claus process (Guidotti, 1996). In sewers, tanneries, Kraft pulping and paper mills, landfills and waste lagoons (as found at CAFOs) where anaerobic conditions occur, reduced sulfur gases including H_2S but also methyl mercaptan (CH_3SH), dimethyl sulfide $(CH_3)_2S$ and dimethyl disulfide $(CH_3)_2S_2$ are produced by sulfate reducing bacteria that decompose sulfur-containing organic constituents (Guidotti, 1996); Rava et al. 2008).

Trends of airborne and non-air H_2S emissions in the USA are shown in Figure 1, based on industry-provided data reported to the U.S. Environmental Protection Agency (EPA) Toxic Release Inventory (TRI) System since 2012 when reporting was first required (EPA 2020). (Section 1.3 following describes the inclusion of H_2S in the TRI.) Most H_2S releases reported to TRI are emissions to air (9114 tons/year), equal to 65% of reported releases in the U.S. averaged over the last three years. Industrial sectors responsible for most air emissions include the paper industry (5367 tons/year, 54% of total air emissions), chemical industry (1889 tons/year, 21%), and the oil/gas industry including extraction (914 tons/year, 10%). Other economic sectors include the food sector, which has only a small share of H_2S releases (384 tons/year, 4% of airborne emissions), and agriculture. Notably, agricultural sources like CAFOs, are not required to report to the TRI. Our “high-end” H_2S emission estimates for CAFOs, discussed below, could double emissions to air. Overall, airborne emissions from the industries covered in TRI appear to have slightly decreased in recent years. In contrast, H_2S releases to other media, such as wastewater, increased from 2012 to 2018 due to growth in the oil/gas sector, which is responsible for most non-air releases (EPA 2020). While Figure 1 does not directly represent exposures or health effects, and TRI information itself has uncertainties and omissions (e.g., agricultural and geothermal sources are not included), the emission trends show continuing emissions and increases in some sectors, supporting the need to understand H_2S exposures and health implications.

The existing health literature focuses on a subset of H_2S sources: geothermal or volcanic sources, concentrated animal feeding operations (CAFOs), pulp or paper mills, and wastewater facilities. As detailed later in this review, exposure and health studies examining the top industrial sources (oil and gas extraction, chemical, and petroleum industries) are limited, while the number of studies examining agricultural sources, specifically CAFOs, is growing.

National-level H_2S emission information from agribusiness was not identified. We attempt a rough and preliminary estimate of CAFO H_2S emissions by estimating the surface area of waste lagoons where most releases occur, then multiply this area by the H_2S flux rate (emission per time per surface area of waste lagoon). Because a national total for lagoon surface area was not identified, we considered the number of swine in the U.S. (72.2 million, USDA 2022), the optimal lagoon area (approximately 285 ft^2/AU across a range of animal ages, where AU = animal unit (AU) or 1000 lbs (453.6 kg) live weight; Chastain and Henry 2002), and assume a weight of 55 lb (25.0 kg) per animal; together this gives 1.05×10^8 m^2 of swine waste lagoons. Available measurements of H_2S fluxes from lagoons are limited and highly variable, e.g., Rumsey and Aneja (2014) used a flux chamber to estimate an average winter and summer flux (0.0324 $\mu g/m^2$-s) at one CAFO in North Carolina (NC), and Grant et al. (2013) used air monitoring coupled with inverse dispersion modeling to estimate long-term fluxes (0.218, 2.148 and 3.849 $\mu g/m^2$-s) at three CAFOs in NC, Indiana and Oklahoma. These flux rates with the estimated lagoon area give a very large range for U.S. emissions: 107 to 12,760 tons/year. The low estimate, based on flux chamber measurements, may incompletely represent mixing processes that might increase emissions; the high estimate, based on inverse modeling, has considerable uncertainty; both may incompletely represent seasonal variation, among other limitations. Overall, the flux rate estimates lack representativeness, a result of the small number of CAFOs tested and strong dependences on the temperature, sulfide content, mixing and pumping activity in the lagoon, wind speed, season, time of day, precipitation, and other factors. In consequence, we cannot provide a reasonably accurate total for CAFO emissions. Because H_2S exposure tends to occur near sources, local conditions are critical. At large waste lagoons (e.g., exceeding 20,000 m^2 in area), annual H_2S emissions may approach 3 tons/year, and short-term emission rates may be considerably higher (Grant et al. 2013).

1.3 Overview of regulations

There is a long and somewhat contorted history of H_2S regulation in the U.S. (e.g., Woodall et al. 2005). In brief, the U.S. Congress removed H_2S as a hazardous air pollutant (HAP) under Title III of the 1990 Clean Air Amendments under pressure from industry (e.g., the American Petroleum Institute; Morris 1997) and the perception that its major impact was nuisance (Kilburn et al. 2010). In its 1993 Report to Congress, the U.S. Environmental Protection Agency (EPA) concluded that there was no evidence that routine releases from the oil and gas industry posed a significant public health or environmental threat and that no legislative action for accidental releases was warranted (EPA, 1993a). EPA's health assessment at that time noted some neurological, respiratory and irritation associated with H_2S exposures below 0.02 ppm, and the lack of long-term and low level epidemiological studies (EPA 1993b). As part of its final rule, EPA added H_2S to the Emergency Planning and Community Right-to-Know Act (EPCRA) Section 313 toxic chemical release reporting (TRI) requirements on December 1, 1993, on the basis of chronic neurotoxicity in humans and acute aquatic toxicity. On August 22, 1994, EPA issued an Administrative Stay of the EPCRA reporting requirements for H_2S to evaluate issues brought to the Agency's attention after promulgation of the final rule, which concerned the human health effects basis for the listing and the Agency's use of exposure analyses in TRI listing decisions (EPA 2011). This occurred despite recommendations by the Agency for Toxic Substance Diseases and Registry (ATSDR), the federal public health agency established to address chemical exposures, in their draft Toxicological Profile for H_2S to set a reference concentration (RfC) of 0.010 ppm. In 1996, H_2S became subject to the Risk Management Program rule under section 112(r) of the Clean Air Act, a state-administered program that applies to many facilities if a short-term emergency release of H_2S can exceed 10,000 lbs (4536 kg), however, this limit would not apply to most sources since H_2S is not stored or accumulated. In 2003, the EPA derived an inhalation RfC for chronic exposure of 0.0015 ppm (2 μg/m^3), based on a no observed adverse effects level (NOAEL) of 10 ppm and a lowest observed adverse effects level (LOAEL) of 30 ppm for nasal lesions. On February 26, 2010, EPA published a notice in the Federal Register (FR) that provided an opportunity for public comment on its review of the available data on the human health and environmental effects of H_2S and EPA's belief that, based on those data, the administrative stay should be lifted (EPA 2010). The FR notice addressed the concerns raised regarding the exposure analyses in the TRI listing decisions, essentially indicating that exposure analyses need not be considered given the moderate-to-high chronic toxicity of H_2S. EPA (2010) determined that H_2S can reasonably be anticipated to cause serious or irreversible chronic human health effects at relatively low doses and thus is considered to have moderately high to high chronic toxicity, and that it is not appropriate to consider exposure for such chemicals assessment when determining a listing for chronic health effects pursuant to EPCRA Section 313(d)(2)(B) (see 59 FR 61432, 61433, 61440–61442). Although beyond the scope of this review, EPA also determined that H_2S causes ecotoxicity at relatively low concentrations and thus it is not required to consider its exposure when determining listings pursuant to EPCRA Section 313(d)(2)(C) (see 59 FR 61432, 61433, 61440–61442). On October 17, 2011, EPA published a FR notice that it was lifting the Administrative Stay of the TRI reporting requirements, and it summarized and responded to comments received regarding the previous FR notice (EPA 2011). In brief, EPA concluded that H_2S can reasonably be anticipated to cause chronic health effects in humans and significant adverse effects in aquatic organisms, and reiterated that an exposure assessment was not required to meet TRI listing criteria. Listed chronic human health effects included both upper respiratory tract toxicity (e.g., nasal lesions) and neurotoxicity. The notice references a controlled study of perception and neurological impacts and two dosimetry studies. The effect of lifting the stay was to once again include H_2S on the TRI list of reportable chemicals under EPCRA Section 313 (40 CFR Part 372, Subpart D) beginning with the 2012 reporting year, as illustrated earlier in Figure 1 which trended reported H_2S emissions. Other regulatory levels are described in Section 4. While H_2S remains off the EPA HAP list, which would require source controls and limit ambient exposure, several states have pursued regulatory programs for H_2S or total reduced sulfur (TRS) compounds (Woodall et al. 2005).

1.3.1 Rationale and context—This report builds upon prior reviews, which noted the inconsistent evidence regarding health effects and the need for more robust exposure assessments (Lewis and Copley 2015; Lim et al. 2016; Roth and Goodwin 2003; Skrtic 2006). The most recent review, conducted by Exxon Mobil, found that chronic low-level H_2S was associated with temporary respiratory impairment and possible ocular and neurological effects (Lewis and Copley 2015). A review of neurological and respiratory health in occupational and community settings found inconsistent associations (Lim et al. 2016). An earlier review examining communities near oil and gas facilities found that chronic exposure to low concentrations of H_2S was associated a range of with neurological symptoms, including fatigue, impaired memory, altered moods, headaches and dizziness (Skrtic 2006). However, low-level H_2S exposures in community settings from sources such as oil and gas facilities, CAFOs and landfills are typically experienced as mixtures of contaminants, and unless the mixture components are sufficiently characterized to minimize the likelihood of confounding in health studies, epidemiological findings may be compromised. The potential for this problem is suggested by conflicting results obtained by the few studies using controlled exposures. These and other issues affecting the understanding of low-level exposures are not unique to H_2S, but their importance and implications should be recognized. Having identified the need for more comprehensive analyses of health effects and emission sources, we take an interdisciplinary approach, contextualizing epidemiological studies with toxicology, exposure science, and regulatory perspectives, to better understand the significance of chronic, low-level and community-wide exposures.

1.4 Objective and approach

This report examines the recent literature pertaining to health effects caused by the inhalation of hydrogen sulfide (H_2S) gas, focusing on effects at low exposure levels that are relevant to community exposure. We seek to gather and critically assess evidence of community exposure to H_2S, identify culpable emission sources, and analyze human health effects associated with chronic exposure to H_2S at low concentrations. We specifically focus on literature relevant to low-level community exposure to assess the minimum exposure levels associated with adverse health effects, although we also consider low-level occupational exposures given its relevance to understanding chronic health effects. We define low level exposures as H_2S concentrations below 0.1 ppm, medium level as between

0.1 and 1 ppm, and high level exposures as above 1 ppm. These limits are flexible given the importance of exposure duration and the variation of concentrations that may be measured or estimated in any particular study. An important distinction, however, is that the low and medium-level categories are distinctly lower than current standards or guidelines for workplace settings, which mostly range from 1 to 50 ppm.

The review is designed to reflect our current understanding of the effects of low level H_2S exposure, as based on published papers, reports and other materials prioritized as follows.

- Articles. Recent, published, peer-reviewed studies in the literature were the primary data source.
- Reviews. The health effects of H_2S have been the subject of many previous reviews. Many of these are authored by well-known authorities, such as U.S. Environmental Protection Agency (EPA), U.S. Agency for Toxic Disease and Registry (ATSDR), and the World Health Organization (WHO), while others have been commissioned by governmental authorities and industry. Reviews were primarily used to summarize older literature and to identify key studies (typically older studies), which were then examined. Key assumptions and statements in the reviews were verified by reference to the original articles.
- Abstracts, conference papers, dissertations, industry studies, and presentations. These sources were reviewed, but published peer-reviewed articles were given priority.
- Dates of publications. This review focuses on the recent H_2S literature, beginning in 2004. Previous reviews were examined for literature prior to this year and, as mentioned, original articles were obtained when applicable.
- Exposure routes. While several exposure routes may be relevant, H_2S exposure is dominated by the inhalation pathway in community settings, as well as in the vast majority of workplaces. Exposures via ingestion (e.g., drinking water) and dermal permeation were excluded from the present review.
- Nature of exposure. We focus on low-level and often chronic exposure that is relevant to community (and many workplace) settings. Generally, concentrations in community and most workplace settings fall well below 100 ppm (1,500 μg/m^3).
- Units. H_2S concentrations are converted to units of parts per million (ppm) at 25 C and 1 bar, which for H_2S means that 0.001 ppm = 1 ppb = 1.5 μg/m^3 and 1 μg/m^3 = 0.00067 ppm = 0.67 ppb. If concentrations in the original report were provided other units, these are shown in parentheses.

2 Health effects of exposures to H_2S

Inhalation is the main exposure pathway for the vast majority of exposed communities, although H_2S can be absorbed through the gastrointestinal tract. H_2S and its metabolites (e.g., sulfate, thiosulfate) are distributed throughout the body after exposure (Beauchamp et al., 1984). Considered a broad-spectrum toxicant, H_2S primarily affects tissues with exposed mucous membranes (eyes, nose) and with high oxygen demand (lungs, brain) (Ammann 1986; Legator et al. 2001). H_2S exposure can cause a wide variety of effects, depending on the concentration, exposure duration, and target tissue, and the literature describes effects on the central nervous, cardiovascular, and gastrointestinal systems. "Primary" toxic effects of H_2S have been characterized as "knockdown" (acute central neurotoxicity), pulmonary edema, conjunctivitis, and odor perception, followed by olfactory paralysis. "Secondary" effects which accompany or are complications of toxicity that include non-specific symptoms such as headaches, memory loss, and acute and chronic respiratory effects (Guidotti 2010). Effects of H_2S exposure can include:

- Asphyxia. At high concentrations, above roughly 200 to 1000 ppm, H_2S acts as an asphyxiant, causing instantaneous loss of consciousness, pulmonary edema, hyperpnoea (rapid breathing), rapid apnea (slowed or temporarily stopped breathing), and death.
- Irritation. At intermediate concentrations (between 100 and 150 ppm), H_2S acts as a tissue irritant, causing keratoconjunctivitis (combined inflammation of the cornea and conjunctiva), respiratory irritation with lacrimation (tears), and coughing (Knight and Presnell 2005). Skin irritation is also common.
- Neurological effects. Neurological effects include dizziness, vertigo, agitation, confusion, headache, somnolence, tremulousness, nausea, vomiting, convulsions, dilated pupils, unconsciousness, anosmia (loss of sense of smell), depression and suicide.
- Cardiovascular and pulmonary effects. Reported effects include cough, chest tightness, dyspnea (shortness of breath), cyanosis (turning blue from lack of oxygen), cardiac arrhythmia and tachycardia, hemoptysis (spitting or coughing up blood), pulmonary edema (fluid in the lungs), apnea with secondary cardiac effects, and impaired lung function in asthmatics.

2.1 Health effects at high exposures

Short duration and high concentration exposures to H_2S are a well-known health hazard, and are among the leading causes of sudden death in the workplace (NIOSH 1978). As mentioned, H_2S is the second most common cause of fatal gas inhalation exposures in the workplace (Guidotti 2010). H_2S exhibits an exceptionally sharp exposure-response curve for lethality (Cantox Environmental 2009; Zelensky 2009), which yields a very small margin of safety, in part due to rapid olfactory paralysis and the loss of consciousness, which reduces the chance of flight. For these reasons, escaping from H_2S exposure can be exceptionally difficult (Guidotti 1996). Deaths from H_2S inhalation have occurred in many different workplace and some non-workplace settings, e.g., sewers, animal processing plants, waste dumps, sludge plants, oil and gas well drilling sites, tanks, cesspools, basements, and bathrooms (ATSDR 2006). Confined spaces, where concentrations can reach high levels, are especially dangerous. Given the significance of the hazard, H_2S awareness training in the workplace has become – or should be – a regular part of health and safety programs where this gas may be encountered. Brief but high exposure of H_2S can cause other impacts, e.g., reactive airways distress syndrome (RADS), a variant of occupational asthma (Bardana 1999; CDC 1993).

2.2 Mechanisms of toxicity

Mechanisms postulated for the toxicity for H_2S have been reviewed by Knight and Presnell 2005; ATSDR 2006; Guidotti 2010, and others. One mechanism is direct inhibition of cellular enzymes, in particular, cytochrome c oxidase, the terminal enzyme of oxidative phosphorylation, which impairs aerobic metabolism and results in cellular anoxia and tissue hypoxia (Ammann 1986). This has been demonstrated by H_2S concentrations in the range of 5 to 10 ppm, which in humans can cause a shift from aerobic to anaerobic respiration (Bhambhani et al. 1996; Bhambhani and Singh 1991). Several mechanisms have been proposed for neurotoxic effects: changes in the membrane and synaptic properties of dorsal raphe serotonergic cells, potentially due to an interaction with free thiols and disulfide bonds present in the membrane proteins; possible inhibition of monoamine oxidase that disrupts neurotransmission in brain stem nuclei controlling respiration (ATSDR 2006); and hypoxia-induced neuronal cell death attributable to cytochrome oxidase inhibition. Fiedler et al. (2008) notes toxicity due to cellular asphyxiation has been challenged by an animal model of H_2S-induced apnea after “knockdown” caused by an afferent neural signal from the lung via the vagus nerve, which innervates the viscera and provides information about the state of the body’s organs to the central nervous system, rather than a direct effect on the brain stem (Almeida and Guidotti 1999), and that the persistent neurologic effects among those experiencing acute H_2S intoxication resulted from hypoxia secondary to respiratory insufficiency, rather than a direct toxic effect on the brain (Milby and Baselt 1999).

H_2S is present in mammalian tissues at concentrations from the high nmol/L to low μmol/L range (Polhemus and Lefer, 2014), a result of endogenous production where it appears to serve a number of functions, probably acting as a neuromodulator and/or as an intracellular messenger or signaling molecule in the brain (Olson 2011; Qu et al. 2008; Varaksin and Puschina 2011). Although not currently used, a decreased concentration of H_2S in expired air has been suggested as a biomarker of inflammation and asthma (Wang et al. 2011).

The details of the mechanisms and toxicity of H_2S at high concentrations (and case reports and other literature) are beyond our present scope. In brief, however, we note that the most commonly reported nonlethal effect following an acute high concentration exposure is “knockdown”: unconsciousness followed by apparent recovery. While typically unmeasured, rough estimates of concentrations in such events are 500 ppm or more, and the exposure duration is short, typically less than 1 hr (Beauchamp et al. 1984). Following such exposures, common permanent or persistent neurological effects reported include headaches, poor concentration ability and attention span, short-term memory impairment, and impaired motor function. Brief exposure to still higher concentrations can result in respiratory arrest and/or pulmonary edema. Although exact mechanisms are unknown, rapid respiratory failure and possibly pulmonary edema are secondary contributors to the action of H_2S on central nervous system depression or tissue hypoxia. Cardiovascular effects (e.g., cardiac arrhythmia and tachycardia) also have been reported following acute exposures. Extensive discussions of toxicity and effects at high concentrations are provided elsewhere (e.g., ATSDR 2006; OEHHA 2008; also see review papers cited previously). Interesting and detailed discussions of dose-response and lethality of H_2S have been developed by Alberta's Energy Resource and Conservation Board (Cantox Environmental 2009; Zelensky 2009).

2.3 Health effects at low and chronic exposures

In contrast to short-term (acute) high concentration exposures, it is much more difficult to evaluate effects of long-term (chronic) and low or medium concentration exposures (below 0.1 and 1 ppm, respectively), the focus of Section 3 of this report. Most epidemiological (or observational) studies have deficiencies in terms of exposure characterization, e.g., obtaining little if any information on individual-level exposures, exposure patterns, peak exposures, and co-exposures to other contaminants. The paucity and limitations of controlled chronic animal studies also lead to knowledge gaps of low level chronic exposures (ATSDR 2006). Controlled chronic human studies are neither feasible nor ethical. Thus, it is unsurprising that the earlier studies and reviews have inconsistent findings with respect to the nature and significance of chronic low level exposures, leading several reviews to conclude that there is "insufficient" evidence to link low level H_2S exposures to significant health impacts (Lewis and Copley 2015; Lim et al. 2016; OEHHA 2000; Roth and Goodwin 2003).

A wide range of health effects at H_2S concentrations below 10 ppm have been reported in both occupational and community settings. For example, ATSDR (2006) states: "Exposure to lower concentrations of hydrogen sulfide can result in less severe neurological and respiratory effects. Reported neurological effects include incoordination, poor memory, hallucinations, personality changes, and anosmia (loss of sense of smell); the respiratory effects include nasal symptoms, sore throat, cough, and dyspnea. Impaired lung function has also been observed in asthmatics acutely exposed to 2 ppm H_2S; no alterations in lung function were observed in studies of nonasthmatic workers." In contrast, Guidotti (2010) states: "Exposures on the order of 5 to 10 ppm are sometimes encountered in community settings, although they are more common as background in workplaces such as oil refineries. Levels above 1 ppm are very uncommon in the community, where concentrations above the odor threshold (generally above 0.05 ppm for most people) are normally unacceptable and prosecuted as a nuisance. It has been alleged that health effects may be observed at exposures below 1 ppm, but the evidence is weak." The remainder of this section reviews the recent literature and discusses various health outcomes and symptoms, with the aim of clarifying the dichotomy regarding the occurrence of health effects from low and chronic H_2S exposures.

2.3.1 Odor, nuisance and irritation

2.3.1.1 Odor classification: H_2S is noted for its strong and offensive odor, which resembles rotten eggs. WHO (2006) and many others observe that H_2S is often accompanied by other odorous compounds from the same source: kraft mills emit reduced sulfur compounds such as methyl mercaptan, dimethyl disulfide, dimethyl trisulfide, dimethyl sulfide and dimethyl monosulfide; the viscose industry emits carbon disulfide; and CAFOs emit reduced sulfur compounds, VOCs including phenyls (fresh sludge), ammonia (in the absence of H_2S), dusts and bioaerosols (Blanes-vidal et al. 2009). Co-pollutants can change the odor quality of the mixture (NRC 1979).

It is important to distinguish between odor detection, odor recognition, odor threshold, olfactory fatigue, and olfactory paralysis. In community settings, the literature shows a degree of consistency with respect to odor detection and nuisance thresholds for acute exposures (30 min to 24 hr) at concentrations in the range of 0.0001 to 0.05 ppm.

- Odor detection threshold. Like other odors, inter-individual variation in sensitivity to H_2S is large. A review of 26 studies showed average odor detection thresholds from 0.00007 to 1.4 ppm (0.10 to 2,100 μg/m^3) (Amoore 1985); the geometric mean (GM) of these studies was 0.008 ppm (12 μg/m^3) (OEHHA 2008). Other reviews note an odor detection threshold for H_2S in pure form as low as 0.000013 to 0.0013 ppm (0.2 to 2.0 μg/m^3), depending on purity (van Gemert and Nettenbreijer 1984; Winneke et al. 1979) to 7.3 ppm (11 μg/m^3; Amoore and Hautala 1983). OEHHA (2000) states that at the reference exposure level (REL) of 0.0067 ppm (6.7 ppb = 10 μg/m^3), H_2S would be likely to be detectable by many people under ideal laboratory conditions, but it is "unlikely to be recognized or found annoying by more than a few." ATSDR (2006) gives an odor detection threshold ranging from 0.0005 to 0.3 ppm. Odor responses summarized by Collins and Lewis (2000) and Woodall et al. (2005) list concentrations of 0.5, 2, 4, 8, and 30 ppb being recognized by 2, 14, 30, 50 and 83% of persons, respectively.

- Odor recognition threshold. H_2S is frequently assumed to have an odor recognition threshold that is three to four times higher than the odor detection threshold, as assumed for other compounds. The threshold for perception lies between 0.02 and 0.13 ppm (Costigan 2003).

- Odor nuisance threshold. Odor nuisance occurs when an odor is perceived to be annoying. For H_2S, this can occur due to aesthetic, behavioral or physiological responses, which can include nausea and headache (Amoore 1985; Reynolds and Kamper 1984). The annoyance threshold often is stated to be about five times greater than the odor detection threshold. Using the geometric mean odor detection threshold, the annoyance threshold is about 0.04 ppm (60 μg/m^3) (OEHHA 2008). Slightly lower concentrations (0.03 ppm) have resulted in odor complaints and reports of nausea and headache near geyser emissions (Reynolds and Kamper 1984). These concentrations appear high for a guidance level, i.e., the California Ambient Air Quality Standard (CAAQS) is 0.03 ppm (OEHHA 2008). WHO (2006) states that on the "basis of the scientific literature, it is not possible to state a specific concentration at which odor nuisance starts to appear," however, text supporting the WHO's Air Quality Guidelines indicate that a 30-min average concentration of 0.0047 ppm (7 μg/m^3) is likely to produce substantial complaints (WHO 2006). The WHO guideline is based on two older citations (Lindvall 1970; NRC 1979). A recent and well-controlled clinical test suggests that at 0.05 ppm, the lowest H_2S concentration tested, participants may not fully habituate to the smell, and that continuing exposure may prove to be annoying (Fiedler et al. 2008).

- Olfactory fatigue. At concentrations above approximately 50 ppm (70 mg/m3), olfactory fatigue prevents detection of H_2S odor (OEHHA 2008).
- Olfactory paralysis. Neurotoxicity affecting the olfactory bulb and fibers may be followed by hyposmia or anosmia (permanent loss or reduction of the ability to perceive odor), which has been found in most men who recovered from severe and potentially lethal H_2S exposure (Guidotti 2010).

2.3.1.2 Odor and health: Odorant compounds can affect human health through several mechanisms (e.g., Schiffman et al. 2005; Wing et al. 2008; Woodall et al. 2005). Odor emissions, odor perception, and odor nuisance present quality of life issues that can cause individuals to modify certain physical and social activities (e.g., outdoor physical activity), which can then lead to other health-related issues. Odor perception is often associated with odor nuisance and complaints, and sometimes with psychological responses, e.g., headache, nausea, and loss of sleep. Ocular effects and nasal lesions are discussed in Sections 2.3.2 and 2.3.3, respectively. The WHO (2006) Air Quality Guidelines state that H_2S levels should not exceed 0.005 ppm (7 $\mu g/m^3$) over a 30-min period to avoid substantial complaints about odor annoyance. OEHHA (2008) in California makes the same statement but uses a higher exposure level, 0.03 ppm, developed in 1984 to reduce odors and physiological symptoms (headache and nausea) with a notation that this may need to be revisited. Several other studies have investigated odors and included H_2S measurements around CAFOs and landfills with the following findings:

- Irritation of the eyes, nose, and throat or other toxicological effects through properties of the odorous molecules and stimulation of the trigeminal nerve, typically at concentrations above the nuisance threshold. This is the “Type 1” classification of Woodall et al. (2005), in which symptoms are produced by irritant properties, rather than being odor-induced, often with the odor providing a “warning” of potential adverse health effects.
- Responses to non-odorant components that may be present in the airborne mixture, such as irritants or endotoxins in the case of CAFOs, which can induce inflammation and airflow obstruction. In this “Type 2” classification, a co-pollutant(s) in the mixture, not the odor itself, produces symptoms (Woodall et al. 2005).
- Innate aversion, conditioning, and/or stress responses to the odor, which produces health effects and/or symptoms including nausea, vomiting, headaches, stress, negative mood, and a stinging sensation. This occurs at concentrations above the olfactory nerve threshold, that is, exceeding the odor recognition or nuisance threshold, but below the antrigeminal nerve threshold, which is associated with irritation. This “Type 3” classification (Woodall et al. 2005) can also include odor-related exacerbation of underlying conditions and odor-related stress-induced illness. Odor may also lead to an acute “stress” state among individuals who perceive that the odor source poses a health risk (Shusterman 2001).

Because most facilities releasing H_2S also emit other pollutants, studies based on odor perception alone cannot confirm the role between H_2S exposure and health and psychological effects. Confirmation requires monitoring of H_2S and potentially other components of the pollutant mixture. Still, at least one study suggests that H_2S is often the predominant odor source. Using the threshold (dilution) olfactometry technique with a small human panel and 24 different slurry samples from swine operations, each tested for 35 gases (e.g., reduced sulfur compounds, phenyls, alcohols, ketones, acetic acid, ammonia), H_2S explained 45 to 68% of odor concentration, with most of the remainder attributable to volatile organic compounds (Blanes-vidal et al., 2009). A review of five olfactory studies examining municipal wastewater odors also states the need to complement olfactometric measurements with other tools, e.g., portable H_2S or SO_2 analyzers (Lewkowska et al., 2016). Unfortunately, relevant olfactometry studies identified in the literature are small, and few allow odor intensity to be correlated to the mixture's components. While more studies are examining co-pollutants associated with H_2S sources, the lack of olfactometry studies that characterize co-pollutants remains a gap in the observational studies examining health effects associated with odor.

2.3.1.3 Studies at livestock rearing systems: Livestock rearing systems include CAFOs as well as manure storage and treatment. As noted above, these facilities emit H_2S and other odiferous co-pollutants, e.g., reduced sulfur compounds, phenyls, and ammonia; these facilities can also emit biological contaminants (e.g., endotoxins, fungi and bacteria), aerosols and particulate matter (e.g., entrained dust).

Many surveys have been conducted in communities with or near CAFOs where individuals experience chronic exposure to CAFO-related pollutants (Donham 2010). Occupational studies at CAFOs have documented health complaints, e.g., eye irritation, sinusitis, chronic bronchitis, nasal mucous membrane inflammation, nasal and throat irritation, headaches, and muscle aches and pains, as well as objective health effects, e.g., respiratory inflammation, cross-shift decline in lung function, and chronic respiratory impairment (Schiffman et al. 2005). Acute high level H_2S exposure due to releases from agitated manure can lead to reactive airway distress syndrome (RADS), permanent neurologic damage, and death (Bardana 1999; CDC 1993). A review of health and social issues associated with CAFOs found over 70 papers addressing health issues affecting workers and communities (Donham et al. 2007). In reviewing health effects associated with airborne exposures at CAFOs, Heederik et al. (2007) noted the uncertainty regarding which effects were due to CAFO emissions; uncertainty also applies to attributing the effects to H_2S as compared to other odiferous and irritation-causing CAFO-related pollutants. Below we examine studies since 2004 focusing on odors and nasal irritation from CAFOs. (Later sections address ocular, nasal lesions, respiratory, neurological, and immune effects associated with CAFOs).

The newer studies examining nasal irritation associated with livestock rearing systems follow:

- Bullers (2005) studied residents living near hog farms in North Carolina, U.S. in 1998 and 1999 enrolled using snowball recruitment methods (n = 48), who were compared to a group without this exposure studied in 1999 enrolled using flyers (n = 34). The exposed group showed increases in 12 of 22 self-reported physical symptoms, including sinus problems. (Additional symptoms are discussed in subsequent sections.) The authors discussed theoretical models regarding effects of environmental stressors. Study limitations include a modest sample size, a non-random sample, lack of control of covariates, differences in interview protocols (interviews in-home, by telephone), payments to participants in the comparison group but not the exposed group, non-simultaneity of interview periods for the two groups, and the lack of objective health and exposure measures.

- Schiffman et al. (2005) used well controlled exposure chamber tests and 48 self-selected human volunteers to evaluate physiologic and psychological responses to 1-hr exposures of dilute swine confinement air, stated to be equivalent to levels that could occur downwind of a swine facility, both within and beyond the property line. Concentrations measured during the exposure were 0.024 ppm (24 ppb) for H_2S, 0.817 ppm (817 ppb) for ammonia, 24 μg/m^3 for particulate matter (PM), 7.4 EU/m^3 for endotoxin, and 56 D/T for odor (factor above the odor threshold). No association between H_2S and nasal inflammation was found. To explain the dichotomy between this and other studies, the authors suggested that either additivity or synergy among the combined components may cause reported effects since no single component was present at sufficiently high concentration to be wholly responsible for symptoms, or that the self-reported "exposure-related avoidance" symptoms are innate or learned warning signals of potential health effects caused at higher concentrations or with prolonged exposure. Study limitations include the short exposure duration, use of healthy volunteers as compared to susceptible individuals (e.g., persons who are sensitized or have asthma) or individuals with involuntary and prolonged exposures, the inability to separate effects of H_2S alone from the CAFO mixture, and differences between experimental tests and occupational or community settings with respect to stress and the resulting neuronal, hormonal and behavioral responses that might affect outcomes.

- A longitudinal study of non-smoking adults (n=101) living within 1.5 miles of industrial hog operations in 16 neighborhoods in eastern North Carolina, U.S. collected survey (twice-daily odor diaries for approximately two weeks) and ambient H_2S and PM_{10} data from 2003 to 2005 (Horton et al. 2009). Typically, nine hog operations were within 2 miles of each community. In nine neighborhoods, odor was reported on ≥50% of study days, and hog odors inside homes were reported on 12.5% of person-days. Odor ratings were strongest in the morning and evening, with higher temperature, humidity and PM_{10} concentration, and both low and high (but not moderate) wind speeds. On 118 occasions, 34 participants reported that they altered activities due to hog odor. The authors concluded that malodor from swine operations was common in the studied communities, reported odors were related to objective environmental measurements, and that malodors interrupted the activities of daily life. Previously, odor was associated with stress levels for a subset of the same sample population (Horton 2007), while ethnographic interviews for another subset also found that malodor limited many daily physical and social activities that can reduce stress and promote health (Tajik et al. 2008).

- Schinasi et al. (2011) tested associations between pollutants and odors near hog operations and acute physical symptoms using a longitudinal approach to help control the confounding possible in cross-sectional studies. The study used the same sample and monitoring approach described above (Horton et al. 2009). Participants were asked to spend 10 min outdoors twice a day at preselected times, assess odor, complete a symptom survey, and perform (unsupervised) spirometry. Simultaneously, ambient air monitoring was conducted for H_2S, endotoxin and PM_{10}, $PM_{2.5}$, and $PM_{2.5–10}$ in each community. Across the communities, the 1-hr H_2S concentration averaged 0.00030 ±0.00186 ppm (0.30 ±1.86 ppb); 12-hr PM_{10} averaged 19.4 ± 11.8 μg/m^3; and 12-hr $PM_{2.5}$ averaged 10.9 ±5.7 μg/m^3. Nasal irritation increased with general odor perception and ambient H_2S (per 1 ppb increase). Study strengths include the repeated and objective exposure measures and the frequent outcome measurements. The authors note the small sample size and the possibility that emissions during the study were reduced.

These investigations recognize that exposures from livestock related systems involve mixtures of pollutants. Identifying the effect of an individual component like H_2S can be difficult, requiring characterization of the mixture by monitoring its major components at the source or in ambient air, ideally in the community or residence of study participants, and further, H_2S levels must be shown to either dominate the health effect or be sufficiently non-collinear to separate effects of the mixture.

2.3.1.4 Studies at landfills, compost, and wastewater facilities: We identified several newer studies conducted at landfills, compost and wastewater facilities. As noted earlier (Section 1.2), these facilities produce H_2S under anaerobic conditions, and thus emissions will include other reduced sulfur gases. In addition, VOCs and fugitive dust containing odiferous or irritating components may arise from active landfills (i.e., operating faces without grass or other cover) and composting facilities. The dispersal of dusts is likely to be limited to locations very near the source given the rapid settling and dust fall expected for larger particles, e.g., greater than 2.5 μm in diameter.

- A community-based study in Pennsylvania, U.S. measured ambient and indoor levels of H_2S at two elementary schools, one of which was located near a composting plant, in two seasons (spring and fall; Logue et al. 2001). School nurses recorded symptoms and medical history from 749 “exposed” and 518 “unexposed” students. At the control school, concentrations never exceeded 0.01 ppm (1-hr average); at the exposed school, concentrations exceeded 0.01 ppm on 9 days in autumn and 3 days in spring). H_2S was not associated with irritation or olfactory symptoms. (Other outcomes from this study are discussed in later sections.) The negative results may have been due to the minimal exposure contrast between the schools, and other exposures that might have caused exposure misclassification.

- Among studies of wastewater treatment plant (WWTP) workers, only Lee et al. (2007) assessed nasal irritation. In Iowa, 109 workers at WWTPs were compared to 66 workers at water treatment plants (WTP), a group with similar work duties and characteristics but without occupational H_2S exposure. Objective measures of H_2S were used, but odor perceptions were not evaluated. Most (95%) monitored concentrations of H_2S were below 1 ppm, and the overall geometric mean concentration was 0.15 ppm (range from 0 to 42.5 ppm) in the WWTP group. The exposed group had a significantly higher risk of sinus problems. Skin and throat irritation were also found at higher rates in wastewater treatment workers, but these associations were not robust. (Additional outcomes in this study, e.g., neurological and respiratory symptoms are discussed later.) The authors suggested that the symptoms may be promoted due to synergistic or additive effects of the contaminant mixture.

- A panel study of 23 adults in Orange County, North Carolina, U.S., living within 0.75 mile of landfills completed a questionnaire twice daily about odor intensity, alteration of daily activities, mood state, and health symptoms (Heaney et al. 2011). At a site between the landfill and community, monitored H_2S levels averaged 0.00022 ppm (range: 0 to 0.0023 ppm), and were used as an indicator of a complex mixture of odorant chemicals. Conditional fixed effects models were used to associate odor perception to the alteration of daily activities, negative mood states, upper respiratory symptoms, mucous membrane irritation (burning eye, nose and throat), several neurological outcomes (dizziness, lightheadedness, “general ill feeling”), and other physical symptoms. The authors suggested that H_2S concentrations, which were below odor detection thresholds, and were likely correlated with other (unmeasured) landfill pollutants, probably associated with fresh garbage. While odor, health and quality of life impacts were associated with landfills, the study has several limitations, e.g., possible reporting bias since both independent and dependent variables are based on diaries, a small sample size, an inability to separate effects of H_2S from other odorous compounds, a lack of pollutant measurements other than H_2S, and a lack of objective (e.g., clinical) outcome measures.

As discussed in the prior section, identifying the effect of H_2S at these facilities requires adequate characterization and separation of mixture components. This was probably a minor issue in the school study given limited penetration and filtering of particulate matter typical in most buildings; this study had negative results. Both the occupational and landfill panel studies monitored H_2S but no other possible components of the exposure; the issue of co-exposure is particularly likely and limiting in the former study, as acknowledged by the authors.

2.3.1.5 Summary of odor and irritation: Few controlled or occupational epidemiological studies have examined odor and/or irritation related to H_2S. Several community-based studies have evaluated individuals living near H_2S emitting facilities, however, comparisons and synthesis are impeded by the very different exposure assessment methods, which include perception-only studies (i.e., without H_2S measures; Horton 2007), both indoor and ambient H_2S measurements (Logue et al. 2001), ambient odor and ambient H_2S measures (Schinasi et al. 2011), and indoor odor and ambient H_2S measures (Heaney et al. 2011; Horton et al. 2009). Simultaneous odor and H_2S measures, collected both indoors and outdoors, are lacking, and information on individual-level exposures is also lacking. In studies using objective H_2S measures, odor was associated with ambient H_2S and nasal irritation, as has been shown in toxicological studies examining the irritant properties of H_2S, however, other symptoms did not show robust associations. H_2S odors may induce or exacerbate conditions such as stress or behavior modification. Importantly, studies using only odor as an exposure metric can be problematic for several reasons: they do not account for other pollutants that may be present; outcomes may be affected by response enhancement bias, i.e., an increase in reported symptoms since respondents are both aware of and potentially sensitized to the exposure (Farahat and Kishk 2010); odor thresholds among individuals vary enormously; and finally, odor perception can trigger a range of responses that may be contextual and difficult to assess.

In summary, odors associated with sources that emit H_2S, including agricultural, waste, wastewater, and industrial facilities, are clearly associated with odor-triggered nuisance, complaints and physiological symptoms that can result in health and quality of life impacts. These impacts occur at concentrations above an individual's odor detection threshold, up to the odor nuisance threshold, at short-term H_2S concentrations from roughly 0.001 to 0.050 ppm (Finnbjornsdottir et al. 2016; Heaney et al. 2011; Horton 2007; WHO 2006). Odor sensitivity to H_2S varies greatly among individuals (by over four or more orders of magnitude), and some individuals can detect H_2S at concentrations well below 0.001 ppm. Because the observational and community studies focus on waste management, industrial and agricultural facilities that emit a mixture of odiferous and irritation-causing pollutants, the reported health effects are not necessarily caused by H_2S exposure alone. However, a recent study suggests that H_2S may be the most important odorant at CAFOs, explaining 45 to 68% of the odor, with the remainder attributable to volatile organic compounds (Blanes-vidal et al. 2009). Given these and other study limitations noted above, the relationship between odor detection and harmful health effects has not been consistently found in epidemiological studies.

2.3.2 Ocular effects—Ocular effects of H_2S have been recognized since at least the 18^{th} century. Lambert et al. (2006) provides a lucid review. At moderate concentrations, H_2S is an ocular irritant that affects the eyes in a condition that has been called "sore eye," "gas eye" (EPA 2003), and "spinner's eye" (Glass 1990). In occupational studies, evidence on eye irritation has been called "inconsistent," largely because effects have been reported over a wide concentration range and because several of the viscose-rayon studies likely involved co-exposures to sulfur dioxide, sulfuric acid, and carbon disulfide (Costigan 2003). More recent occupational epidemiology studies show eye irritation attributable to H_2S (e.g., Kilburn 2012; Lee et al. 2007).

The older guidance and recommendations for threshold limit values (TLVs) for occupational exposure listed ocular toxicity at concentrations from 5 to 30 ppm, and ACGIH (2001) noted that a 1-hr 50 ppm exposure results in superficial inflammation and conjunctivitis with ocular pain, lacrimation, and photophobia, which can progress to keratoconjunctivitis and vesiculation of the corneal epithelium. The AIHA TLV guidance was based on ~10 studies from 1939 to 1969, which examined concentrations that generally are not relevant for community exposures (and thus omitted in this review). As discussed later (Section 4.2.1), the TLV guidance was revised in 2010 and ocular effects are no longer considered a critical effect, i.e., the effect occurring at the lowest concentration that “drives” the TLV.

2.3.2.1 Studies at geothermal sources: Bustaffa et al. (2020) has recently reviewed the health effects associated with populations exposed to emissions from natural geothermal events and geothermal energy plants. Evidence of increased eye damage is based on a few studies that are all ecological in design and limited to a single area of New Zealand. Lambert et al. (2006) reviewed several ocular studies, including community studies in Finland and New Zealand (the latter are discussed in Bustaffa et al. (2020) and reviewed below), and concluded that in community settings, short-term H_2S exposures of ~0.025 ppm appears to be the lowest concentration observed that irritates the eyes, and that chronic exposure is associated with serious ocular effects.

- The New Zealand studies examined communities in Rotorua, the largest naturally H_2S-exposed population in the world, due to geothermal emissions (Bates et al. 1998). About a quarter of its population of 40,000 is routinely exposed to H_2S at concentrations of at least 0.143 ppm (200 μg/m^3); the highest 30-min concentrations exceed 1 ppm (1,500 μg/m^3; Fisher 1999); the median concentration is 0.014 ppm (20 μg/m^3); 35% of measurements exceed 0.05 ppm (70 μg/m^3) and 10% exceed 0.286 ppm (400 μg/m^3). Based on hospital discharge data from 1981 to 1990, standardized incidence rates of ocular disorders -- cataracts, diseases of the eye and adnexa (eyebrow, eyelids, and lacrimal apparatus), disorders of the conjunctiva, and disorders of the orbit -- were statistically higher than rates elsewhere in New Zealand (Bates et al. 1998). This ecological analysis did not address the sharp concentration gradients of H_2S observed across the city (Horwell et al. 2005) or the differences between exposed and unexposed populations.

- Bates et al. (2002) updated their earlier study with 1993 to 1996 morbidity data and grouped community exposures into three categories using exposure data based on passive air sampling of H_2S. Again, Rotorua residents experienced significantly higher incidence of adnexa and eye disorders compared to residents elsewhere in the country, and exposure-response trends held across all four ethnicity–gender categories. While improved in the updated study, the exposure assessment remained ecological in nature (individual exposure data were unavailable), and the authors acknowledge the lack of information on possible confounders, e.g., smoking and socio-economic status (SES), and possible selection bias.

2.3.2.2 Studies at sulfate pulp mills and composting facilities: Pulp and paper production is the single largest source of H_2S emissions (Section 1.2). A series of Finnish studies have studied populations living near sulfate pulp mills.

- In Imatra, South Karelia, Finland, Haahtela et al. (1992) examined exposures to H_2S and other reduced sulfides (methyl mercaptan, dimethyl sulfide, dimethyl disulfide). Local mills released an estimated 2,800 tons/year of H_2S in 1989. During a plant upgrade in September 1987, emissions at one mill increased for two days, resulting in a maximum 4-hr concentration of 0.096 ppm (135 μg/m^3) and 24-hr averages of 0.025 and 0.031 ppm (35 and 43 μg/m^3) measured 1 km from the source; these levels are 4–20 times higher than those during a reference period believed to be representative. During the 2-day event, sulfur dioxide (SO_2) levels were low, but an intensive "catty" odor due to mesityl oxide was reported. Unfortunately, this unsaturated ketone, as well as reduced sulfur compounds other than H_2S, were not measured; mesityl oxide is also an irritant to eyes and other tissues and has an acute Reference Exposure Level (REL) of 10 ppm (OEHHA 1999) and a US occupational Permissible Exposure Limit (PEL) for the time weighted average (TWA) of 25 ppm (ACGIH 2001). (Occupational limits are discussed later in Section 4.2.) Surveys distributed to persons (n=60) in the affected community shortly after the exposure event and in a subsequent reference period (n=66) showed that a statistically significant number of persons (22% of the sample) experienced direct irritative effect on mucous membranes and eye conjunctivitis, symptoms that corresponded to the physiological effects of acute H_2S exposure.

- A cross-sectional study by Marttila et al. (1994) evaluated ocular (and other symptoms) among children (n=134) under 15 years of age in three communities in South Karelia, Finland. The annual average H_2S levels predicted using air quality dispersion models were 0.00067 and 0.0053 ppm (1 and 8 μg/m^3) in the moderately and severely polluted communities, respectively, and the 24-hr maxima were 0.01 and 0.067 ppm (15 and 100 μg/m^3); the available monitoring data indicated lower levels. Parent's reports over the past 4 weeks and 12 months showed increases in the children's eye irritation over time, but changes were not statistically significant; the small sample size and issues in symptom ascertainment may have limited associations. Concentrations of other reduced sulfur compounds were not reported. SO_2 levels were low (averaging 2–3 μg/m^3) and not indicated as a significant confounder. As in the previous studies, several sulfur compounds were present, including methyl mercaptan (CH_3SH; annual mean from 2 to 5 μg/m^3 [0.001 – 0.0025 ppb]; maximum 24-h concentration of 150 μg/m^3 [0.075 ppm]; high exposure area). CH_3SH has a low odor threshold (0.002 ppm), and the acute REL and PEL are 0.5 and 10 ppm, respectively. However, confounding was not expected given that the CH_3SH irritation threshold was estimated to be two orders of magnitude higher than that for H_2S. Still, the potential effects of both acute and chronic exposure CH_3SH, as well as other sulfur compounds, over a long period of time should be considered.

- Marttila et al. (1995) carried out a longitudinal study of adults (n=81) in Lappeenranta, Finland living 1.5 km from a pulp mill. Baseline and six follow-up surveys were administered to the cohort, and pollutants (TRS, SO_2, TSP, NO_x) were monitored continuously in the community over 15 months. Large and statistically significant differences in symptom intensity were found between the reference, medium and high exposure periods, suggesting a dose-response relationship. The intensity of eye (and nasal and pharyngeal) symptoms was significantly higher during days when TRS levels exceeded 0.0067 ppm (10 µg/m^3). H_2S was estimated to account for two-thirds of the TRS released in the region; concentrations of other reduced sulfur compounds were not presented; and SO_2 levels were low (5 – 50 µg/m^3) and not considered to be a significant confounder. The authors concluded that relatively low daily concentrations of malodorous sulfur compounds, i.e., TRS exceeding 0.0067 ppm (10 µg/m^3), can cause exposure related short-term adverse effects.

- Logue et al. (2001) carried out a community-based study of students at an elementary school near a composting plant located in southeastern Pennsylvania, U.S (described earlier in Section 2.3.1.4). The 749 students from the H_2S exposed school (where measured 1-hr H_2S levels exceeded 0.010 ppm on 9 days) and 491 students from the control school (no such events) participated in the survey of symptoms and medical conditions. Associations between H_2S and ocular symptoms were not statistically significant.

2.3.2.3 Studies of livestock rearing systems

- In well-controlled chamber tests to a CAFO mixture described earlier in Section 2.3.1.3, Schiffman et al. (2005) found increased prevalence of eye irritation. This mixture contained H_2S (0.024 ppm), ammonia (0.817 ppm), total suspended particulates (0.0241 mg/m^3), endotoxin (7.40 endotoxin units/m^3), and odor (57 times above odor threshold).

- Kilburn (2012) compared 25 individuals living from 0.17 to 3 km (most within 0.9 km) of hog manure lagoons with 22 age- and gender-matched individuals living beyond 3 km in Paulding, Ohio (and also to 58 additional controls in Tennessee) for pulmonary performance in a 3-day period in April, 2003. (The main objective of this study was to evaluate neurological endpoints, as described later.) H_2S levels in 12 homes averaged from 0 to 0.03 ppm (but reached 2.1 ppm and varied over 10-fold in one-day's spot check samples), and two outdoor samples exceeded 1.1 ppm; these high levels appear to be outliers. Other airborne constituents, e.g. ammonia, SO_2, NO_2 and particulate matter, were not considered. Questionnaires asked about frequencies of 35 common health complaints, respiratory symptoms, occupational history, exposure history (chemicals, pesticides, tobacco, alcohol, drug use, etc.), and medical history. While outcomes were uncorrelated with distance to the lagoons, frequencies of 18 of 35 symptoms, including eye irritation, differed significantly between exposed and (local) control populations. (Other outcomes in this study are discussed elsewhere in the present report.) Many of the same (and some additional) differences were found between the exposed Ohio population and the Tennessee referent population. While a number of objective outcome measures and some H_2S monitoring were utilized, the sample size was small, co-pollutant exposure was likely, and the exposure assessment was incomplete.

- Schinasi et al. (2011), described earlier, reported increased acute eye irritation following 10 minutes outdoors with perception of odor, as well as correlation with 12-hour mean levels of H_2S, $PM_{2.5}$ and PM_{10}. The log odds of acute eye irritation following 10-min outdoor exposure increased by 0.15 per 1 ppb of H_2S, by 0.84 per 10 μg/m^3 of $PM_{2.5}$, and by 0.36 per 10 μg/m^3 of PM_{10}.

2.3.2.4 Studies at wastewater treatment plants

- Lee et al. (2007), described previously, found that eye irritation was more commonly reported by WWTP workers exposed to mean H_2S concentration of 0.15 ppm (range: 0 – 42.5 ppm) compared to unexposed workers.

2.3.2.5 Summary of ocular effects: The Finnish studies around pulp mills (Haahtela et al. 1992; Marttila et al. 1995, 1994) addressed both acute and chronic exposures and showed statistically significant increases in eye symptoms at (24-hr) concentrations as low as 0.007 ppm. However, these are ecological studies using small populations that likely involve co-exposures to other sulfur gases. In the geothermal area of Rotorua, New Zealand, an ecological approach was also used by classifying the city into high, medium, or low H_2S exposure areas (Bates et al. 2002, 1998). These studies also involve co-exposures, but to different pollutants than the Finnish studies given the different (volcanic) H_2S source. While ocular effects may be experienced at lower concentrations, as concluded by Lambert et al. (2006), the evidence is more consistent that single or repeated short-term H_2S concentrations in the range of 0.007 to 0.025 ppm can produce eye irritation. However, the available observational studies have limitations: they incompletely address the nature of ocular effects other than irritation, their exposure assessments provide limited detail regarding exposures (e.g., short-term but high concentration events are not characterized), and they do not address whether chronic low level H_2S exposure causes irreversible effects on the eye.

In summary, concentrations from about 0.007 to 0.025 ppm correspond with the low end of the range that has been associated with eye irritation in the older cross-sectional studies examining short- and long-term exposures in Rotorua (Bates et al. 2002, 1998) and Finland (Haahtela et al. 1992; Marttila et al. 1995, 1994). Several recent community studies around CAFOs and similar facilities have reported eye irritation (Heaney et al. 2011; Kilburn 2012; Schinasi et al. 2011), as have short-term controlled tests at 0.024 ppm as part of a CAFO mixture containing ammonia and other contaminants described earlier (Schiffman et al. 2005). However, a short-term controlled test of H_2S alone at 0.05, 0.5 and 5 ppm H_2S did not present eye irritation (Fiedler et al. 2008), which suggests the possible role of co-pollutants, rapid fluctuations in H_2S concentrations (that are averaged out in sampling), or longer exposure periods. The available studies have limitations: they do not address the nature of ocular effects other than irritation (Lambert et al. 2006); the exposure assessments provide little spatio-temporal information; the exposure contrasts may be minimal; and the question of whether chronic low level H_2S exposure causes irreversible effects on the eye is not approached.

2.3.3 Nasal lesions—The olfactory epithelium is vulnerable to H_2S induced pathology due to cytochrome oxidase inhibition at lower concentrations than damage to the nasal respiratory epithelium, and thus this effect has formed the basis for both occupational and environmental exposure standards (Schroeter et al. 2006), including EPA's current RfC and the ATSDR's intermediate duration MRL (Section 4.1.2). These guidelines were informed by Brenneman et al. (2000), who exposed groups of 12 male Sprague-Dawley rats to 0, 10, 30 or 80 ppm H_2S for 6 hr/day for 10 weeks with subsequent examination of nasal epithelium. No adverse changes in olfactory or respiratory epithelia were seen at 10 ppm (13.9 mg/m^3), and thus this concentration became the current NOAEL. At higher concentrations (30 ppm), olfactory lesions and basal cell hyperplasia (a response to the olfactory lesions) occurred throughout the nose; these increased in extent at 80 ppm. As described below, the only updates in the literature pertaining to nasal lesions are dosimetry refinements for an animal study, and a small case-report occupational study (Brenneman et al. 2000; Mousa 2015; Schroeter et al. 2006).

2.3.3.1 Pharmacokinetic modeling: Using interspecies pharmacokinetic computational fluid dynamics (PK-CFD) models, Schroeter et al. (2006) derived a human NOAEL of 5 ppm by extrapolating the nasal lesion and extraction data observed in rats to humans. The modeling used a conservative physiologically-based dosimetric approach for interspecies extrapolation and differences in exposed nasal surface areas, airflows, partitioning, diffusivity and reaction kinetics. Although some data were lacking to support the extrapolation, modeling was consistent with interspecies clearance data, and results showed good correlation with the incidence of olfactory lesions in rats. An investigation of interhuman variability, which simulated H_2S uptake on olfactory epithelium for 5 adults and 2 children using anatomically correct models of the olfactory region generated from magnetic resonance imaging (MRI) or computed tomography (CT) scan data and steady-state inspiratory airflows, showed similar dosimetry (within 20%) over a range in olfactory airflow (Schroeter et al. 2010). While the modeling may incompletely represent population variability, it suggests that differences in nasal anatomy and ventilation do not significantly affect H_2S uptake in the olfactory region. Additional discussion regarding derivation of the NOAEL and modeling contrasting nasal airflows rat and human noses are given by Dorman (2004).

2.3.3.2 Occupational studies: A recent case-report assessed symptom frequencies of oil field workers (n=34) in Iraq exposed to a wide range of H_2S levels (daily ambient average concentrations from 4 – 50 ppm) and an unexposed comparison group (Mousa 2015). No median or interquartile range (IQR) for exposures was reported. 53% of the exposed workers experienced nasal bleeding, and a few experienced additional bleeding.

2.3.3.3 Summary: The effect of the PK-CFD modeling used to extrapolate nasal lesions in rats to humans (Brenneman et al. 2000; Schroeter et al. 2006) would be to halve the current NOAEL of 10 ppm to 5 ppm. This modeling is consistent with observations, and the rat-to-human extrapolation reduces uncertainty compared to simpler dosimetric approaches. However, human data in this concentration range are insufficient for confirmation, and the NOAEL remains at 10 ppm. As discussed later in Section 4, these studies are important as the risk of nasal lesions remains the basis for several H_2S standards and guidelines.

2.3.4 Respiratory and allergic effects—This section first reviews several older controlled studies describing changes in lactate and oxygen levels in blood and muscle measured during H_2S exposure, which remain important in the regulatory context, then proceeds to recent epidemiological studies examining effects of chronic exposure in community settings due to emissions from volcanos, CAFOs, and other sources, and lastly reviews several occupational studies.

2.3.4.1 Controlled experiments: Several controlled experiments examined biochemical markers of respiratory-related function during and after H_2S exposure, most recently in the 1990s. The two studies discussed below (Bhambhani et al. 1996; Bhambhani and Singh 1991) were used to establish Occupational Exposure Limits (OELs) in the United Kingdom (Costigan 2003) and are cited in the REL documentation (OEHHA 2008). More recent studies on lactate or oxygen stress were not identified. The two studies involved short-term exposure to small numbers of healthy individuals, and they may be most relevant to occupational settings. They update an older controlled study by Jappinen et al. (1990), which may be the first controlled study of H_2S effects on respiratory function.

- Jappinen et al. (1990) tested 26 male pulp mill workers with typical exposures from 2 to 7 ppm, and 3 men and 7 women with mild or moderate asthma. (Individuals with severe asthma were excluded.) Among the 10 individuals with asthma, a 30-min exposure to 2 ppm H_2S caused a marginally significant increase in airway resistance R_{aw} (average 26% change), but no change in FEV_1, FVC, $FEF_{25–75}$, or specific airway conductance (SG_{aw}). In 2 of 10 subjects, both R_{aw} and SG_{aw} changed by >30%, a sign of bronchial obstruction.

- Bhambhani and Singh (1991) used 16 healthy young male adults and oral exposures to 0 (control), 0.5, 2 and 5 ppm (7 mg/m3) H_2S under conditions of exercise. Lactate in blood and oxygen uptake showed a graded response, and results at 5 ppm were statistically different from those in controls. The authors suggested that at H_2S doses from 2 to 5 ppm with higher exercise rates, oxygen is being utilized to detoxify H_2S and that the activity of the enzyme cytochrome oxidase is inhibited. Both processes increase dependency on anaerobic metabolism and thus elevate blood lactate levels.

- Bhambhani et al. (1996) compared effects of 0 (control) and 5 ppm exposures on the biochemical properties of skeletal muscle in 25 healthy young subjects (13 men, 12 women), who underwent two 30-min tests a moderate level of exercise, after which biopsies of the vastus lateralis muscle (part of the quadriceps) were obtained and analyzed for markers of anaerobic and aerobic metabolism. In men, levels of citrate synthase decreased significantly with exposure; lactose and lactate dehydrogenase increased although not significantly, and cytochrome oxidase decreased. Although most aerobic enzymes did not have statistically significant changes, short-term H_2S exposure affected aerobic metabolism in a large proportion of men and women tested. Furthermore, exposure at half of the (U.K.) occupational exposure limit (OEL) resulted in a shift from aerobic to anaerobic metabolism. The authors remarked on the need to examine a larger sample to account for variability, as well as longer duration and higher concentration exposures.

- In a detailed review of the physiological, pharmacological and toxicological effects of H_2S, Olson (2011) noted the classical hormesis relationship between H_2S exposure and O_2 consumption: at low concentrations, H_2S stimulates oxygen consumption (and may even result in net ATP production); while at elevated levels, H_2S inhibits consumption. However, the H_2S concentrations in tissues and blood that cause these effects have not been resolved. The few studies employing controlled H_2S exposures to evaluate respiratory outcomes, which use small sample sizes and only very short exposure periods, are consistent in showing that short (30 min) exposures at or around 2 ppm cause changes in indicators related to respiratory function in both healthy and (mild-to-moderate) asthmatic adults.

2.3.4.2 Community studies near geothermal and volcanic sources: Respiratory impacts of H_2S are not limited to high exposures; low levels also increase the risks of respiratory symptoms, respiratory disease mortality, and anti-asthma drug use (Bustaffa et al. 2020) as shown by studies examining communities near geothermal and volcanic H_2S sources including Reykjavik (Iceland), Rotorua (New Zealand), the Azores (Portugal), and Mt. Amiata (Italy). (Geothermal emissions and hazards have been reviewed by Bustaffa et al. (2020) and Hansell and Oppenheimer (2004).) Portions of these communities experience chronic exposure to H_2S, estimated to be between 0.02 and 1.0 ppm; Nuvolone et al. (2019) found a lower range of 0.0003 to 0.0224 ppm. Both the older and the newer studies have associated chronic exposure with noninfectious respiratory symptoms and disease. For example, in Rotorua, Durand and Wilson (2006) used improved exposure mapping to show greatly elevated risks of a variety of respiratory symptoms and diseases; in Furnas, Amaral and Rodrigues (2007) showed a greatly increased rate of chronic bronchitis with exposure; in Reykjavik, Carlsen et al. (2012) found adverse impacts on individuals with asthma at H_2S concentrations in the range of 0.0067 ppm; and in Tuscany, Nuvolone et al. (2019) found that an increase of 0.0047 ppm (90-day avg) could have both harmful and beneficial respiratory effects, results that may be partly explained by not testing for multiple outcomes. These studies do not demonstrate causal linkages to H_2S exposure given potential confounding with other pollutants and, in some cases, issues regarding the comparability of the populations. The Reykjavik study (Carlsen et al. 2012) appears the strongest given its multiyear time series analysis, large sample, inclusive population, and objective measures of H_2S and other pollutants. Further details on these studies follow.

- Durand and Wilson (2006) investigated respiratory disease among residents in Rotorua, New Zealand, a city of 61,000 where H_2S exposure occurs from geothermal emissions (including sulfur springs, soil gas, and fumaroles). An H_2S mapping survey using passive samplers and several weeks of sampling showed considerable spatial variation in concentrations, which results from varying soil gas emissions and meteorological influences. The analysis used 11 years (1991–2001) of hospital discharge morbidity data, a cross-sectional analysis with groupings that assigned residential census area units (CAUs) to low, medium or high exposure categories (typical H_2S concentrations of 0.03 – 0.04, 0.5 and 1.0 ppm, respectively), and ecological controls for age, ethnicity, smoking status and socioeconomic status (deprivation). Greatly elevated risks (2 to 5-fold) were seen for all respiratory diseases, chronic obstructive pulmonary disease (COPD), asthma, and respiratory and chest symptoms. Study strengths include the large sample size, control of several potential confounders, and a more detailed exposure mapping than previously available. Study limitations include a lack of individual identifiers, inability to identify repeat hospital visits by an individual, the ecological smoking and deprivation data (linked to the CAU) that is a particular issue for Maori women due to their very high smoking rates, possible exposure misclassification due to short-term temporal fluctuations in H_2S levels, sharp spatial gradients of H_2S levels (Horwell et al. 2005), the likelihood of indoor exposures (Durand and Scott 2005), and (unknown) exposures at work and other non-residential environments.

- Amaral and Rodrigues (2007) investigated the risk of chronic bronchitis using a population-based retrospective cohort design that compared two areas in the Azores, Portugal: one with volcanic activity (Furnas) that emitted H_2S as well as water vapor, carbon dioxide, SO_2, and other gases; and a second area (Santa Maria) without volcanic emissions. H_2S exposures were not quantified, but earlier reports measured SO_2 at average levels between 0.01 and 0.08 ppm in Furnas (Baxter et al. 1999). Age and sex-adjusted incidence rates of chronic bronchitis, based on local medical records and census data from 1991 to 2001, were elevated in the exposed area relative to international norms, and the (all age) relative risk was 4.0 for males and 10.7 for females, based on a comparison of exposed to unexposed areas. High rates of chronic bronchitis in Furnas were partially attributed to chronic H_2S and SO_2 exposure in a very humid atmosphere; co-exposure with SO_2, a known toxicant and bronchoconstrictor, is a potential confounder.

- A population-based time-series study examined the daily number of adults (>18 years of age) in Iceland's capital Reykjavik and the surrounding municipalities who were dispensed anti-asthma drugs as a function of daily air pollution levels over a nearly 4-year period (Carlsen et al. 2012). Geothermal sites outside the city emit H_2S concentrations producing long term concentrations that averaged 0.0058 ppm (8.7 µg m^{-3}; maximum of 0.062 ppm [93 µg m^{-3}; 24-hr average]), and 1-hr levels that averaged 0.021 ppm (32 µg m^{-3}; maximum of 0.345 ppm [518 µg m^{-3}]). Poisson regression models using 3-day moving H_2S averages, typically lagged several days, along with other pollutants (PM_{10}, NO_2 and O_3) and covariates (e.g., temperature, humidity, pollen count, influenza season, day-of-week, time trend and seasonal trend) showed that a small increase in H_2S levels, 0.0067 ppm (10 µg m^{-3}), was associated with a modest (2%) but statistically significant increases in the number of individuals dispensed anti-asthma drugs, specifically inhalant adrenergics (both long- and short-acting bronchodilators). The authors noted that this was the first study outside of occupational settings to associate short-term changes in H_2S levels with health-related outcomes. Study strengths include capturing essentially all drug prescriptions and considering multiple pollutants; weaknesses include the ecological design, the use of a single monitoring site, the lack of $PM_{2.5}$ data, a large amount of missing data, the inability to identify individual or group risk factors, and the surrogate indicator used for asthma exacerbation. While other pollutants were monitored, SO_2, a known respiratory irritant, was not mentioned. However, continuous monitoring in Reykjavik shows that SO_2 levels are low relative to 24-hr and annual average limit values (Skúladóttir and Þórðarson 2003).

- Bates et al. (2013) assessed the effect of H_2S on asthma among 1,637 adults in Rotorua City, New Zealand. Recruitment used a 2-stage stratified strategy with mail and phone calls to individuals selected from a centralized patient registry, who then visited the study clinic and completed a questionnaire and clinical tests. Participant age ranged from 18–65 years; most (60%) were female; 50% were former or current smokers; and 24% reported a prior or current asthma diagnosis. A city-wide monitoring network, consisting of 50 passive samplers deployed for 2 weeks in summer and 53 samplers in winter of 2010, was spatially interpolated via kriging to estimate quartiles of ambient H_2S levels at each participant's residence and workplace for the prior 30 years. Ambient levels ranged from 0 to 0.064 ppm (IQR: 0.011 – 0.031 ppm). The H_2S exposure groups were not associated with increased asthma risk or most symptoms, with exceptions of increased coughing in the third exposure quartile (overall not statistically significant) and slightly reduced wheeze in the fourth (highest) exposure quartile. The authors discuss possible issues including selection bias, survivor effect, confounding due particulate matter exposure due to wood smoke (modeled PM_{10} levels were noted to fall below 100 µg/m^3 and were inversely related to H_2S levels based), NO_2 and traffic pollutant levels (stated to be positively correlated with H_2S). Only minor differences were noted in analyses using exposures at home or work. While participants were required to live in Rotorua for at least 3 years prior to the study, residential and workplace histories were not obtained (only current addresses were used) and participation was limited to city residents.

- Effects of ambient H_2S in Reykjavik also were reported by Finnbjornsdottir et al. (2016). In regions near a geothermal power plant, the risk of an emergency hospital visit (also heart disease and stroke as discussed later) among the 151,095 residents was investigated using a time series model and daily H_2S levels at residences of the 13,383 patients visiting the hospital (32961 visits) over the 7.5 year study period. H_2S levels were estimated using a simple plume-type model, and 24-hr H_2S levels ranged from 0 to 0.047 ppm (69.5 µg/m^3; IQR: 0 – 0.003 ppm). No association was found between H_2S and respiratory-related emergency visits. An important limitation of this study concerns ascertainment of outcomes, which used only collective categories (heart disease, respiratory disease, stroke).

- Nuvolone et al. (2019) studied 33,804 residents near Mt. Amiata, Tuscany, Italy, home to geothermal power plants. Risks of neoplasms, respiratory diseases, central nervous diseases, and cardiovascular diseases were calculated using mortality and hospital data (non-respiratory effects are discussed later). Individual H_2S exposures (maximum 90-day moving average estimated using dispersion modeling and geocoded addresses) ranged from 0.00034 to 0.022 ppm (0.5 to 33.5 μg/m^3; mean of 0.005 ppm, SD of 0.005 ppm). A 0.005 ppm (7 μg/m^3) increase in H_2S levels was associated with a 12% increase in respiratory mortality and a 27% increase in pneumonia hospitalizations, and with reduced risk respiratory disease hospitalizations. Lower mortality risks (protective effect) were observed for cardiovascular diseases. Other respiratory effects were found to be less robust. While using medicate records and successfully geocoding most addresses to obtain model-based exposure estimates, the residential cohort design did provide information on individual-level confounders, e.g., smoking, alcohol consumption and diet.

2.3.4.3 Studies regarding livestock rearing systems: Respiratory effects associated with H_2S emissions from livestock rearing systems, including CAFOs, have been investigated in a few controlled and occupational epidemiological studies. However, a number of community-based studies have suggested increased prevalence of respiratory and asthma symptoms and lung function impacts among children and adults experiencing chronic exposure. While designs of these studies vary considerably, as summarized below, all but one identified respiratory-related disease or health symptoms, including breathing difficulty, chest tightness, wheeze (Bullers 2005; Campagna et al. 2004; Mirabelli et al. 2006a, 2006b; Radon et al. 2007; Schinasi et al. 2011), increased asthma prevalence and/or aggravation (Campagna et al. 2004; Merchant et al. 2005; Radon et al. 2007; Sigurdarson and Kline 2006) lung function (PEF and FEV_1) decrements (Radon et al. 2007; weakly in Schinasi et al. 2011), and COPD (Eduard et al. 2009), though the latter association was weak and only present in in farmers with atopy. The single negative study, Villeneuve et al. (2009), had significant limitations: it examined a relatively small farm, had a small sample size, and the "high" exposure group extended 3 km radius from the farm, longer than the distance usually considered for CAFO impacts. Many of these studies used residential proximity to livestock as an exposure surrogate, but several recent studies used objective air quality measurements. Other issues include selection bias, measurement error, and multiple exposures (Section 2.4.3). Of particular note, H_2S exposure due to livestock rearing systems can be accompanied with elevated levels of endotoxins, ammonia, and organic dusts, all of which are strongly implicated in the development of respiratory disease (Woodall et al. 2005). Two studies with objective pollutant measures used time series analyses to show increased rates of unscheduled hospital visits for aggravation of asthma and respiratory disease at 30-min H_2S concentrations above 0.03 ppm in Nebraska (Campagna et al. 2004), and a dose-response relationship for breathing difficulty and wheeze with odor and H_2S at mean levels of 0.0003 ppm in North Carolina (Schinasi et al. 2011).

- Bullers (2005), described previously (Section 2.3.1.3), associated residential proximity to hog farms for 12 of 22 self-reported symptoms investigated, including respiratory problems.
- A time series analysis examined daily unscheduled or emergency hospital visits (N=5009) for respiratory disease among residents of Dakota City and South

Sioux City, Nebraska, U.S. from January 1998 to May 2000 (Campagna et al. 2004). This area contained 13 known reduced sulfur sources; the largest, a beef slaughter and leather tanning facility with a waste treatment complex, emitted an estimated 1,900 pounds/day of H_2S. TRS and H_2S were measured in the community at 3 and 14 sites, respectively, and daily levels were categorized as "high" if any 30-min rolling averages exceeded 0.03 ppm (30 ppb) and as "low" otherwise. Previous sampling identified H_2S as the only sulfur contaminant present in sufficient concentrations to cause concern. High days occurred on ~25% of days in the study. For children less than 18 years of age (N=174 visits), asthma hospital visits were associated with 1-day lagged TRS levels, and hospital visits for all respiratory diseases were associated with 1-day lagged H_2S and TRS levels. Adult asthma hospital visits (N=281 visits) also were associated with 1-day lagged H_2S levels. The study included diagnostic controls (visits for digestive diseases), which was negative. Linkages between TRS and H_2S with exacerbations of asthma and other respiratory diseases appear robust given the community-wide exposure monitoring and the near-complete capture of visits in the local hospitals. Study limitations include issues regarding the quality of exposure data, the lack of individual measures, possible outcome misclassification, and possible omission of residents treated outside the community.

- In Iowa, U.S., children living on farms that raised swine had a very high prevalence rate of asthma-related outcomes (44.1%); children on farms that raise swine adding antibiotics to feed had an even higher rate (55.8%), despite generally lower rates of atopy and personal histories of allergy in farm populations (Merchant et al. 2005). No environmental measurements were conducted, although high occupational exposures to respirable and total dust, endotoxin, H_2S and ammonia have been shown in other Iowa farm studies. Several asthma symptoms were attributable to these co-exposures.
- The controlled study by Schiffman et al. (2005), previously detailed (Section 2.3.1.3), found no association between a CAFO mixture containing H_2S at an average concentration of 0.024 ppm and lung function or vital signs.
- In Saxony, Germany, Radon et al. (2007; 2005) studied 3,131 individuals with farm contact and 2,425 individuals without farm contact living near CAFOs. Among the group without farm contact, odds for all respiratory symptoms and for physician-diagnosed asthma increased with increasing self-reported level of odor annoyance. Odds of self-reported wheeze increased for individuals living within 500 m of 5 or more animal houses, and FEV_1 decreased for those living within 500 m of 12 animal houses. Study strengths include a large sample size, the development of dose-response curves relating health impacts to the number of animal houses, and the exclusion of individuals with professional or private contact with farming environments; author-noted limitations include the surrogate exposure metric, specifically that the number of animal houses is a poor exposure indicator, and the lack of ammonia and endotoxin co-pollutant measurements that be confounders.

- Mirabelli et al. (2006a; 2006b) studied the prevalence of wheezing among children 12 to 14 years of age living in North Carolina, USA. Wheeze prevalence among children with allergies was 5% higher at schools located within 3 miles of swine feeding operation, and 24% higher at schools where livestock odor was noticeable indoors twice or more per month, compared to schools at further distances or without odors.
- Sigurdarson and Kline (2006) conducted a cross-sectional study of children attending two elementary schools in Iowa, USA, one located within 0.5 mile from a CAFO (n=61) and the other distant from large scale agricultural operations (n=248). The former school had a much higher prevalence of physician-diagnosed asthma (19.7%) than the control school (7.3%). Although the two populations differed (e.g., parents in the study school were more likely to work on a farm and to smoke), adjusted models showed that children remained at risk (adjusted odds ratio = 5.71, p = 0.004). No exposure measurements were taken.
- An occupational study by Eduard et al. (2009) examined associations between H_2S and respiratory morbidity and mortality among 4,735 Norwegian farmers on crop-only, livestock-only, and crop-and-livestock farms. Based on personal air sampling, the median annual average exposure was 1.1 ppb (IQR: 0.2 – 36 ppb). If H_2S-related tasks and H_2S odor were absent, levels were assumed to be 0 ppb. Cattle and swine farms had the highest H_2S levels, 0.036 and 0.029 ppm (36 ppb and 29 ppb), respectively; sheep/goats and poultry farms both had levels of 0.0002 ppm (0.20 ppb), and crop-only farms had 0 ppm (0 ppb). A subset of 1,213 farmers with atopy showed a weakly elevated risk of COPD when comparing with high vs. low exposure groups. No dose-response relationship was observed, and H_2S exposure was not associated with chronic bronchitis or lung function. While the study results were negative or inconclusive, the use of personal air sampling is unique among the studies and has the potential to reduce exposure measurement error.
- A cross-sectional study in rural Sarsfield, Ottawa, Canada, found that self-reported respiratory health disease and symptoms (asthma, rhinitis, sinusitis, chronic bronchitis, allergies) of 723 adults and 285 children/adolescents were not associated with distance between residences and hog farm operations (Villeneuve et al. 2009). The authors noted the lack of direct exposure measures and possible biases from using self-reported health measures. (This study did find a higher prevalence of depression and lower health related quality of life measures.)
- Schinasi et al. (2011), described earlier (Section 2.3.1.3), found that wheeze and breathing difficulty increased with general odor perception and ambient H_2S levels in a dose-response fashion (per 1 ppb), and that cough increased with general odor perception. Pulmonary function (PEF and FEV_1) was only weakly associated with odor and pollutant levels (not limited to H_2S). A study limitation acknowledged by the authors is the low quality of lung function data.

- Kilburn (2012), discussed previously (Section 2.3.2.3), found significant differences between exposed and (local) control populations for 18 of 35 symptoms, including chest tightness, palpitations, shortness of breath, dry cough, and several pulmonary function measures (FVC, FEV_1).

2.3.4.4 Studies near other industries: Health effects of H_2S exposures have been examined in industrial settings other than CAFOs.

- Logue et al. (2001), a community-based study detailed above (Section 2.3.1.4), found no association between H_2S and respiratory effects among children attending an elementary school near a composting facility.
- Lewis et al. (2003) examined mortality and morbidity associated with H_2S among 25,292 petroleum workers in Canada in an inception cohort from 1964 onwards. A job-exposure matrix (JEM) estimated cumulative lifetime occupational exposure, which were validated using workplace measures. The median annual H_2S exposure was 0.07 ppm, the IQR was 0.01 – 0.60 ppm, and the 95th percentile is 4.76 ppm. The study included estimates of possible exposure to cigarette smoke, hydrocarbons (solvents, fuels and lubricants), coke and catalysts. No association was found between H_2S exposure and respiratory disease. (Results for additional endpoints (cancer, neurobehavior) are discussed elsewhere (Sections 2.3.6.2 and 2.3.6.3)
- Mirabelli and Wing (2006) found that residential proximity within 10 miles to four pulp and paper mills in North Carolina, U.S. was weakly associated with elevated prevalence of daytime wheezing among students who reported using cigarettes or experiencing second-hand cigarette smoke exposure. The association is based on questionnaires provided by over 64,000 children attending public schools. Although associations attained marginal significance and exposures were not quantified, the study suggests the importance of considering interactions between environmental exposures and personal or household exposures, and possibly that children exposed to cigarette smoke may represent a particularly vulnerable population.
- Lee et al. (2007), discussed previously (Section 2.3.1.4), found that workers exposed to H_2S had higher risks of respiratory symptoms including dry cough, cough with phlegm, wheeze, chest tightness, and breathlessness.
- Al-Batanony and El-Shafie (2011) analyzed effects of sulf-hemoglobin, used as a biomarker of H_2S exposure, in 43 workers at a wastewater treatment plant (exposed) and 43 unexposed workers in Egypt. Respiratory symptoms and cardiovascular functioning were assessed using self-reported data and clinical tests. Sulf-hemoglobin levels were significantly higher among the exposed than unexposed workers (0.41±0.13% vs. 0.08±0.02%, $p<0.001$). No findings linking H_2S exposure and respiratory function were reported. (Results for cardiovascular effects are discussed in the following section.) This is the only study reviewed that used sulf-hemoglobin as an exposure biomarker, however, the characteristics of this biomarker were not well defined.

- Heldal et al. (2019) examined the respiratory function of 148 mostly male wastewater workers (121 exposed; 47 unexposed) using an exposure index derived from personal sampling that reflected the number and duration of H_2S peaks above 0.1, 1, 5 and 10 ppm (Austigard et al. 2018). Airway symptoms were significantly higher in H_2S-exposed workers than unexposed workers, however, H_2S was not associated with FEV_1 or FVC. No interactions were seen between H_2S and endotoxin, a common co-exposure. Nausea and fever were not significantly associated with H_2S.

2.3.4.5 Summary of respiratory and allergic effects: Most of the controlled studies examining acute H_2S exposures are older studies that remain important in the regulatory context. Using 30-min exposures and H_2S concentrations from 2 to 5 ppm, these studies show changes in several indicators of respiratory function in both healthy and (mild-to-moderate) asthmatic adults (Bhambhani et al. 1996; Bhambhani and Singh 1991; Jappinen et al. 1990). The only newer controlled study is Schiffman et al. (2005), who used 1-hr exposures of dilute swine confinement with H_2S at a concentration of 0.024 ppm to show increase prevalence of headache, eye irritation and nausea, but no significant effects on vital signs, lung function, nasal inflammation, salivary IgA, mood, attention or memory were found.

The recent epidemiological studies have examined chronic exposure near volcanic areas, CAFOs, and industrial sources, often extending on older studies. Community studies around geothermal and volcanic emission sources in Iceland, the Azores, Tuscany, and New Zealand tend to show higher prevalence rates of respiratory symptoms and disease. Carlsen et al. (2012), the strongest of these studies, found exacerbation of asthma at H_2S concentrations of 0.0067 ppm; Durand and Wilson (2006) and Amaral and Rodrigues (2007) showed greatly elevated risks of a range of respiratory symptoms and disease; while Nuvolone et al. (2019), Bates et al. (2013) and Finnbjornsdottir et al. (2016) found weak or contradictory associations. A number of new studies examined CAFOs and similar sources, adding to some 70 earlier studies that examined these sources. These show many common impacts, including sore throat, cough, nasal irritation, difficulty of breathing, chest tightness, wheezing, increased asthma prevalence and/or aggravation, lung function decrements, and other impacts. Many of these studies use distance from emission facilities as a proxy for exposure, and the role of H_2S cannot be isolated in most of the studies (Sections 2.4.3.4 and 2.4.3.5). Two studies are notable for their rigor and methodological contributions: Campagna et al. (2004) found statistically significant though small increases in unscheduled hospital visits for asthma aggravation and respiratory disease at 30-min H_2S concentrations above 0.03 ppm; Schinasi et al. (2011) found a dose-response relationship between breathing difficulty and cough with odor and H_2S at mean levels of 0.0003 ppm.

In addition, the recent epidemiology literature has suggested populations that are susceptible to chronic low level H_2S exposure: Campagna et al. (2004) identified that individuals with asthma are more susceptible to respiratory disease aggravation; Eduard et al. (2009) found that farmers with atopy are more susceptible to increased prevalence of COPD; and Mirabelli et al. (2006a) remarks that children using cigarettes or experiencing second hand tobacco smoke are susceptible to increased prevalence of wheeze with H_2S exposure. Such results are unsurprising given the increased sensitivity of individuals with asthma and/or allergies to odors and respiratory irritants (EPA 2017).

The community and occupational studies hint that industrial emission sources such as wastewater facilities may affect respiratory health (Lee et al. 2007), although evidence is severely lacking and scattered across many industries.

2.3.5 Cardiovascular and metabolic effects—Over the past several years, many studies have investigated the effects of H_2S on the cardiovascular system using animal models. In large part, this is motivated by the therapeutic potential of H_2S, which has been considered a "hot" new signaling molecule that seemingly affects all organ systems and biological processes, as discussed in several recent reviews (Olson 2011; Qu et al. 2008; Varaksin and Puschina 2011). On systemic blood vessels and other organ systems, H_2S can have a vasodilatory effects via signaling and other mechanisms, although mechanisms remain unclear and may involve interactions between H_2S, NO and CO. The cited reviews discuss multiple metabolic mechanisms and effects. For example, male mice exposed to H_2S at 80 ppm for 6 hr showed marked but reversible cardiovascular abnormalities, including bradycardia (50% reduction in heart rate and irregular heart rate), lower cardiac output, lower core body temperature, lower respiratory rate, and reduced spontaneous physical activity, possibly due to inhibitory effects of H_2S on metabolism, among other reasons (Volpato et al. 2008). ACGIH (2001) discusses metabolic changes in people exposed to H_2S at 20 ppm and above (Blackstone et al. 2005), and similar studies and potential applications are discussed by Aslami et al. (2009). Because studies are animal-based, typically use high concentrations, and are not intended to address concerns related to community exposures and public health, they are not further discussed in this report. The following summarizes epidemiological studies that have investigated cardiovascular effects of H_2S at low concentrations in community and occupational settings.

- An occupational study by Al-Batanony and El-Shafie (2011), detailed previously (Section 2.3.4.4), assessed the relationship between sulf-hemoglobin, which they used as a biomarker for H_2S exposure, and cardiovascular functioning. Overall, workers with higher exposure (higher percent sulf-hemoglobin) were more likely to have heart problems but the sample size was very small (n = 12) and no additional statistical tests were conducted.
- A previously-described study (Section 2.3.4.2) by (Finnbjornsdottir et al. 2016) assessed the relationship between ambient H_2S and risk of emergency hospital visits due to heart disease and stroke. H_2S concentrations exceeding 0.005 ppm (7 μg/m^3) were associated with a slight increase in same-day emergency hospital visits with heart disease as the primary diagnosis. This association with heart disease was higher among males and among those 73 years and older. Associations were weaker when analyzing H_2S measurements from days prior to hospital admittance. H_2S was not associated with stroke.
- A community-based study by Nuvolone et al. (2019), described previously (Section 2.3.4.2), concluded that a 0.005 ppm (7 μg/m^3) increase in H_2S was associated with an increased risk of hospitalizations for heart failure and vein/

lymphatic disease, but also a lower risk of ischemic heart disease mortality. Other effects were suggested with weaker associations.

2.3.5.1 Studies regarding livestock rearing systems.: Livestock rearing systems have been studied in relation to various health effects, as discussed earlier. Only one study by Kilburn (2012) has evaluated possible cardiovascular effects associated with proximity to CAFO facilities. Kilburn (2012), described in Section 2.3.2.3, found significant differences between exposed and control populations for 18 of 35 symptoms, including chest tightness and palpitations.

2.3.5.2 Summary of cardiovascular and metabolic effects.: Epidemiological studies of cardiovascular effects are inconclusive, suggesting both weak positive and negative associations with outcomes such as ischemic heart disease mortality, acute myocardial infarction mortality, and vein or lymphatic disease hospitalization among others. The studies assessing additional cardiovascular outcomes generally found no significant effects.

2.3.6 Neurological and neurobehavioral effects—In animals, chronic medium level H_2S exposure (6.7 ppm) has been shown to adversely affect myelination of the central nervous system (Solnyshkova 2003; Solnyshkova and Shakhlamov 2002). Earlier human studies of low-to-medium level exposures suggested many neurological/neurobehavioral symptoms, e.g., memory defects, lack of concentration, depression, and other cognitive and sensory defects. These studies have highlighted a lack of understanding regarding H_2S toxicity and the pathophysiological mechanisms affecting brain function, and they reinforce the need for larger and better controlled studies (ATSDR 2006; Fiedler et al. 2008; Hirsch 2002). Many of these studies can be criticized given the general lack of objective measures of cognitive performance, imprecise and highly variable exposure estimates, and the mixture of pollutants involved in most cases. Exceptions are the controlled study by Fiedler et al. (2008), a community study by Inserra et al. (2004), and the newer studies by Kilburn (1999, 2012); Kilburn and Warshaw (1995).

2.3.6.1 Controlled studies: Two recent controlled studies examined neurological and neurobehavioral effects:

- Schiffman et al. (2005), previously described (Section 2.3.1.3), positively associated H_2S exposure with the prevalence of headache and nausea; associations were not found with mood, memory, or attention.
- Fiedler et al. (2008) exposed 74 adults to concentrations of 0.05, 0.5 and 5 ppm H_2S in 2-hour periods over three consecutive weeks; the subjects completed ratings and tests before and during the final hour. The subjects were relatively young (mean of 24.7 ± 4.2 years of age), highly educated (16.5 ± 2.4 years), and healthy. A broad set of symptoms were investigated, and included physical (headache, fatigue, lightheaded, drowsy, nausea), cognitive (difficulty concentrating, disoriented/confused, dizzy), eye irritation (burning, dryness, itching, runny/watery eyes), anxiety (feel jittery in body, feel nervous, heart palpitations, feel tense, worried), upper respiratory (sneeze, nasal congestion, choking, throat irritation, nose irritation), lower respiratory (shortness of breath,

wheezy, chest tightening, chest pain, coughing, somatic control (skin irritation or dryness, stomach ache, numbness, ear ringing, leg cramps, back pain, sweating, body aches), environmental quality (light intensity, ventilation, air movement, air quality, noise level, room temperature, humidity, odor level), and odor ratings (irritation, intensity, pleasantness). Dose–response relationships were observed for odor intensity, irritation and unpleasantness, but not for sensory or cognitive measures. While the total symptom severity was not significantly elevated for any exposure condition, anxiety symptoms significantly increased at 5 ppm compared to 0.05-ppm; verbal learning was also affected. The authors concluded that while exposure increased several symptoms, the magnitude of the changes was relatively minor, and that increased anxiety was due to irritation associated with odor. They also noted the need for further investigation to confirm effects on verbal learning, which could represent a threshold effect of H_2S, fatigue, or some other factor, and issues in generalizing results to communities or workers who are chronically exposed with a range of health conditions and ages.

2.3.6.2 Occupational studies: A number of occupational studies have investigated neurological endpoints associated with mostly acute H_2S exposures above 10 ppm. Headaches have been associated with acute (30 – 60 min) and high (240 – 500 ppm) H_2S exposures, followed by neuropsychiatric clinical disorders, unconsciousness, and respiratory failure (Hirsch 2002; Kilburn 1993; Sjaastad and Bakketeig 2006). In a survey of residents of Vågå, Norway, Sjaastad and Bakketeig (2006) found 2 cases of “hydrogen sulphide headaches” among 1,838 WWTP workers exposed to at least 100 ppm, but no individuals in the (mostly soapstone) mining industry reported such headaches. Kangas et al. (1984) reported headaches at 20 ppm. More commonly, headaches are reported following acute exposures at concentrations of 300 – 500 ppm (Sjaastad and Bakketeig 2006). In addition to headaches, earlier studies have investigated neurobehavioral function among acutely exposed workers (n = 16) in several industries in Texas, Louisiana, and elsewhere, among residents living downwind of oil fields in Kentucky and Texas (Kilburn 1997), and among highly exposed individuals (n = 19) in several states and Canada (Kilburn 2003).

The following studies have examined chronic, low-level exposure in occupational settings.

- Kilburn and Warshaw (1995) found that H_2S-exposed workers (n = 13) at and residents (n = 22) living near an oil refinery in California, U.S. had different neurophysiological outcomes (e.g., reaction time, balance, color discrimination, digit symbol, immediate recall) and mood state scores than controls, which consisted of residents drawn randomly from towns free of known contamination (N=359). H_2S exposures averaged 0.01 ppm (1-week average) and peaks reached 0.1 ppm at neighboring homes and 8.8 ppm (24-hr average) at the refinery. Other pollutants measured included carbonyl sulfide (2.6 – 52.1 ppm) and mercaptans (1 – 21.1 ppm; 24-hr averages). Workers and exposed residents were combined into one “exposed” group, which increased power but reduced the exposure contrast and precluded the opportunity to observe a potential dose-response relationship. The petroleum refinery, which included coking units and a desulfurization plant, likely emitted a number of pollutants in addition to H_2S, e.g., mercaptans, carbonyl sulfide, combustion-related gases, particulate matter, and VOCs, that were not characterized in this early study.

- Lewis et al. (2003), described earlier (Section 2.3.4.4), examined the relationship between H_2S exposure and potentially neurological-related outcomes, including accidental falls and transportation accidents. For workers exposed to a (median) lifetime H_2S concentration of 0.07 ppm (IQR: 0.01 – 0.60 ppm), males showed no association between H_2S and neurological-related mortality or death due to accidental falls, but a slight positive association was shown for mortality due to transportation accidents when comparing upper and lower exposure tertiles (≥1.5 versus <0.1 ppm-years). The median cumulative concentration was 0.17 ppm after adjustments for employment duration (average 8.8 years). This study has a small sample size (n = 15) and lacks a dose-response relationship. More recent assessments note that individuals with underlying neurological conditions or temporary impairment to motor functioning, cognition, or vision may be at greater risk to adverse neurological outcomes from H_2S exposure (Lococo et al. 2018; WHO 2018).

- In the study of 175 WWTP and WTP workers in Iowa, U.S. discussed earlier (Section 2.3.1.4), workers with H_2S exposure had higher prevalence of neurological symptoms (headache, dizziness, memory or concentration difficulties, tiredness), and higher rates of depression (Lee et al. 2007).

- In Egypt, H_2S exposure was associated with cognitive impairment among sewer maintenance workers (n = 33) compared to an unexposed group (n = 30) matched for age, education and socio-economic status (Farahat and Kishk 2010). H_2S levels measured in and around manhole openings ranged from 9 to 11 ppm (12 – 15 mg/m^3) and 5 to 7 ppm (7 – 9 mg/m^3), respectively. The exposed group had higher rates of non-specific neurological symptoms (headache, memory defects, lack of concentration), prolonged reaction time, delayed P300 latency, and poorer performance on most neuropsychological tests. As noted earlier, a H_2S biomarker of exposure, urinary thiosulfate, was elevated among exposed workers, although no quantitative relationship was found between this marker, H_2S exposure, and neurological outcomes. Possibly the most significant outcome was delayed P300 latency, suggesting slowing of cognitive function, in contrast to the non-specific symptoms (Guidotti 2010). The authors noted that sewer workers are exposed to multiple chemical and biological hazards, as well as occasionally high levels of H_2S, although levels are normally low during routine work, and that their results are generally supported by other studies of sewer workers, e.g., in Sweden (Thorn et al. 2002).

2.3.6.3 Community studies: Neurological symptoms and outcomes in community settings were examined in a number of older studies, mostly using self-reported questionnaires. For example, Partti-Pellinen et al. (1996) used a cross-sectional design and a self-administered questionnaire to examine central nervous system symptoms (as well as eye irritation and respiratory-tract symptoms) in adults (n=336) living near a pulp mill and an unpolluted reference community (n = 380) in South Karelia, Finland. In the exposed community, TRS levels averaged approximately 0.001 – 0.002 ppm (2 – 3 μg/m^3) and 24-hr levels ranged from 0 to 0.038 ppm (0 – 56 μg/m^3) and SO_2 averaged 1 μg/m^3 and 24-hr levels ranged from 0 – 24 μg/m^3; TRS levels were below 0.0007 ppm (1 μg/m^3) in the reference community. An elevated risk of headache was found in the exposed community for the prior 4 week and 12 month periods. (Risk of cough also increased for the preceding 12-month period.)

The newer studies examining neurological outcomes in community settings are diverse.

- Portions of Khozestan Province, Iran experience leakage of natural “sour gas” that contains up to 40% H_2S. Saadat et al. (2006) evaluated exposed (n = 64) and unexposed adults (n = 64) matched by sex, age, and educational levels for depression and hopelessness using Beck’s depression inventory (BDI) and Beck’s hopelessness (BHS) questionnaires. Airborne reactive sulfur compounds in the exposed areas are reported as 0.023 ± 0.002 ppm of SO_2 equivalents; unfortunately this metric is difficult to interpret. Exposed individuals had elevated risk of depression and hopelessness, supporting earlier findings of increased rates of suicide attempts and suicide in the same area (Saadat et al. 2004).
- Kilburn et al. (2010) contrasted neurotoxic effects among 49 adults in three towns located in sour gas/oil areas in New Mexico and 42 unexposed adults in Arizona, U.S. H_2S exposures occurred resulted due to emissions from several oil refineries, a gas desulphurization facility, and a WWTP. Short-term (grab) samples showed 2 – 74 ppm at the WWTP and H_2S odors were detected at the other sites; few other measurements were available. An earlier study in this area showed daily H_2S levels from 0 to 0.014 ppm (0 – 14 ppb) (Dubyk and Mustafa 2002). H_2S exposure was associated with higher rates of neurological and cognitive dysfunction (e.g., vocabulary, short- but not long-term recall memory, attention/coordination), neurophysiological indicators (e.g., reaction time, balance, hearing, grip strength), and mood state (e.g., tension, vigor, anger, confusion, fatigue). Findings for the three exposure groups were consistent for impairment of neurobehavioral function, mood disturbance, and increased frequencies of irritative, indigestion, respiratory, mood, sleep, balance, memory and limbic system symptoms. Study limitations include a small sample, the likelihood of both acute and chronic exposures in each town (due to episodic releases associated with malfunctions at the WWTP), and the lack of exposure data.
- Reed et al. (2014) examined cognitive function among adults in Rotorua City, New Zealand exposed to H_2S, using the same study population and design as Bates et al. (2013). No effect was seen for visual and verbal episodic memory, attention, fine motor skills, psychomotor speed, or mood.
- Finnbjornsdottir et al. (2016), described earlier, found no association between ambient H_2S at concentrations up to 0.047 ppm (69.5 μg/m^3; IQR: 0 – 0.003 ppm) in the Reykjavik capital area and the risk of emergency hospital visits due to stroke.

- In Rotorua City, New Zealand, Pope et al. (2017) examined peripheral nerve function using the same study design and almost-identical study population (n = 1,635) as Reed et al. (2014) and Bates et al. (2013). H_2S concentrations ranged from 0 to 57.9 ppb (IQR: 5.6 – 18.4 ppb). Peripheral nerve function was not associated with H_2S.
- In the community-based study by Nuvolone et al. (2019), discussed earlier, a 0.005 ppm (7 μg/m^3) increase in H_2S was associated with an increased risk of hospitalizations for peripheral nervous system, as well of suggestions of additional effects. They did not account for the problem of multiple testing, which may have led to spurious findings.

2.3.6.4 Community studies of livestock rearing systems: Recent studies examining neurological and neurobehavioral effects potentially associated with exposures due to livestock rearing systems are discussed below.

- Bullers (2005), described previously (Section 2.3.1.3), found an association between residential proximity to hog farms and 12 of 22 self-reported symptoms including nausea.
- In Dakota City, Nebraska, U.S., Inserra et al. (2004) used computer-assisted standardized neurobehavioral tests to investigate differences among residents (n = 171; ≥16 years of age) living in an area with repeated H_2S exposure due to emissions from a beef slaughter/leather tanning facility and wastewater lagoon and a reference population (n = 164) with comparable demographic characteristics and health conditions. An exposure map was generated using the monthly highest 1-hr H_2S concentration measured at 14 residential locations, which was then classified into exposed (≥0.09 ppm) and comparison (<0.05 ppm) areas (Inserra et al. 2002); these classifications were consistent with odor complaints. A battery of 14 tests was administered to study participants that addressed sensory (vision, vibration, grip strength, fatigue), affect (health and physical functioning), cognitive (complex function, memory, attention), and motor (response speed, coordination) domains. H_2S exposure was associated with sensory function (increased vibration sensitivity), motor skills (lower hand grip strength), cognitive (memory) function (match to sample score, and 8-s delay test of match to sample). Of the 28 neurobehavioral tests, 21 showed no adverse relationship with residence area (the H_2S exposure surrogate), after adjustment for potential confounders. Overall, the authors concluded the two groups showed similar or only marginal differences. This study's strengths include the use of standardized tests (potentially reducing measurement error), standardized protocols (reducing interviewer bias), random sampling of participants (reducing selection bias), and standardized protocols including "blinded" examiners (reducing interviewer bias); its limitations include the possibility of exposure misclassification, uncontrolled occupational exposures, and modest participation rate (<75%).

- Horton et al. (2009), described earlier (Section 2.3.1.3), associated CAFO emissions (malodor, H_2S concentrations, and semi-volatile PM_{10} concentrations) with stress and negative mood states, e.g., being stressed or annoyed, nervous or anxious, gloomy and angry). In this study, participants spent 10 min outdoors before returning indoors to complete surveys; these assessments were made repeatedly. The study obtained objective measurements of pollutants including H_2S, which averaged from 0.00001 to 0.0015 ppm (0.01 to 1.5 ppb) and ranged to 0.09 ppm (90 ppb) (averaging time not specified). The contemporaneous and subjective assessment of both exposure and outcome is susceptible to response enhancement bias that can increase reports of symptoms since respondents are aware of and potentially sensitized to their exposure (Farahat and Kishk 2010), however, this potential bias should not affect associations with H_2S.
- A cross-sectional Canadian study, discussed previously (Section 2.3.4.3), found a higher prevalence of depression (18.2%) among people who lived within 3 km of farms relative to those who lived more than 9 km distant (8.0%; Villeneuve et al. 2009). Individuals living near farms were more likely to worry about environmental issues (water quality, outdoor and indoor smells, air pollution) and had lower health-related quality of life scores. No associations were observed with migraines. This study's strengths included a relatively large sample and the use of a standardized instrument; limitations were modest participation rates, differences in socioeconomic characteristics among the groups, and the lack of direct exposure measures.
- Kilburn (2012), detailed previously (Section 2.3.2.3), found significant differences between exposed and control populations for 18 of 35 symptoms, including headaches, dizziness, and lightheadedness.

2.3.6.5 Summary of neurological and neurobehavioral effects: Memory and learning impairment lead complaints that are associated with H_2S exposure (Partlo et al. 2001), although a broader set of persistent neurological effects (e.g., headaches, poor concentration ability and attention span, impaired short-term memory, and impaired motor function) have been reported in persons recovering from H_2S-induced unconsciousness resulting from very high concentration exposure (ATSDR 2006). Animal studies have demonstrated effects on brain function, e.g., rats exposed to 125 ppm for 4 hours/day, 5 days/week for 5 consecutive weeks showed impaired performance and learning of spatial tasks (Partlo et al. 2001), findings stated to have relevance for humans (Woodall et al. 2005). Other animal studies with H_2S inhalation exposure suggest decreased motor activity and task response rates from which a LOAEL of 80 ppm for 3 hr/day for 5 days has been derived (ATSDR 2006). Biochemical changes include decreased brain stem total lipids and phospholipids shown in guinea pigs exposed to 20 ppm H_2S for 1 hr/day for 11 days (Haider et al. 1980), and harmful CNS myelination after chronic exposure to 6.7 ppm (Solnyshkova 2003; Solnyshkova and Shakhlamov 2002). Still, the NOAEL for impaired performance in rats remains 100 ppm for 2 hr (Elovaara et al. 1978). No new animal studies on learning relevant to this review were identified.

We identified two recent controlled studies of humans. Schiffman et al. (2005) used 1-hr exposures of dilute swine confinement with H_2S at 0.024 ppm and showed increased prevalence of headaches, eye irritation, and nausea. Fiedler et al. (2008) used 2-hr exposures of H_2S alone at 0.05, 0.5 and 5 ppm and found dose–response relationships for odor intensity, irritation and unpleasantness; compromised verbal learning was shown without a dose-response relationship. A small and older controlled study reported headaches among 3 of 10 asthmatics exposed to 2 ppm H_2S for 30 min (Jappinen et al. 1990). Additional neurobehavioral effects in humans and animals include alterations in balance, reaction time, visual field, and verbal recall, with effect severity depending on exposure duration and concentration (ATSDR 2006). While the few controlled human studies have shown odor, irritation and nuisance symptoms, e.g., irritation and headache, neurological or neurobehavioral affects have not been observed. However, many of the studies examined a single acute exposure event with a small number of healthy individuals, and the ability to capture subtle neurological impairments may be limited (EPA 2011). Additionally, these studies may not be generalizable to other populations, e.g., communities and workers experiencing chronic exposure, or individuals that have greater susceptibility due to their health conditions and age (Fiedler et al. 2008).

The observational studies, both occupational and environmental, complement the controlled studies, but can be challenging to evaluate and synthesize. In comparison to community conditions, both the controlled and occupational epidemiological studies tend to reflect higher concentrations, as do the case reports. Further, all of the observational studies have significant limitations in their exposure assessments that preclude an understanding of potential dose-response relationships pertinent to neurological and neurobehavioral outcomes. As has been noted (and see Sections 2.4.3.4 and 2.4.3.5), other pollutants often accompany H_2S in community and occupational settings, and isolating effects of H_2S in a mixture can be challenging. In addition, objective evaluation of many neurological and neurobehavioral outcomes can be difficult for due to their linkage to educational attainment and other factors, the potential of measurement bias, the likely wide range of sensitivity among individuals, the influence of psychological responses to odor, irritation and nuisance perceptions accompanying H_2S exposure (e.g., headache and nausea), and the flight response, though such biases in outcome ascertainments can be controlled using blinded assessments, objective tests, and other means. Additional issues in cross-sectional studies include generally modest sample sizes, the comparability of groups, and adequate control of potential covariates and confounders. Several of the newer epidemiological studies, which tend to better address these issues, highlight behavioral and neurological effects at low but chronic exposure, and often report similar outcomes as earlier studies. The older studies show, for example: persistent cognitive impairment (reaction time delay, neurological and neurobehavioral deficits) in individuals acutely exposed to high but unknown concentrations of H_2S, but unremarkable neurological and physical examinations (Wasch et al. 1989); reduced perceptual motor speed, impaired verbal recall and remote memory, visual field performance decrements, and abnormal mood status was found in subjects (n = 16) referred for evaluation of effects of reduced sulfur gas exposure compared to referents (n = 353; Kilburn 1997); differences in neurophysiological outcomes (reaction time; balance, color discrimination, digit symbol, immediate recall) and mood state scores

(Kilburn and Warshaw 1995); and some memory impairment (Kilburn 1999). Among the newer studies, Nuvolone et al. (2019) assessed a variety of neurological-related mortality and hospitalization diagnoses, but a dose-response effect was seen only for peripheral nervous system hospitalizations (per 0.0047 ppm increase in ambient H_2S); and Legator et al. (2001) reported elevated risks of self-reported central nervous symptoms (e.g., fatigue, headache, and difficulty sleeping) in Odessa, Texas (n = 126) and Puna, Hawaii (n = 97), two communities with H_2S levels averaging from 0.007 to 0.027 ppm, compared to reference communities (n = 170); short-term H_2S levels (1–8 hr averages) were reported to reach 0.5 ppm. The effects observed in these and the other newer studies examining workplace and community populations are not well understood mechanistically, and some of the past literature has been criticized (Guidotti 2010).

Sixteen new observational studies evaluated a range of neurological and neurobehavioral effects among workers and communities in geothermally active regions or around CAFOs, sewer, oil and gas facilities. Three of these studies had negative findings for visual and verbal episodic memory, attention, fine motor skills, psychomotor speed, mood, peripheral nerve function, or stroke (Finnbjornsdottir et al. 2016; Pope et al. 2017; Reed et al. 2014); each of these studies employed spatially modeled estimates of ambient H_2S exposure. A study using universal kriging to estimate residential exposure positively associated H_2S and some neurological outcomes (Inserra et al. 2004). The dozen other studies with positive associations used a variety of designs and instruments, and showed a degree of agreement with respect to non-specific neurological symptoms (headache, memory defects, memory or concentration difficulties (Farahat and Kishk 2010; Inserra et al. 2004; Kilburn 2012; Kilburn et al. 2010; Lee et al. 2007; Partti-Pellinen et al. 1996), more objective neurophysiologic outcomes (e.g., peripheral sensation and discrimination; Inserra et al. 2004; Kilburn 2012; Kilburn and Warshaw 1995; Nuvolone et al. 2019), affect (Fiedler et al. 2008; Kilburn et al. 2010), and mood states or feelings of stress, hopelessness or depression (Bullers 2005; Horton et al. 2009; Kilburn et al. 2010; Kilburn and Warshaw 1995; Lee et al. 2007; Saadat et al. 2006; Villeneuve et al. 2009). The relatively few studies with robust H_2S measures more commonly associated non-specific neurological symptoms and mood states than objective neurophysiologic outcomes (Farahat and Kishk 2010; Inserra et al. 2004; Kilburn et al. 2010; Kilburn and Warshaw 1995; Nuvolone et al. 2019; Partti-Pellinen et al. 1996). Finally, several community studies indicated health-related quality of life impacts on populations living within ~3.6 km (2 miles) of large-scale farming operations (e.g., Horton et al. 2009; Villeneuve et al. 2009), a finding which diverges from (short-term) controlled studies that show only irritation and anxiety (e.g., Fiedler et al. 2008). Full explanations for the dichotomy between controlled and observational studies, the identification of specific and plausible neurological and neurobehavioral mechanisms at play, and the dose-response relationships involved, all remain unresolved.

2.3.7 Reproductive and developmental effects—No new reproductive or developmental studies were identified. The existing literature is summarized here.

- Several animal studies found harmful neurodevelopmental effects from chronic H_2S exposure at the following concentrations: 75 ppm (Hayden et al. 1990); 20 and 50 ppm (Roth et al. 1997; Skrajny et al. 1992); 25 and 75 ppm (Skrajny et al. 1992). All of these concentrations exceed 10 ppm, our cutoff for low-level exposure.

- ATSDR's (2006) review notes that only limited human data links maternal or paternal exposure to H_2S to an increased risk of spontaneous abortion among rayon textile, paper mill, or petrochemical workers (or spouses), although other hazardous chemicals present in these occupations may have contributed to the increased risk. The reproductive performance of rats exposed to between 10 and 80 ppm H_2S for an intermediate duration was unaffected, and the available animal data suggest that H_2S is not a developmental toxicant at concentrations below 80 ppm. ATSDR (2006) concludes that no structural anomalies, developmental delays, performance in developmental neurobehavioral tests, or impacts in brain histology were observed in a well-conducted rat study, and that while alterations in Purkinje cell (large neurons in the brain) growth was noted in offspring of rats exposed to 20 or 50 ppm H_2S during gestation and lactation periods, the significance of this finding given unaltered neurobehavioral performance is unknown (ATSDR 2006).
- California's OEHHA (2008) review highlights Xu et al. (1998), a retrospective study examining spontaneous abortion among never-smoking married women (n = 2,853), 20 to 44 years of age who reported at least one pregnancy during employment at a large petrochemical complex in Beijing, China. Based on employment records, most (57%) workers had occupational exposure to petrochemicals during their first trimester. Comparisons within and across plants showed that frequent exposure to petrochemicals greatly increased the risk of spontaneous abortion. Similarly, increased risk of spontaneous abortion was found for the 106 women exposed to only H_2S; unfortunately, this study did not report concentrations. Exposures at refineries can involve many pollutants, and this study is atypical given the stated exposure conditions.
- Finally, a review of occupational, environmental and lifestyle factors associated with spontaneous abortion (Kumar 2011) discusses several additional studies, including an older Russian study examining effects of H_2S exposure on menstrual function and the estrous cycle (Vasiljeva 1973).

2.3.7.1 Summary of reproductive and developmental effects.: Animal studies examining exposures above 10 ppm have not shown reproductive or developmental toxicity. Of the few human studies, several suggest that maternal or paternal exposure to H_2S is associated with an increased risk of spontaneous abortion (ATSDR 2006; Xu et al. 1998), however, these studies likely are confounded by simultaneous exposures to multiple pollutants.

2.3.8 Carcinogenic effects—Inhalational exposure of H_2S has not been consistently shown to cause cancer in humans, and its ability to cause cancer in animals has not been studied. For these reasons, H_2S has not been classified in relation to cancer (ATSDR 2006). While clinical studies have linked sulfate-reducing bacteria or H_2S in the colon with chronic disorders, e.g., ulcerative colitis and colorectal cancer, evidence remains circumstantial and underlying mechanisms undefined (Attene-Ramos et al. 2007). Several recent studies have evaluated potential carcinogenic effects of low-dose H_2S exposure in community and occupational settings, including those reviewed by Bustaffa et al. (2020):

- Lewis et al. (2003), described earlier in Section 2.3.4.4, found no evidence of increased risk of cancer with occupational exposure.
- Kristbjornsdottir and Rafnsson (2012) examined cancer incidence among 74,806 Icelandic children and adults, contrasting rates among individuals living in geothermal and non-geothermal areas. Residing in a high temperature geothermal location was positively associated with increased risk of cancers (both individual cancer types and overall cancer risk); the greatest risks were found for pancreatic cancer followed by non-Hodgkin's lymphoma. The analysis stratified by age groups to control for possible biases, however full results were not reported and H_2S was not measured, and thus the use of residence location may have resulted in exposure measurement error and confounding, particularly with radon.
- A community-based study in Italy by Nuvolone et al. (2019), described earlier in Section 2.3.4.2, found that a 0.005 ppm (7 μg/m^3) increase in H_2S was associated with slightly reduced risk of malignant neoplasm mortality. The protective dose-response relationship was minimally significant and the analysis did not account for multiple testing.

2.3.8.1 Summary of carcinogenic effects.: Two of the three recent studies that examined cancer found some effect on the incidence of some cancers with H_2S exposure, but each study had methodological weaknesses, including a lack of direct exposure measurements. The finding by Nuvolone et al. (2019) of a protective association between H_2S and neoplasm(s) is likely spurious. The strong positive associations with risks of pancreatic cancer, breast cancer, basal cell carcinoma, and non-Hodgkin's lymphoma found by Kristbjornsdottir and Rafnsson (2012) might be explained by factors other than H_2S. Overall, the literature on carcinogenic effects of H_2S is inconclusive.

2.3.9 Immunological effects

- A review by Heederik et al. (2007) notes the limited evidence regarding changes in immunoglobulin A responses in individuals that have been associated with odor, which might result from psychophysiological changes related to stress and sensitization.
- Heldal et al. (2019), described earlier, investigated effects of H_2S (and other wastewater workplace-related exposures) on inflammatory reactive markers (C-reactive protein; CRP), surfactant protein D (SpD), club cell protein 16 (CC16), interleukin 8 (IL-8), intercellular adhesion molecule 1 (ICAM-1), and macrophage inflammatory protein (MIP)-1alpha. The H_2S exposure index was negatively associated with the level of ICAM-1, but not with CPR, SpD, CC16, IL-8, or MIP-1alpha.

2.3.9.1 Studies regarding livestock rearing systems.: Earlier sections of this review have discussed a variety of health endpoints associated with livestock rearing systems; here we focus on immune effects.

- Avery et al. (2004) investigated CAFO exposures and immune function suppression using secretory immunoglobulin A (sIgA) measurements obtained twice daily for 14 days from 15 adults living within 2.4 km of hog farming operations in North Carolina, USA, along with odor intensity perceptions. The longitudinal analysis suggested that odor intensity was associated with a decline in sIgA, although the association was not statistically significant and sIgA levels stayed within the normal range. The authors noted that salivary glands are largely under autonomic central nervous system control, are part of "stress" circuits and centers for homeostatic regulation, and that sIgA forms a response to invading microorganisms at mucosal surfaces. Like most of the CAFO studies, exposure to co-pollutants (especially endotoxin) can confound results. Additionally, H_2S levels were not measured.
- Schiffman et al. (2005), described previously (Section 2.3.1.3), found no association between H_2S and salivary IgA.

3.3.9.2 Summary of immunological effects.: Very few studies have examined immune effects of low-level H_2S exposure. At higher exposure levels, an occupational study has associated H_2S exposure with lower ICAM-1 levels although CPR, SpD, CC16, IL-8, and MIP-1 alpha levels were unchanged (Heldal et al. 2019). Other studies have not found significant results, and are limited by a lack of H_2S measures, often using proximity or odor as an exposure proxy. Overall, the literature on the immunological impact of H_2S is inconclusive.

2.3.10 Effects on livestock—While an analysis of the literature pertaining to environmental exposures of H_2S on beef cows and other animals is beyond the scope of this report, we note several papers examining beef cattle in Alberta, Canada, a major oil and (sour) gas producing area, due to the study size (27,000 cattle in 207 herds), chronic low-level exposures, and data completeness (including exposure monitoring). The study methodology is presented by Waldner (2008a; 2008b; 2008c) and commented on by the study's Science Advisory Board co-chair (Guidotti 2009). H_2S concentrations ranged from 0.00009 to 0.00033 ppm (0.09 to 0.33 ppb) (5th to 95th percentile). Results are summarized below.

- Waldner (2008d) found that SO_2, H_2S and VOC exposures during gestation were not associated with the odds of calf treatment in the first 3 months of life, however, exposure in the first month after calving was associated with a small increase in these odds after the first month of life (typically for diarrhea, pneumonia and umbilical infections), and that the H_2S linkages were consistent with possible mechanisms.
- Bechtel et al. (2009) found that VOC exposure was associated with an increase in CD4 T lymphocytopenia in cattle, showing modulation of the immune system,

although the significance of the change is unclear. In addition, H_2S exposure was associated with an increase in rabies antibody titer; the authors noted several discrepancies and stated that it was unlikely that this exposure would increase antibody production.

- Waldner (2009) found no evidence that SO_2, H_2S and VOCs exposures affected abortions or still births in the beef herds.
- Waldner and Clark (2009) found associations between VOCs (measured as benzene) and respiratory lesions for calves older than 3 weeks, and between SO_2 and lesions during gestation.

2.4 Synthesis of the studies

2.4.1 Weight of the evidence—We start with a general "weight of the evidence" discussion to provide context and a conceptual framework for evaluating study strengths and weaknesses. Discussions pertaining to weight of the evidence are presented elsewhere (e.g., EPA 2005; OEHHA 1999), and typically involve both qualitative and qualitative assessments, a summary narrative encompassing the individual lines of evidence, and a critique often using (Austin Bradford) "Hill's Criteria." These nine well-known "criteria for causation" date from a 1965 article on smoking and include consistency of association, strength of association, dose-response, temporality, experimentation, specificity, biologic plausibility, coherence, and analogy. Key issues in the weight of evidence discussions include the following:

1. The strength of associated adverse health effect with a chemical exposure can be measured in terms of high observed effect incidence or high relative risk, statistical significance of differences between control and exposed groups, and a positive dose-response relationship.
2. The consistency of associated adverse health effect with a chemical exposure is noted by the similarity of effects found in different studies and among different populations and/or species.
3. The specificity of associated adverse health effect to an exposure strengthens the case for causality; however, it is well-recognized that such highly specific associations are rare.
4. The temporal association between the adverse health effect should occur at a time following exposure that is consistent with the nature of the effect, e.g., respiratory irritation immediately following H_2S exposure is temporally consistent, as would be tumor development that involve a latency period of months or years.
5. The coherence of the adverse health effect with the exposure reflects the scientific plausibility of the association, which is based on an understanding of the pharmacokinetics and mechanism of action.
6. Results utilizing human data are most relevant to assessing human health effects. Sources of human data, i.e., epidemiological studies, controlled exposure

experiments, and case reports, can each provide important information, but each has strengths and weaknesses.

As an example of the application of weight-of-evidence considerations, OEHHA's (1999) evaluation of acute RELs emphasized dose-response relationship, reproducibility of findings, mechanism of action, and consistency with other studies. More recent thinking for causality consolidate and refine the necessary criteria to four factors: the strength of association (including analysis of plausible confounding); temporality; plausibility (addressing articulate mediation and interaction); and experimental support (including implications of study design on exchangeability) (Shimonovich et al., 2021).

As noted earlier, while hazards and risks from high concentrations of H_2S are well known, information pertaining to low level human exposure remains relatively scarce and more difficult to interpret. In the following, we discuss key weight-of-the-evidence issues that pertain to many or most of the studies.

2.4.2 Definition and scope of adverse effects—Definitions of adverse effects vary. OEHHA (1999) cited EPA (1989) in defining adverse effects: "A biochemical change, functional impairment, or pathological lesion that either singularly or in combination adversely affects the performance of the whole organism or reduces an organism's ability to respond to an additional environmental challenge." Thus, the perception of even an objectionable odor was not necessarily considered as an adverse health effect unless accompanied by other symptoms or signs, e.g., nausea and vomiting, or by actions or behaviors that affected quality of life. Similarly, odor complaints to city or state departments do not constitute a permit violation, although they may trigger an inspection of a facility. Because self-reports of symptoms (and exposure) can be influenced by many factors, including odor, socioeconomic status and interviewer bias (e.g., Radon et al. 2007), the general preference is to control for such factors using objective outcome measures and not to rely on symptoms, although odors may affect quality-of-life issues. Temporary and reversible impacts, including odor, also are sometimes excluded, especially in occupational settings. WHO's (1948) well-known definition of health, "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity," encompasses a broader view of adverse effects that would include odors and symptoms that might affect mental and social well-being. Inclusion of odor impacts as an adverse effect is further supported given that objectionable H_2S odors can inhibit outdoor activity of individuals, including exercise that can contribute to their well-being, as noted in several studies (Brancher et al. 2017; Heaney et al. 2011; Ulutaş et al. 2021).

Adverse effects investigated in the H_2S literature are predominantly morbidity outcomes, mostly ocular, respiratory, and neurological/neurobehavioral symptoms and disease. Only one study has examined mortality due to chronic, low-level H_2S exposure (Bates et al. 1997), and only few older studies were identified that examined immunological, reproductive or pregnancy outcomes in humans.

2.4.3 Nature and characterization of exposure—Many of the observational studies of H_2S are limited with respect to the exposure assessments, and addressing and minimizing adverse effects of *exposure measurement error* is important to obtain credible results. These errors can result from multiple factors, e.g., the difficulty of differentiating acute from chronic exposure, estimating exposure using distance proxies or spatial models, and multi-pollutant mixtures, among other challenges. *Reporting or awareness bias*, noted earlier, also can affect self-reported exposures. Such concerns are particularly pertinent to community-based studies of livestock rearing operations and geothermal sources that use non-objective or proxy measures of H_2S exposure, often due to difficulties of collecting samples at or near emission sources, or due to a focus on generating hypotheses that might explain observations in a region known for a particular industry, e.g., hog farms in North Carolina, U.S., or geothermal plants in Tuscany, Italy. The following discusses challenges in characterizing exposure, addressing biological monitoring, duration of exposure, spatial variation, pollutant mixtures, and cumulative effects.

Measurements (or validated estimates) of H_2S concentrations are needed to develop dose-response information relevant for establishing air quality guidelines and standards, comparing results among studies, confirming exposure estimates, and other purposes. A growing number of community-based and occupational epidemiology studies have included concentration measurements. Organized by health effect investigated, objective measures of H_2S were used in studies investigating odor and sinus irritation (Heaney et al. 2011; Horton et al. 2009; Lee et al. 2007; Logue et al. 2001; Schiffman et al. 2005; Schinasi et al. 2011); ocular effects (Bates et al. 2002, 1998; Fisher 1999; Haahtela et al. 1992; Kilburn, 2012; Lee et al., 2007; Logue et al., 2001; Marttila et al., 1995, 1994; Schiffman et al., 2005; Schinasi et al. 2011); nasal lesions (Mousa 2015); respiratory health (Bates et al. 2013; Campagna et al. 2004; Carlsen et al. 2012; Durand and Wilson 2006; Eduard et al. 2009; Farahat and Kishk 2010; Finnbjornsdottir et al. 2016; Heldal et al. 2019; Kilburn 2012; Lee et al. 2007; Logue et al. 2001; Nuvolone et al. 2019; Schinasi et al. 2011); cardiovascular health (Finnbjornsdottir et al. 2016; Kilburn 2012; Nuvolone et al. 2019); neurological and neurobehavioral health (Bates et al. 2013; Dubyk and Mustafa 2002; Farahat and Kishk 2010; Horton et al. 2009; Inserra et al. 2002, 2004; Kilburn 2012; Kilburn et al. 2010; Kilburn and Warshaw 1995; Lee et al. 2007; Nuvolone et al. 2019; Partti-Pellinen et al. 1996; Pope et al. 2017; Reed et al. 2014); immune (Heldal et al. 2019; Schiffman et al. 2005); reproductive and developmental health (Vasiljeva 1973); and cancer (Nuvolone et al. 2019). Given that H_2S is found as a component of a mixture of pollutants emitted from most sources of concern, other components in the mixture that might be associated with the health effect of interest must also be characterized to avoid confounding, as described below in Section 2.4.3.4.

Studies without H_2S measurements can serve several purposes. These include: helping to confirm and extend results of other studies, e.g., showing the prevalence of health issues; evaluating the effectiveness of interventions and emission controls, e.g., documenting reduced numbers of complaints or symptoms; generating hypotheses; and providing preliminary investigations.

2.4.3.1 Biological monitoring: In an attempt to better understand the relationship between external and internal exposure, H_2S measures may be combined with biological monitoring of sulfhemoglobin or urinary thiosulfate. Several studies, noted above, lack H_2S

measurements and instead utilize biological monitoring. Depending on the circumstance, biomarkers in blood and urine may be more difficult to obtain than ambient or indoor air samples. However, if a biomarker is not specific to the compound of interest and data for potential confounding factors are not collected, the biomarker may not be useful in assessing true exposure.

Urinary thiosulfate is the most common biomarker of H_2S exposure (ATSDR 2016). Thiosulfate is produced through oxidative metabolism of H_2S. The process occurs in two steps, which may explain the delayed buildup of thiosulfate in the body following H_2S exposure (WHO 2003). Urinary thiosulfate can be used to confirm low-level exposures, although the responsiveness of this biomarker to low-level exposures may vary significantly between individuals (Durand and Weinstein 2007). H_2S can promote red blood cells (RBCs) to form sulfhemoglobin, a sulfheme protein complex (Kurzban et al. 1999; Ríos-González et al. 2014). H_2S is produced endogenously (see Section 3.10) but at levels too low to form sulfhemoglobin, while exogenous H_2S may occur at levels high enough to warrant the use of sulfhemoglobin to assess its presence in tissues and cells (Ríos-González et al. 2014). However, blood sulfhemoglobin is not specific to H_2S, and can be formed following exposure to drugs (e.g., phenacetin, dapsone, and sulfonamides) as well as other sulfur-containing agents (Gharahbaghian et al. 2009; Bhagavan 2002). If sulfhemoglobin accumulates, it can cause sulfhemoglobinemia and cyanosis, although these are rare conditions.

Biological monitoring of H_2S in epidemiological studies is rare; exceptions are a few studies that measure urine thiosulfate (Farahat and Kishk 2010) or blood sulfhemoglobin (Al-Batanony and El-Shafie 2011). Other studies have measured these biomarkers to assess exposure in humans (Ensabella et al. 2004; Saeedi et al. 2015) and animals (Drewnoski et al. 2012). In Italy, Ensabella et al. (2004) used ambient workplace H_2S measures to verify blood sulfhemoglobin as a reliable measure of individual worker exposure to environmental H_2S. In contrast, Saeedi et al. (2015) found that workers exposed to higher levels of H_2S had lower mean sulfhemoglobin levels, yet these results are largely inconclusive due to the study's minimal exposure contrast and the limited statistical analysis. Drewnoski et al. (2012) investigated cattle exposed to environmental sulfate, which is converted to H_2S in the rumen of cattle, by measuring both urine thiosulfate and blood sulfhemoglobin. To date, use of H_2S biomarkers is uncommon, and all of the human biological monitoring studies discussed occurred in occupational settings. Validation of H_2S biomarkers for low level exposures in community settings must consider sources of H_2S – endogenous or exogenous, clearance rates, sensitivity, and other factors to avoid exposure measurement error. Thus, at present, it would be prudent to collect ambient or personal H_2S air samples in addition to urine thiosulfate or blood sulfhemoglobin. Further, the invasiveness and inconvenience of conventional blood draws may limit the use of biomonitoring in community studies to clinical settings, however, this may change as techniques evolve that allow convenient and minimally invasive (e.g., finger prick) sampling and analytical techniques.

2.4.3.2 Duration of exposure: acute, intermediate, and chronic: Exposure to H_2S (and other chemicals) in community and occupational settings will involve both acute and chronic exposures. In practice, these terms are not well defined. Acute exposure events, vary in concentration, length of exposure period, and their periodicity. For many pollutants including H_2S, acute exposures are characterized as the maximum 15-min, 1-hr, or 24-hr average concentration. (Section 4 discusses the form of standards and guidelines that utilize different averaging periods.) Additionally, acute exposures can be a once-in-a-lifetime event, e.g., a result of a rare natural disaster or major industrial failure. In contrast, chronic exposures result from repeated exposure events over multiple years, and sometimes from a continuous or an ongoing release. Chronic exposures also vary in concentration, and are usually represented as an annual average concentration. For some pollutants (e.g., lead), intermediate durations are also sometimes used, e.g., a 3-month average.

Real-world H_2S exposures can include both acute events, e.g., one or few events in a lifetime, intermediate or intermittent exposures, e.g., multiple events in a week or month, and chronic exposures, e.g., occurring on nearly a daily basis due to occupational exposures or proximity to emission sources.

Exposures in community settings near H_2S emission sources (e.g., volcanoes, CAFOs, oil and gas facilities) will likely include intermediate duration and chronic exposures, although acute exposures also may occur. For example, upsets due to malfunctions at an industrial source may greatly increase levels over the chronic exposure normally expected, as documented by Haahtela et al. (1992). More generally, for pollutants like H_2S that are primarily emitted by localized outdoor sources, community exposures will be time varying due to the combined effects of: (1) the emission rate, which changes depending on activity, temperature, and other factors; (2) meteorological influences on dispersion, which is determined by winds, insolation, atmospheric stability, boundary layer height, precipitation, landscape features, and other factors; (3) sheltering or attenuation of H_2S concentrations in buildings and other “microcompartments”, which are affected by air change rates, mixing, filtration, etc.; and (4) an individual’s activity patterns (movement between microcompartments), breathing rate, and other individual-level factors. A key point in community settings is that time-averaged concentrations of H_2S are likely to be low, but occasional concentration spikes at much higher levels for periods of minutes to hours may occur. High pollutant events lasting several days can occur if sufficient H_2S emissions are released and if certain meteorological conditions that inhibit dispersion are persistent, e.g., prolonged subsidence inversion. These factors produce considerable spatial and temporal variation in H_2S concentrations, including daily and seasonal patterns, that affect both occupational or environmental exposures, discussed further the following section.

The time-varying (dynamic) behavior of pollutant concentrations can be captured with fast-response real-time instruments, which are available for H_2S and some other pollutants (e.g., SO_2, CO, $PM_{2.5}$, O_3), but not for other pollutants (e.g., endotoxin). Several studies have used continuous monitors for H_2S at locations designed to reflect population exposure, and several studies have used (short-term) indoor measurements in residences. Unlike the low-cost $PM_{2.5}$ sensors now being widely deployed across the world, low-cost (less than say $200) H_2S sensors that operate reliably at low concentrations (0.001 – 0.1 ppm) are unavailable.

The use of biomarkers or personal exposure monitoring, the "gold standard" in exposure assessment, has not been attempted in community studies of H_2S. As described earlier (Section 2.4.3.1), H_2S biomarkers have limitations, and personal monitoring can involve substantial cost, logistical and participant burden impacts. As noted, only a subset of studies reviewed employed monitoring for H_2S and other pollutants. In the studies that did use monitoring, there was little discussion of the temporal nature of exposures. Because different averaging times were used, it can be difficult to compare studies examining acute impacts. Generally, temporal fluctuations of H_2S levels in a community would be expected to be similar to that of other pollutants arising from localized outdoor sources. *A recommendation is to collect and analyze long-term (ideally ≥1 year) continuous monitoring records of H_2S at sites representative of population exposure around various types of sources*. Such data for several other pollutants exist in both public and industry-operated ambient air quality monitoring networks in the U.S., Canada and elsewhere. Occasionally, citizen complaints or permit violations may initiate such monitoring for a limited period, in the U.S. most typically conducted by the U.S. ATSDR, states or industry as part of a exposure and health assessment, e.g., MDHHS (2023). While primarily used to compare community exposure to reference levels (discussed in Section 4.1), such initiatives rarely yield peer-reviewed publications that advance epidemiology, possibly a missed opportunity.

Ideally, data with 5-min or higher time resolution would be obtained and used to analyze concentration distributions at 5-min, 10-min, 30-min, 1-hr, and 24-hr averaging periods. In recent years, new technology has enabled the measurement of H_2S with ppb precision e.g., cavity ring-down technology with high performance.

2.4.3.3 Spatial variation of community exposure: For mostly the same reasons just discussed, ambient H_2S concentrations in a community will vary from place to place. Spatial variation will always occur from localized outdoor sources and can lead to measurement error. Issues of cost and logistics generally preclude the use of a sufficient number of monitors to fully understand spatial variation across a community, although reasonable estimates can be made with a small set of monitors. Several (Finnish) epidemiological studies have used dispersion models to attempt to "fill-in" the inevitable data gaps from monitoring data (Häkkinen et al. 1985; Marttila et al. 1994; WHO 2006), an approach which is reasonable if data exist to confirm ("ground-truth") model predictions. Using measured or modeled concentrations, researchers may divide a region or city into zones based on concentration levels (i.e., high, medium, and low). The definition of cut-off points for exposure categories should consider climate factors such as wind direction and good characterization of background levels. For example, in the geothermally active city of Rotorua, New Zealand, the main emission sources of H_2S are spatially clustered and thus not all residents are equally exposed; three zones were defined as high (~1 ppm), medium (0.5 ppm), and low/background levels (0 – 0.04 ppm) (Bates et al. 2002). Considering the lack of standardized exposure category definitions, it is vital to consider each study's definition of exposure and exposure groups. The use of spatially-defined groups or zones (defined by monitoring, modeling, proximity, or other data) in an cross-section epidemiological study design requires careful consideration and control of covariates to avoid potential bias and confounding..

The majority of community studies around geothermal sources or livestock rearing operations used indirect proxy exposure measures, most often residential or school proximity to a facility or the number of facilities in the community (Bustaffa et al. 2020). Such indirect measures do not capture differences among sources and emissions, effects of meteorology and terrain on contaminant dispersion, impacts from other emission sources, and other factors that affect exposure (Huang and Batterman 2000). Thus, it is not expected that concentrations will be proportional to inverse distance from the source, or radially symmetric around the source, assumptions that have been used in the literature. Urban/rural differences are additional spatial challenges in studying the health effects of environmental exposures around geothermal plants or CAFOs. Urban and rural populations may differ with respect to sensitization and acclimatization to CAFO pollutants, e.g., a potential bias may result due to the lower prevalence of respiratory allergies sometimes seen among populations with early farm-animal contact (Radon et al. 2007).

Exposure assessments for H_2S are just beginning to use the hybrid approaches that have become common in air pollution epidemiology for pollutants like $PM_{2.5}$ and NO_2. These approaches synthesize a variety of data sources (satellite and remote sensing, *in situ* or ambient monitoring, land use features, emission inventories, chemical transport modeling, and sometimes housing features) to improve accuracy in comparison to any single approach. These techniques are particularly applicable to obtaining intermediate to long-term (e.g., weekly to annual) concentration estimates over large areas with high spatial resolution. A recent pilot study couples *in situ* and satellite data to estimate concentrations and emissions of several pollutants (CO_2, CH_4, H_2S, and NH_3) from a California dairy (Leifer et al., 2020), an approach that may have considerable value when linked to health data.

2.4.3.4 Pollutant mixtures: Air pollution exposures experienced in communities and often workplaces involve mixtures of many chemicals. Measurement error can occur in trying to characterize exposure to an individual pollutant without considering potential co-pollutants. Both the components in the mixture, and the relative concentrations of components in the mixture depend on emission sources that are present. Thus, the "typical" exposure can vary considerably between individuals and between studies. As examples, H_2S exposures from oil and gas facilities will likely include other reduced sulfur compounds and combustion-related compounds like SO_2 and CO; H_2S exposures associated with CAFOs and manure management will likely be accompanied with other gases such as ammonia, mercaptans, sulfides, and ketones, and may also include particulate matter containing organic dusts containing bioactive substances (endotoxins, glucans, fungi and molds) (Donham 2010; NRC 2003). In addition, the composition and rate (strength or intensity) of emissions from most sources (e.g., oil and gas facilities, geothermal plants, or CAFOs) will differ among facilities and during different operations. For example, emissions may increase during hot weather and during manure spraying, an intermittent activity. Thus, the composition and concentration of exposures in community settings will vary in time and space, and the correlation among mixture components will also vary.

Ideally, each individual pollutant would be separately and objectively measured, otherwise effects of individual pollutants will be difficult to disentangle. Of the newer community-based livestock rearing studies identified, only five measured H_2S (Campagna et al. 2004;

Eduard et al. 2009; Inserra et al. 2004; Kilburn 2012; Schinasi et al. 2011). Even fewer measured additional co-pollutants likely to confound observed health effects (Campagna et al. 2004; Eduard et al. 2009; Schinasi et al. 2011); these may provide the best dose-response information for setting air quality standards. In their controlled exposure study, Schiffman et al. (2005) opines that while individual components of the mixture at low concentrations were not expected to produce health effects, the observed health effects may represent a combined and potentially synergistic effect. To date, no attempt has yet been made to evaluate health effects of components isolated from real CAFO mixtures, although this is technically possible. For example, subjects could be exposed only to CAFO-related gases by using filters to remove particulate matter and microorganisms. However, for practical reasons, controlled chamber studies are limited to short-term exposures and small sample sizes. Although exposure to the entire mixture may be more relevant to community exposure, such tests could be useful in demonstrating the effectiveness of occupational interventions e.g., N95 masks for workers and mechanical ventilation with particulate filtration for facilities. The results of both controlled and observational studies suggest the need for or desirability of a multipollutant approach to control emissions from livestock-related and potentially other types of facilities. Thus, controls should include both regulation of individual pollutants and broader technology or performance requirements. This approach would be more responsive to health impacts resulting from additive or synergistic effect of multiple pollutants from H_2S sources.

The presence of pollutant mixtures is a real-world condition. In observational studies it may be difficult to discern effects of an individual pollutant when present in a mixture, however, effects may still be discerned despite spatial, temporal, and compositional variability if a study involves a sufficiently large sample of subjects, large geographic domain, sufficient duration, and appropriate pollutant measurements. Moreover, observational studies usually are the only practical approach to examine chronic and low-level exposures, to investigate potential synergies between mixture components and host factors like susceptibility, and to study large populations. The nascent but evolving hybrid models noted in the prior section may be valuable to provide exposure estimates for these studies.

If multiple pollutants are present and reasonably likely to influence a particular health outcome due to their concentration and toxicity, then ideally each pollutant should be objectively measured. It may be sufficient to screen for co-pollutants, or use the threshold olfactory technique (Section 2.3.1.2) in certain studies, to target the exposure assessment. Otherwise, effects of an individual pollutant in the mixture may be difficult or impossible to disentangle. Given information regarding the major components of the mixture, then controlled, occupational and community studies can utilize a variety of experimental and statistical techniques to understand effects of individual components, including potential interactions (e.g., synergies) with other mixture components, as discussed in the next section.

2.4.3.5 Cumulative effects of multiple chemical exposures: The term “cumulative effects” refers to the overall impact of concomitant exposures to multiple chemicals and other stressors in a particular condition or scenario. For exposure to chemical mixtures, this can include effects that are equal to (additive), less than (antagonistic), or greater than (synergistic) predictions based on the effects observed with exposures to individual chemicals.

As discussed above, H_2S exposures often occur with exposures to other pollutants. Of the current literature, few studies provided information that can shed light on cumulative effects. Schiffman et al. (2005) addressed CAFO emissions, which involve a mixture of H_2S, other reduced sulfur compounds, endotoxin and dust that may act on the same target tissues. One of few controlled human studies, it offers some evidence that the mixture may increase the hazard of H_2S at low concentrations (documented as headaches, eye irritation, and nausea), since no single component was present at sufficiently high concentration to be wholly responsible for these symptoms (H_2S levels were only 0.024 ppm) (Schiffman et al. 2005). Lee et al. (2007) also opined that symptoms observed may result from synergistic or additive effects of the mixture components; they found WWTP workers to have higher risks of respiratory symptoms (dry cough, cough with phlegm, wheeze, chest tightness, breathlessness), although H_2S concentrations averaged 0.15 ppm and 95% of measurements were below 1 ppm (although the maximum value was high, 42.5 ppm). Finally, Mirabelli et al. (2006a) suggested that children using cigarettes or experiencing secondhand tobacco smoke were susceptible to increased prevalence of wheeze, suggesting co-exposure to environmental exposure as an additional risk factor.

Although more complex than investigating a single component, multipollutant studies are needed to provide the most meaningful approach to deal with actual exposures and health effects from pollutant mixtures (Dominici et al. 2010; Greenbaum and Shaikh 2010; Mauderly et al. 2010). Multipollutant approaches may lead to better management strategies because real world H_2S exposures often occur with other toxic pollutants.

2.4.4 At-risk populations and susceptibility—Three definitions are intended to provide some consistency in the discussion, although these terms are often comingled in the literature.

- The term "susceptibility" or "susceptible population" has been used to recognize groups that are at greater risk than the general population for health risk(s) from a specific pollutant, generally due to biological or intrinsic factors (e.g., life stage, gender, health and preexisting disease/conditions, nutritional status, and effects of exposure to other toxic substances such as cigarette smoke). A susceptible population would exhibit a different or enhanced response to a pollutant (like H_2S) than most persons with the same exposure, and detoxification or excretion of the pollutant, organ function or other processes may be reduced or compromised (ATSDR 2006).
- The term "vulnerability" or "vulnerable population" typically refers to nonbiological or extrinsic factors (e.g., socioeconomic factors, limited access to health care, lower quality housing located near emission sources). Vulnerability may affect susceptibility, and thus these terms are often comingled.
- Finally, the term "at-risk" or "at-risk population" refers to groups more that are likely to have higher risk of health effects than the general population, potentially

a result of separate or combined influences from susceptibility, vulnerability, and higher exposure. (Populations with unusually high exposure to H_2S are discussed in Section 3.)

Generally, the scope of the H_2S studies available permits limited insight with respect to susceptibility, and only to some health outcomes. Few studies examined potential effect modifiers that might identify more susceptible or vulnerable populations. Given the malodor of H_2S, it is reasonable to anticipate that individuals with asthma, who show increased sensitivity to odors, would have a worsening of their condition upon exposure (ATSDR 2006). Strong supporting evidence of asthmatic vulnerability is provided by Carlsen et al. (2012) who studied a population exposed to volcanic emissions with daily H_2S averages of 0.006 ppm and daily peaks of 0.062 ppm (1-hr averages of 0.021 ppm and 1-hr peaks of 0.345 ppm), and by Campagna et al. (2004) who studied a population around CAFOs with 30-min concentrations above 0.030 ppm. Earlier, controlled 30-min tests with 2 ppm H_2S of a small group of subjects with mild-to-moderate asthma noted some sensitivity by increased airway resistance and decreased specific airway conductance, implying bronchial obstruction; however, this study excluded individuals who may be most susceptible, specifically, severe asthmatics and children (Jappinen et al. 1990). Finnbjornsdottir et al. (2016) found a weak association between H_2S and heart disease in adults that increased slightly among those 73 years and older. Besides underlying conditions such as asthma, environmental and social factors have been evaluated as potential effect modifiers. Being raised on a farm may increase a child’s risk of asthma, even after accounting for atopy and allergy (Merchant et al. 2005). Children may be more susceptible to a broader range of respiratory diseases than adults (Campagna et al. 2004). Children who smoke cigarettes or experience secondhand smoke have higher risk of wheezing than children who do not (Mirabelli and Wing 2006). However, not all studies that stratified health risk by susceptibility factors have found significant effects. Villeneuve et al. (2009) found no difference in health effects between children/adolescents and adults. Sigurdarson and Kline (2006) noted that children with parents who farmed and smoked were not more likely to have asthma than children of parents who did not.

The broader literature points to several groups that are at-risk for morbidity and mortality effects from air pollutants. Examples for two pollutants are given. For particulate matter ($PM_{2.5}$), susceptible and at risk groups include children and older adults, individuals with pre-existing heart and lung disease, and persons with lower socioeconomic status and with genetic differences. Emerging though still limited evidence exists for additional potentially at-risk populations, including individuals with diabetes, people who are obese, pregnant women, and the developing fetus (EPA 2012). For sulfur dioxide (SO_2), at-risk groups include those with pre-existing respiratory disease, children and older adults (but possibly not adolescents), and people who spend extended periods of time outdoors and/or at elevated ventilation rates (EPA 2017). EPA concluded that large portions of the US population are likely to be at increased risk from these pollutants, and health-protective standards were set based on the at-risk groups. Clearly, a very large number of individuals are exposed and affected by air pollutants $PM_{2.5}$ and ozone. Over the past four decades, SO_2 emissions, concentrations, and the numbers of individuals affected have likely dropped considerably e.g., in 2021, nonattainment areas for SO_2 included 26 areas with a population of 2.13 million persons (EPA 2010b). In this report, the number of individuals affected by high concentrations of H_2S is not estimated, however considering the many facilities that routinely or intermittently release H_2S across the nation (e.g., refineries, CAFOs, wastewater facilities, etc.), the population exposed or potentially exposed may be substantial.

2.4.5 Potential biases in observational studies—While observational studies provide opportunities to examine chronic low-level exposures, results of these and other epidemiological studies can be limited by several types of biases. *Reporting or awareness bias* can affect self-reported symptom assessments, potentially important for H_2S considering its odor that may make subjects more aware and likely to report effects and symptoms. Reporting bias also occurs for other reasons, e.g., economic interests associated with industry and study participants. *Recall bias* is a second potential issue in symptom studies, particularly for longer recall periods. A third bias is the *sensitization* – or conversely *tolerance bias* – to exposures and odors; this bias also may affect results of experimental (chamber) investigations. Schiffman et al. (2005), for example, discusses possible differences in responses obtained from volunteers in chamber studies compared to those who are chronically and involuntarily exposed, however, the literature is equivocal on this topic, showing that repeated exposure can increase sensitivity to an odor (especially among women), but that some workers appear tolerant of swine confinement air.

Other types of biases in observational studies, particularly in community-based studies, include *selection bias* (e.g., the need for a randomly selected case population and, in case-control studies, an appropriately selected comparison population), the possibility of *confounders* (including co-pollutants), and *effect modifiers* (e.g., due to urban/rural differences) (Donham 2010; Heederik et al. 2007; Radon et al. 2007).

Section 2.4.3 earlier discussed issues and weaknesses in exposure estimates used in the observational studies. Exposure measurement error or misclassification is a topic that has received considerable attention in the epidemiological literature (Carroll et al. 2006). *Exposure measurement error,* that is, differences between the measured (or predicted) exposure used in the analysis compared to the underlying or true exposure, or *exposure misclassification,* the analogous term for a categorical exposure variable, can lead to incorrect inference, specifically, biased and/or imprecisely estimated effect coefficients that may be serious enough to invalidate the inference regarding the effect of H_2S on health (Sheppard et al. 2012). The framework for exposure measurement or misclassification error refers to standard categories: *classical measurement error* due to random errors resulting when the true exposure is measured but with noise, which causes biased effect estimates as well as higher or lower standard errors; *Berkson measurement error* when only part of the true exposure or aggregated exposure is measured, which causes unbiased but more variable exposure-response (effect) estimates; *Berkson-like measurement error* due to smoothing the exposure surface; and *classical-like measurement error* when noise is not independent (Szpiro and Paciorek 2013). Related classifications of errors due to spatial issues include: the *modifiable areal unit problem* (MAUP), which can bias outcomes when a point-based measure (e.g., H_2S level measured at a site) is assumed to apply to a district (e.g., census tracts) and lead to the so-called ecological fallacy (Ganguly et al. 2015; Shafran-Nathan et al. 2017); *location-based covariate measurement error*, e.g., when proximity to a H_2S source like a CAFO is used to define exposure; and differences between *ambient and personal exposures* (Kioumourtzoglou et al. 2014). Finally, studies investigating chronic disease can be susceptible to *exposure timing bias*, e.g., the use of current exposure conditions that may have limited relevance for a disease that developed years or decades earlier (Lipfert and Wyzga 2008).

2.4.6 Summary of the studies—Table 1 summarizes many of the health effects associated with H_2S. Only a subset of studies that measured or estimated H_2S levels are included. Estimates listed of H_2S exposure levels, durations, and co-pollutants are approximate. The case reports and the available epidemiologic and toxicological literature clearly indicate that the high H_2S concentrations that sometimes occur in occupational settings such as viscose rayon and pulp manufacture, and oil, gas and geothermal energy production have the potential to produce morbidity and death. The dose-response relationship for mortality is well understood. However, the literature does not include any large occupational epidemiological studies that address morbidity or mortality due to chronic occupational exposures. Such studies are recommended and could shed light on the low-level exposures that are the focus of this report. There is also a paucity of large studies addressing chronic low level H_2S exposures occurring in community settings. Such studies are needed to evaluate the potential of H_2S to cause health effects on susceptible and vulnerable individuals. In addition, although there are numerous reports of adverse effects, many involve concurrent exposures and the data and/or analyses do not quantitatively link effects with H_2S exposure for this and other reasons (ACGIH 2001).

The newer literature includes several medium-sized studies using (daily) time-series analyses and objective measures of both pollutants and respiratory-related symptoms and disease. Unscheduled hospital visits for aggravation of asthma and respiratory disease increased at H_2S concentrations above 0.03 ppm in Nebraska (Campagna et al. 2004); irritation (nose and eye), odor, difficulty of breathing and cough was associated with higher H_2S concentrations or odor in North Carolina (Schinasi et al. 2011); and exacerbation of existing asthma at H_2S concentrations of 0.0067 ppm was indicated by (increased) dispersal of anti-asthma drugs in Reykjavik (Carlsen et al. 2012). The latter study has the strength that multiple pollutants were considered, which due to differences in pollutant emissions may have had greater influence on the CAFO-oriented studies (i.e., Campagna et al. 2004; Schinasi et al. 2011). These studies strongly suggest that short-term (30 min to 24-hr) H_2S concentrations in the range of 0.007 to 0.03 ppm, roughly around the odor detection/nuisance threshold, can significantly exacerbate asthma. Individuals with asthma are highly susceptible to air pollutants, and thus this finding is consistent with the literature for other pollutants. Although findings in these studies appear robust, ecological designs (and typically a single monitoring site) were used, which limits the ability to identify and control for individual or group risk factors (effect modifiers and covariates).

Many of the other studies discussed in this review show elevated risks for other symptoms and diseases, including ocular symptoms, sore throat, cough, nasal irritation, nasal lesions, difficulty of breathing, chest tightness, wheezing, increased asthma prevalence and/or aggravation, lung function decrements, depression, neurological and neurobehavioral changes among individuals in communities and workplaces where H_2S concentrations are elevated or likely to be elevated. In particular, eye irritation may result at concentrations starting in the range of 0.007 to 0.025 ppm. The modeling by Schroeter et al. (2010; 2006) had the effect of changing the NOAEL for nasal lesions. In community settings, odor-triggered nuisance, complaints and physiological symptoms are expected with short-term concentrations in the range of 0.001 to 0.050 ppm, and odor nuisance thresholds are in the range from 0.03 to 0.05 ppm or lower. The newer observational studies document neurological and neurobehavioral abnormalities in community settings around H_2S sources, but the identification of the causal mechanisms and the dose-response relationships remains unresolved.

Exposure assessment limitations in these studies just mentioned, including a lack of objective monitoring, preclude establishments of dose-response relationships. Exposure assessments continue to represent a significant weakness of H_2S studies (OEHHA 1999); this is a common problem in air pollution epidemiology. Additionally, results of some studies may have been affected by co-pollutants, biases in participant recruitment/selection, symptom ascertainment (especially when self-reported), occupation and exposure history, and other factors. Many studies used cross-sectional designs that have a high likelihood of bias due to the difficulty of accounting for covariates and confounding variables. Good discussions of methodological limitations are provided by Radon et al. (2007) and (OEHHA 2000) for the H_2S studies, and by Götschi et al. (2008) for air pollutants in general.

There is a large divergence between experimental animal and human studies with respect to the concentrations that are associated with adverse effects. These types of studies typically employ different types of health effect measures (OEHHA 2000). Moreover, animal and controlled human exposures are typically very short-term in nature, likely to miss health effects with long latency periods, rarely evaluate effects relevant to susceptible individuals (including children, the elderly, and persons with preexisting medical conditions), and may not reflect other factors important to actual exposures and real-world conditions. However, experimental studies represent an essential criterion in causality determinations (Section 2.4.1)

As in most of the epidemiological literature, it is difficult to assess publication bias in the H_2S literature. Few studies with exclusively null findings were identified, although Inserra et al. (2004) and Villeneuve et al. (2009) reported largely negative findings. The lack of negative studies and the preponderance of smaller studies suggest that publication bias is likely (Götschi et al. 2008).

3 Exposure to H_2S

A short discussion is provided of populations exposed to H_2S. Elevated levels and exposures of H_2S occur near several types of air pollution sources.

- Industry. H_2S is emitted more or less continuously in certain industries. These include natural gas production, shale oil industry, petroleum refining, petrochemical synthesis, municipal sewage pumping and treatment plants, landfills, swine containment and manure handling (including confined animal confinement facilities or CAFOs), pulp and paper production, construction in wetlands, asphalt roofing, pelt processing, animal slaughter facilities, tanneries, coke production plants, viscose rayon manufacture, sulfur production, iron smelting, ocean fishing, and food and meat processing, pulp and paper mills, oil refineries, hot springs and geothermal energy installations, Superfund and other waste sites, and chemical (and other) waste lagoons (ATSDR 2006, 2002; Glass 1990).

- Accidental releases. H_2S can be emitted in large amounts resulting in acute exposures due to industrial accidents, pipeline failures, and geothermal sources. Based on a multistate surveillance program, 637 H_2S events occurred from 1993 to 2001, resulting in 63 public evacuations and 185 people injured (ATSDR 2002). In Alberta, Canada, 357 sour gas incidents occurred from 1990 to 2005 along pipelines, including hits, leaks, releases and ruptures (Section 3.8).
- Natural sources include volcanoes, sulfur springs, undersea vents, swamps and stagnant bodies of water and in crude petroleum and natural gas. Additionally, bacteria, fungi, and actinomycetes release H_2S during the decomposition of sulfur-containing proteins and by the direct reduction of sulfate (SO_4^{2-}; ATSDR 2006).

Typically, background levels (away from industrial or strong natural sources) are low, falling below 0.001 ppm (1 ppb), while proximity to strong natural sources or industries emitting H_2S can produce much higher concentrations that often exceed 0.09 ppm (90 ppb) (ATSDR 2006).

This section emphasizes exposures of H_2S reported in the scientific literature relevant to community exposure. It does not include the “gray literature,” which potentially includes a large number of exposure assessments that sometimes result from citizen complaints, regulatory requirements, or permit violations that are conducted by the U.S. ATSDR, states, and industry (e.g., MDHHS 2023).

3.1 General urban levels

In one report, the average ambient H_2S level was estimated at 0.0002 ppm (0.3 μg/m^3). In north-west London, over a period of 2.5 years, air levels of H_2S were generally <0.0001 ppm (0.1 ppb; 0.15 μg/m^3) under clear conditions (WHO 2006, 1981). ATSDR (2006) reports that ambient air concentrations from natural sources range between 0.00011 and 0.00033 ppm (0.11 and 0.33 ppb), and that levels in urban areas are generally below 0.001 ppm (1 ppb).

3.2 Geothermal sources

H_2S has been continuously monitored in the city of Rotorua, New Zealand, where geothermal activity is sufficient to cause odors and where studies of mortality (Bates et al. 1997), cancer (Bates et al. 1998), morbidity (Bates et al. 2002), respiratory disease (Durand and Wilson 2006) and cognitive function (Reed et al. 2014) have been performed. H_2S concentrations exceeded 0.05 ppm (80 μg/m^3) over 55% of the time in the mid-winter months (WHO 2006, 1981). Horwell et al. (2005) mapped levels in the city using passive samplers and indicated that maximum 8-hr levels in the center city may reach 1 ppm regularly, while 10-min peaks may be order of magnitude higher. Other studies in Rotorua have detected similarly low levels: a range of 0.03 to 1.0 ppm (Durand and Wilson 2006); IQR of 0.0056 to 0.184 ppm (Pope et al. 2017); IQR of 0.011 to 0.031 ppm (Bates et al. 2013); median of 0.014 ppm (Bates et al. 2002, 1998). Different sampling techniques and spatial variation in concentrations due to soil gas emission fluxes and meteorological influences could explain the differences in measured ambient levels (Durand and Wilson 2006). Durand and Scott (2005) reported on levels inside nine buildings in Rotorua and discussed the lack of effectiveness of preventative measures, such as under-laying of concrete floors with a gas-proof butanol seal, under-floor ventilation systems, and positive-pressure air conditioning.

Reykajavik, Iceland is also known for high geothermal activity with ambient H_2S at concentrations averaging 0.0058 (Carlsen et al. 2012). According to Finnbjornsdottir et al. (2016), the interquartile range (IQR) of H_2S levels is 0 to 0.003 ppm. In another geothermal "hotspot," Mt. Amiata, Tuscany, ambient H_2S concentrations averaged 0.0003 to 0.022 ppm (Nuvolone et al. 2019).

3.3 Oil and gas production facilities, including sour gas wells and pipelines

H_2S is both routinely and episodically released at sour gas wells, gas and crude oil batteries, gas and oil processing plants, oil refineries, and tar sands mining operations. Possibly the most extensive H_2S monitoring has been performed in Alberta, Canada. Alberta Environment (2004) provides statistics from about 80 monitoring stations in Alberta over a three-year period at sites potentially affected by oil and gas exploration and production facilities. The three highest (1 hr) concentrations ranged to 3 ppm; excluding these values, the average concentration was 0.006 ppm (6 ppb or 8.5 µg/m^3). Alberta Environment also summarized pipeline incidents, including hits, leaks, releases and ruptures, reports 10 to 41 sour gas incidents per year (total 357 from 1990 to 2005), most of which were attributed to corrosion (AEUB 2007). The overall rate of sour gas pipeline incidents ranges from 1.2 to 3.2 incidents per year per 1000 km, and a declining trend is noted across the Province of Alberta. Pipeline accident rates are typically expressed in terms of number of incidents per year per km of pipeline, and rates can vary significantly in different regions. A health study of Canadian petroleum workers did not directly measure H_2S but used a job-exposure matrix to back-estimate lifetime occupational median exposures of 0.07 ppm (Lewis et al. 2003).

The US EPA conducted some monitoring around the Gulf Coast in the aftermath of the BP oil spill (AER 2022). Based on website notes, most sites had levels below detection limits (0.1 ppm); some levels exceeded 0.5 ppm in Venice, Alabama, and typical values at Chalmette, Louisiana (some 50 miles from Venice) were 0.002 to 0.004 ppm (EPA 2016). Lusk and Kraft (2010) reported on H_2S monitoring (and an avian risk assessment) in oil and gas production facilities in New Mexico and found that most peak levels were below 6 ppm; the maximum peak level was 33 ppm. Another occupational study of oil/sour gas facilities in New Mexico found levels ranging from 0 to 0.014 ppm (Dubyk and Mustafa 2002).

Natural gas venting during well testing and development, as well as testing and maintenance of other energy infrastructure, can be a short-term source of H_2S emissions and exposure. This appears to have become more common in the past decade due to the expansion of hydraulic fracturing and natural gas fields in North America, e.g., sour gas fields in Alberta, Canada. Typically, venting during well tests and other non-routine activities has been limited to a maximum duration of three days, and monitoring and modeling may be required to ensure that ambient H_2S concentrations (and SO_2 concentrations if flaring is used) do not cause odors (1-hour level H_2S level below 0.01 ppm) or exceed standards (AER 2022; AH 2020). Venting typically would not be utilized subsequently, e.g., during well operation.

3.4 Pulp and paper mills

Emissions from pulp and paper mills can include a mixture of particles, sulfur dioxide and several malodorous compounds including H_2S, methyl mercaptan, and methyl sulfides, which are often measured and reported as total reduced sulfur (TRS). H_2S can constitute a variable form of TRS, e.g., Jaakkola et al. (1990) indicate 70%. Some of the studies reporting concentrations around these facilities are listed below.

- Peak concentrations up to 0.13 ppm (200 μg/m^3) were measured near a pulp and paper-mill in California (WHO 2006, 1981).
- In an occupational survey of H_2S and other sulfides at six kraft mills in Finland, concentrations ranged from below 0.05 ppm (75 μg/m^3) to 20 ppm (30,000 μg/m^3), the highest concentrations being found near vacuum pumps (Kangas et al. 1984; WHO 2006).
- In a Finnish town with two sulfate pulp mills (annual emissions of 1993 and 794 T/year of H_2S, respectively), dispersion models estimated average annual concentrations up to 0.037 ppm (55 μg/m^3), monthly average concentrations up to 0.067 ppm (100 μg/m^3), 24-hr concentrations up to 0.36 ppm (540 μg/m^3), and 1-hr concentrations up to 1.07 ppm (1600 μg/m^3) (Häkkinen et al. 1985; WHO 2006).
- Observational health studies of communities near sulfate pulp mills in South Karelia, Finland reported average concentrations of 0.00067 to 0.0053 ppm (Marttila et al. 1994) and 0.001 to 0.002 ppm (Partti-Pellinen et al. 1996).
- Monitoring data near five kraft mills in Alberta, Canada is reported by Alberta Environment (2004).
- Korhonen et al. (2004) summarized occupational exposures in the paper industry across 12 countries; however, relative few measurements of H_2S are reported.
- Mirabelli and Wing (2006) reported odors near four pulp and paper mills in North Carolina, but exposures are not quantified.
- H_2S monitoring in seven localities near around Ružomberok, Slovakia, a polluted area containing a kraft pulp mill, showed long-term average concentrations (2002 through 2004) up to 0.004 ppm (5.8 μg/m^3) and maximum levels of 0.014 ppm (21 μg/m^3) (Drimal et al. 2010). Using the 95th percentile 24-hr samples as a worst-case, a RfC of 0.001 ppm (2 μg/m^3) (EPA 2003), the authors report hazard quotients up to 7. This represents the first air monitoring of H_2S in Slovakia.

3.5 Viscose rayon mills

Near a viscose rayon mill in Finland, H_2S concentrations were measured and predicted using a dispersion model (FNBH 1982; WHO 2006). For a 55 m high smokestack, average annual concentrations exceeded 0.007 ppm (10 µg/m^3), 24-hr concentrations were approximately 0.134 ppm (200 µg/m^3), and hourly concentrations reached 0.302 ppm (450 µg/m^3). A higher smokestack reduced maximum annual, 24-hr and hourly concentrations to 0.003, 0.023, and 0.054 ppm, respectively (4, 35 and 80 µg/m^3). A Japanese survey of 18 viscose rayon plants showed very high occupational exposures of H_2S, which ranged from 0.3 to 7.8 ppm (450 to 11,700 µg/m^3), with a mean of 3 ppm (4,500 µg/m^3) (Higashi et al. 1983; WHO 2006).

3.6 Livestock rearing systems

Livestock rearing systems include confined animal feeding systems (CAFOs) and manure storage and treatment. H_2S is the main toxic emission from livestock rearing systems with liquid manure storage; other emissions can include ammonia, mercaptans, sulfides, ketones and particulate matter, which can include organic dusts with endotoxins, glucans, fungi, molds and other microbes. A very complete review of emissions, with recommendations, is provided by NRC (2003). Acute exposures have been reviewed by Donham et al. (1982), and updated reviews of community and occupational concerns are given by the same team (Donham 2010; Donham et al. 2007). An increasing number of studies are examining odors and contaminants in communities near CAFOs.

- H_2S and TRS measurements at multiple indoor and outdoor locations in Dakota City and South Sioux City, Nebraska, an area affected by a large animal waste treatment facility and other sources, exceeded 0.030 ppm (30 ppb) about a quarter of the time (ATSDR 1997; Campagna et al. 2004; Inserra et al. 2002; White et al. 1999).
- Donham et al. (2006) measured H_2S outside 35 homes located near swine farms in three regions -- those with CAFO facilities, hoop structure facilities, or crop-only production (control) -- in the Upper Midwest, U.S. The time weighted average concentrations of H_2S (8.42 ppb) was higher ($p = 0.047$) in the CAFO area than the control area (3.48 ppb). The concentration of H_2S exceeded the ATSDR limit (30 ppb) for chronic exposure at two of the 12 homes in the CAFO area (17%). Average H_2S levels exceeded the EPA recommended community standards (0.7 ppb) in all three regions.
- Wing et al. (2008) measured odors, H_2S and PM_{10} at 16 neighborhoods in eastern North Carolina, US that had between one and 16 CAFOs within a radius of 2 miles. Monitoring periods in each neighborhood were at least 2 wks. Average H_2S concentrations ranged from 0.00 to 0.00148 ppm (0.00 to 1.48 ppb), and 15-min levels reached 0.090 ppm (90 ppb). Odor ratings made by 101 participants during 10-min periods of sitting outside twice a day were associated with weather conditions and concentrations of H_2S and PM_{10} (Horton et al. 2009; Wing et al. 2008).

- Eduard et al. (2009) used personal air monitors to measure individual-level H_2S exposure among 4,735 Norwegian livestock farmers. The authors reported levels ranging from 0.0002 ppm (sheep, goat, poultry farms) to 0.036 ppm (cattle farms).
- Thorne et al. (2009) collected measurements of toxicants upwind, downwind and in barns of swine facilities in central Iowa, U.S., including $PM_{2.5}$, endotoxin, odor threshold, H_2S, bacteria, fungi and airborne microbes. H_2S measurements averaged 0.0024 to 0.0032 ppm at a distance of 160 m from the barn; indoor measurements averaged between 0.020 and 0.146 ppm, depending on the type of confinement building. H_2S levels were low compared to earlier literature, in part as the facilities studied were relatively small, and site activities (e.g., manure pumping) and meteorological conditions were noted to affect the downwind concentrations.
- Across 16 communities in eastern North Carolina, U.S., 12-hr H_2S concentration averaged 0.00030 ±0.00186 ppm, 12-hr PM_{10} averaged 19.4 ± 11.8 $\mu g/m^3$, and 12-hr $PM_{2.5}$ averaged 10.9 ±5.7 $\mu g/m^3$ (Schinasi et al. 2011).
- Kilburn (2012) reports some measurements in and outside of homes within 3 km of hog manure lagoons in Paulding, Ohio, U.S. Average H_2S levels in 12 homes ranged from 0 to 0.03 ppm (but reached 2.1 ppm in one home and varied over 10-fold in one-day’s spot check samples). Two outdoor samples exceeded 1.1 ppm.
- In Iowa, U.S., Pavilonis et al. (2013) measured ambient H_2S near (<40 m) a single, medium sized swine CAFO over 7 months to determine the temporal and spatial variability of H_2S, near two schools over a 2 weeks period, and near 13 CAFOs also over a 2-week period. Near the single CAFO, concentrations ranged from 0.0002 to 0.0486 ppm, depending on the sampling period and proximity to a lagoon on the property. 2-week concentrations near the schools were below 0.001 ppm, and 2-week concentrations near the 13 CAFOs were 0.001 to 0.043 ppm, although several measurements exceeded the state’s ambient limit of 30 ppb (24-hr average).
- Additional community-based health studies have assessed odor but not H_2S (Avery et al. 2004; Radon et al. 2005).

It is significant to note that the NRC (2003) expert panel made management recommendations for H_2S: “For air emissions important on a local scale (hydrogen sulfide [H_2S], particulate matter [PM], and odor), the aim is to control ambient concentrations at the farm boundary and/or nearest occupied dwelling. Standards applicable to the farm boundary and/or nearest occupied dwelling must be developed.”

3.7 Sewage and waste treatment facilities

H_2S exposure is a well know hazard for WWTP workers. Ho et al. (2008) reviewed a number of H_2S sources associated with wastewater facilities. A study of WWTPs in Iowa, U.S. found the average H_2S level typically below 1 ppm (95% of samples were below this value), an overall geometric mean of 0.15 ppm, and a range from 0 to 42.5 ppm (Lee et al. 2007). A study of wastewater pump stations in Tianjin, China, measured 15 volatile organic compounds (VOCs) including H_2S and found that it occurred at levels higher than other VOCs, with a geometric mean of 0.020 ppm (29.42 μg/m^3) and range of non-detect to 0.059 ppm (87.50 μg/m^3); researchers then used modeling to predict that at these levels, H_2S would confer non-carcinogenic health risks, most likely olfactory mucosa damage, with a hazard quotients of 1.14 and 1.13 for the mean and median exposures, respectively (Niu et al. 2014). Additional occupational studies of wastewater workers have found concentrations ranging from 0.4 to 13.1 ppm (Austigard et al. 2018); from 5 to 11 ppm (Farahat and Kishk 2010); and from 2 to 74 ppm (Kilburn et al. 2010). Exposure to H_2S from wastewater plants may extend beyond the industrial setting into nearby communities.

Attention has been increasing with respect to H_2S levels from municipal and other solid waste management facilities, possibly due to the development of nearby or adjoining residential development. A study of residential exposure nearby a landfill found average ambient levels of 0.00022 ppm with a range from 0 to 0.0023 ppm (Heaney et al. 2011). Ko et al. (2015) measured levels of H_2S at and near landfills and evaluated technologies to control H_2S emissions at landfills; Colón et al. (2017) focused levels within waste processing plants in Spain using mechanical-biological waste treatment designed to reduce the biodegradable fraction and stabilize municipal wastes. The highest H_2S concentrations (1.85 ppm) were found in a mechanical-biological treatment facility for municipal solid waste in Portugal, followed by a biofiltration unit (0.546 ppm), over the landfill (0.022 ppm) and then a composting treatment hall (0.019 ppm); this paper also summarizes H_2S levels found at eight other landfills or waste processing facilities (Nunes et al. 2021).

3.8 Accidental exposures

During accidental exposures, concentrations from 100 ppm (150 mg/m^3) to 12,000 ppm (18,000 mg/m^3) have been reported (WHO 1981). Accidental releases can have severe effects. For example, the malfunction of an oil field flare in the small community of Poza Rica, Mexico resulted in a H_2S release that caused 320 people to be hospitalized and 22 deaths; H_2S levels were not measured (WHO 1981). Haahtela et al. (1992) presents an epidemiological study of short-term upset at a paper mill that greatly increased exposures for several days. Leaks in sour gas pipelines, discussed earlier (Section 3.3), are another potential source of accidental exposure, although the number of individuals affected appears small in most cases.

Failures of flares, a rudimentary emission control system, and other controls used at industrial sources of H_2S and other pollutants can produce periods of high emissions and high exposures. Emergency, process and production flaring at refineries, sour gas processing facilities, and gas extraction well development normally convert H_2S, if present in the waste stream, to SO_2, which is considerably less toxic and odiferous. (In developed countries, process flaring would not normally be utilized to control H_2S given concerns over SO_2 emissions and exposures.) There are no known statistics on flare failure rates that have led to sizable H_2S emissions and such events are rarely documented in the scientific literature, although such incidents have led to community exposure in multiple settings.

3.9 Other exposures

H_2S exposure can result from other environmental and industrial sources, including production of pesticides and intermediates, in particular, sodium tetrathiocarbonate (STTC), and a need for more studies on co-exposure to CS_2 (another by-product) and H_2S has been expressed (Silva 2013).

H_2S exposure can result from mining activities, including underground and surface mining, as well as the injection of waste slurry into abandoned underground mines. These activities can generate large quantities of sulfate, which under anaerobic conditions in the presence of carbon, can be reduced to sulfide by naturally occurring bacteria; some of the sulfide will remain dissolved in groundwater (Simonton and King 2013). In mining regions in West Virginia, U.S., Simonton and King (2013) found sulfate in all 73 residential drinking water wells tested and observed rotten-egg odor in all homes, however, H_2S concentrations were not measured. Further studies of mining related H_2S exposure are needed to quantify levels and temporal and spatial variability.

3.10 Endogenous production

Exposure to H_2S occurs endogenously, that is, from the production of H_2S in the body, in addition to the external sources discussed previously. In brief, most endogenous production results from the metabolism of sulfhydryl-containing amino acids by bacteria in the intestinal tract and the mouth, and some is produced in the brain and several smooth muscles by enzymes in these tissues (ATSDR 2006). In the mouth, H_2S is a component of halitosis, and concentrations between 0.001 and 0.1 ppm (1–100 ppb) have been measured in mouth air. In the large intestine, H_2S can be generated by bacterial reduction of inorganic sulfate and sulfite, and by fermentation of sulfur-containing amino acids. H_2S can compose up to 10% of intestinal gases, and mean concentrations range in flatus are between 1 and 4 ppm, although levels reaching 18 ppm have been recorded among individuals on a normal diet. In the brain, H_2S produced from reactions catalyzed by the cystathionine β-synthase enzyme from the desulfhydration of cysteine acts as a neuromodulator, enhancing the N-methyl-D-asparate (NMDA) receptor-mediated response, facilitating the induction of hippocampal long-term potentiation, and serving as a widely distributing signaling or messenger molecule (Section 2.2).

3.11 Summary of exposure sources

This section has focused on airborne emissions of H_2S from various types of sources that produce on-site (occupational) and off-site (downwind community) exposures. In communities near pulp and paper mills, the largest source of airborne emissions, H_2S concentrations can vary widely, e.g., a Slovakian study (Drimal et al. 2010) reported a long-term average of 0.004 ppm and maximum concentrations up to 0.014 ppm, while a Finnish study (Häkkinen et al. 1985; WHO 2006) showed annual average concentrations up to 0.037 ppm (annual average) and 1-hr peaks up to 1.07 ppm). Typically, much higher levels are found in occupational settings, e.g., up to 20 ppm in kraft mills in Finland (Häkkinen et al. 1985; WHO 2006), and 42.5 ppm at sewage and waste treatment facilities in Iowa, U.S. (Lee et al. 2007). Yet greater differences between community and occupational exposures have been found at viscose rayon mills (FNBH 1982; Higashi et al. 1983; WHO

2006). Oil and gas production facilities, the next largest H_2S emission category, include a diverse set of sources, e.g., sour gas wells, pipelines, gas and crude oil batteries, processing plants, and refineries. These facilities may routinely (e.g., continuously) release H_2S that produce generally modest concentrations and exposures in community settings, but more widespread and sometimes much higher exposures may result from facility startup or testing activities, e.g., well-development, and sometimes from upsets and accidents, e.g., spills and pipeline leaks. As examples: across 80 monitoring sites in communities with sour gas facilities in Alberta, Canada, H_2S concentrations averaged 0.006 ppm and 1-hr peaks reached 3 ppm (Alberta Environment 2004); and concentrations in coastal communities following the large BP oil spill Louisiana, US were mostly below 0.1 ppm (EPA 2016). The third largest emission category, livestock rearing systems including CAFOs, has had the largest number of studies. These have reported some of the higher H_2S concentrations in community settings, e.g., short-term measurements exceeding 1 ppm in and outside of near swine facilities in Iowa, U.S. (Kilburn 2012). However, these levels appear atypical and long-term average concentrations generally average well below 0.1 ppm and often much lower, below 0.01 ppm (Schinasi et al. 2011; Thorne et al. 2009). Other potentially important H_2S sources can include water and waste processing facilities. Finally, community exposures to volcanic and geothermal sources of H_2S, have received attention in Portugal, Iceland, New Zealand and Italy; community monitoring shows great variability with long term averages typically below 0.1 ppm but occasional short term peaks that may reach one to two orders of magnitude higher (Section 3.2).

Emissions of H_2S from industrial and agricultural sources can be controlled or further controlled to protect workers and community members, unlike the volcanic or geothermal sources. It is notable that H_2S emissions – in comparison to on-site or environmental concentrations – are rarely measured, and the reliability of the existing emission data is unknown.

4 Exposure recommendations and regulatory levels

H_2S exposure limits recommended for workers and the general population range over several orders of magnitude, differing for a number of reasons including the literature that was available and selected as relevant and meaningful, the type of endpoint or critical effect considered, the duration of exposure, the populations considered, the degree of protection desired, and the adjustment, safety and uncertainty factors applied. Guidelines and limits may differ among agencies even though the same study may be used to define the critical effect, reflecting the agency's assessment of the evidence, attitudes towards risk averseness, and agency practices and policies. This concern is particularly relevant for community standards and guidelines developed from occupational, controlled human or animal studies given the need to protect susceptible and vulnerable populations. Adjustment and uncertainty factors (sometimes called safety factors) reflect animal-to-human (or other) dosimetry issues, as well as the recognition that community exposure can occur to susceptible and vulnerable populations who are not adequately represented in the underlying studies. To date, guidelines and limits for H_2S have not utilized approaches or adjustment factors that consider H_2S as a surrogate for the toxicity of a mixture of co-pollutants emitted from the same source.

4.1 Community standards and guidelines

Existing community guidelines in the U.S. are summarized in Table 2 and discussed below. Several European guidelines are discussed later in the text.

4.1.1 U.S. Reference concentration (RfC)—The EPA defines the inhalation RfC as an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily inhalation exposure of the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. It is based on the assumption that a concentration or exposure *threshold* exist for certain toxic effects such that no adverse effect will occur below a given exposure. The inhalation RfC considers toxic effects for both the respiratory system (portal-of-entry) and for effects peripheral to the respiratory system (extra-respiratory effects). The current RfC for H_2S (EPA 2003) is derived from a no-adverse-effect level (NOAEL) of 10 ppm based on a controlled exposure of rats by Brenneman et al. (2000) described in Section 3.3.3. The RfC was derived following EPA guidance, which adjustments for a continuous exposure concentration (factor of 4), dosimetric and physiological adjustments for differences between rats and humans (factor of 5), and standard uncertainty factors for interspecies extrapolation, sensitive populations and subchronic exposure (factors of 3, 10 and 10, respectively), resulting in a RfC of 0.0013 ppm (2 µg/m^3). The product of the uncertainty factors is 300, the highest among agency standards and guidelines reviewed. As noted in Section 3.3.3, Schroeter et al. (2006) derived a NOAEL of 5 ppm for this effect using data from Brenneman et al. (2000), which would have the effect of changing the dosimetric and physiological adjustment (formerly 5) to a factor of 2, thus increasing the RfC to 0.0033 ppm.

4.1.2 Minimal risk level (MRL)—The MRL is an estimate of daily human exposure to a substance that is likely to be without an appreciable risk of adverse effects (noncarcinogenic) over a specified duration of exposure (ATSDR 2006). MRLs are derived when reliable and sufficient data exist to identify the target organ(s) of effect or the most sensitive health effect(s) for a specific duration within a given route of exposure. They do not consider carcinogenic effects. MRLs can be derived for acute, intermediate, and chronic duration exposures for inhalation and oral routes. Although methods have been established to derive these levels, uncertainties are associated with these techniques. Furthermore, ATSDR acknowledges additional uncertainties inherent in the application of the procedures to derive less than lifetime MRLs. As an example, acute inhalation MRLs may not be protective for health effects that are delayed in development or are acquired following repeated acute insults, such as hypersensitivity reactions, asthma, or chronic bronchitis. As these kinds of health effects data become available and methods to assess levels of significant human exposure improve, MRLs will be revised.

Several estimates of MRLs have been made for H_2S (derivation shown detailed in ATSDR 2006). The following summarizes ATSDR's discussion.

- Acute MRL: ATSDR (2006) has set an inhalation MRL of 0.067 ppm (100 µg/m^3) for acute exposure duration (≤ 14 days) based on suggestive evidence of bronchial obstruction among asthmatics exposed to 2 ppm H_2S for 30 min (Jappinen et al. 1990). This concentration was considered a minimally adverse effect level because changes in airway resistance and specific airway conductance were observed in only 2 of 10 subjects. The MRL was calculated by dividing the unadjusted LOAEL by an uncertainty factor of 27 (3 for use of a minimal LOAEL, 3 for human variability, and 3 for database deficiencies). The LOAEL from Jappinen et al. (1990) is supported by the LOAEL of 5 ppm for increased blood lactate levels observed in exercising subjects (Bhambhani et al. 1996). As noted, the Jäppinen study excluded individuals with severe asthma.

- Intermediate duration MRL. An MRL of 0.02 ppm has been derived for intermediate-duration inhalation exposure to H_2S (15 – 364 days). ATSDR noted the limited data on the toxicity of H_2S in humans following intermediate-duration exposure. Acute- and chronic-duration studies suggest that the respiratory tract and nervous system are sensitive targets of H_2S. Like the EPA (2003), the Brenneman et al. (2000) study was selected as the basis of the intermediate-duration inhalation MRL, and the critical effect was nasal lesions. The MRL was derived using the NOAEL/LOAEL approach, utilizing an uncertainty factor of 30 (3 for extrapolation from animals using dosimetric adjustments and 10 for human variability), adjusting for duration, and adjusting for regional gas dose ratio for the extra thoracic region. The same limitations, noted above, would apply to the MRL.

- Chronic MRL. ATSDR cites several human studies that have examined the chronic toxicity of inhaled hydrogen sulfide dating from 1951 to 1990, including Jaakkola et al. (1990), Jappinen et al. (1990) and Kangas et al. (1984) in the present review, plus several others. Most of these studies reported increases in the occurrence of subjective symptoms of respiratory irritation in workers or residents living near paper mills. However, due to limitations including poor exposure characterization (including the lack of information on peak exposure levels), co-exposures to other chemicals, and the lack of animal studies examining chronic toxicity, a chronic-duration inhalation MRL was not derived.

4.1.3 California reference exposure level (REL)—Similar to the EPA RfC, OEHHA (1999) defines the REL as the concentration level at or below which no adverse health effects are anticipated for a specified exposure duration. RELs are based on the most sensitive, relevant, adverse health effect reported in the medical and toxicological literature and are designed to protect the most sensitive individuals in the population by the inclusion of margins of safety. Since margins of safety are incorporated to address data gaps and uncertainties, exceeding the REL does not automatically indicate an adverse health impact. A chronic inhalation REL of 0.0067 ppm (10 $\mu g/m^3$) was established by OEHHA (2000) on the basis of histopathological inflammatory changes in the nasal mucosa of mice study (CIIT 1983). Adjustments to human exposures included a subchronic uncertainty factor of 3, interspecies uncertainty factor of 3, intraspecies uncertainty factor of 10, and cumulative uncertainty factor of 100. It was noted that 50% of the population would be able to detect the odor of H_2S under controlled conditions, but only 5% would find it annoying at this level. An acute REL of 0.028 ppm (42 $\mu g/m^3$) for 1 hr was established by OEHHA (2008) on the basis of headache, nausea, and other physiological responses to odor.

4.1.4 WHO Air Quality Guidelines—

WHO (2006) Air Quality Guidelines provide a value of 0.1 ppm (0.15 mg/m^3) with an averaging time of 24 hr based on ocular damage. WHO also states that to avoid substantial complaints about odor annoyance. H_2S concentrations should not be allowed to exceed 0.0046 ppm (7 μg/m^3) with a 30-min averaging period.

4.2 Occupational standards and guidelines

There are several widely used occupational standards and guidelines. As pointed out specifically for H_2S by Milby and Baselt (1999), acceptable air levels in workplace environments are based on very different considerations than acceptable levels in community air. In brief, persons in the workplace are assumed to be in reasonably good health, generally remain in the workplace environment for no more than 8 hr/day and 40 hr/wk, and generally are exposed to a limited number of agents. In contrast, community residents comprise all ages and all states of health and may be physically present in the community for most or all of any 24-hr period or longer. Residents also tend to have a reasonable expectation that their community air will be generally free of noxious substances that create health or nuisance problems. Thus, while H_2S levels possibly as high as 10 ppm have been considered acceptable for workplace settings (but see the new TLVs below), much lower concentrations (well below 0.1 ppm) can create unacceptable health and nuisance conditions in community settings (Table 1). For example, community health assessments performed by state agencies have used the US EPA RfC (Section 4.1.1) of 0.0015 ppb as a long-term level that might result in an increased risk of nasal irritation (MDHHS 2023).

4.2.1 U.S. threshold limit values (TLV)—

The TLV-TWA is defined as “the time-weighted average concentration for a conventional 8-hr workday and a 40-hr work week, to which it is believed that nearly all workers may be repeatedly exposed, day after day, without adverse effect” (ACGIH 2001). The TLV recommendations are widely used in occupational settings throughout the world. Since 1966, ACGIH (2001) has recommended a TLV-TWA (time weighted average) of 10 ppm and a TLV-STEL (short-term exposure limit) of 15 ppm for H_2S to protection against significant health risks of sudden death, eye irritation, neurasthenic symptoms such as fatigue, headache, dizziness, and irritability, or permanent central nervous system effects that may result from acute, subchronic, or chronic exposure. In part, the basis was a number of studies indicating that 10 ppm exposure will not cause eye irritation, the most commonly reported adverse physical effect of exposure to H_2S at concentrations of 50 to 100 ppm.

In 2010, ACGIH revised the exposure limits to 1 ppm (TWA) and 5 ppm (STEL) (ACGIH 2001). The basis and rationale for the changes is to be protective of upper respiratory tract irritation and central nervous system impairment. The TLV documentation cites that 1 ppm should be sufficient to protect against all the unwanted effects of H_2S and that peak exposures of 5 ppm may produce minor irritation and a brief change in oxygen uptake but would not be expected to produce more serious effects on the respiratory, central nervous or cardiovascular system. Cited studies supporting this conclusion included Bhambhani et al. (1996), Bhambhani and Singh (1991), Blackstone et al. (2005), Brenneman et al. (2000), Dorman et al. (2004), and Fiedler et al. (2008), among others. ACGIH (2001) also notes that it may be necessary to control exposures below the TLV to prevent complaints of odor.

4.2.2 U.S. Occupational Safety and Health Administration (OSHA) permissible exposure limits (PELs) and National Institute for Occupational Safety and Health (NIOSH) recommended exposure limits (RELs)—
OSHA has a Ceiling Limit of 20 ppm, Short-Term Exposure Limit (STEL) of 50 ppm (maximum 10-min peak per 8-hr shift), and a TWA of 10 ppm (vacated in 1989). These levels date back to 1978 (NIOSH 1978). The NIOSH REL is a ceiling of 10 ppm and an Immediately Dangerous to Life and Health (IDLH) limit of 100 ppm.

4.2.3 U.K. Occupational Exposure Standards (OES)—
In the U.K., OES were set in 2002 at 5 ppm for the 8-hr TWA and 10 ppm for the STEL. The basis for these levels are studies on young, fit, and healthy adult human volunteers undergoing maximal and submaximal exercise which demonstrated that brief periods (15 – 30 min) of exposure to 5 and 10 ppm, respectively, caused a shift towards anaerobic respiration (Bhambhani et al. 1996; Bhambhani and Singh 1991; Costigan 2003).

4.2.4 Scientific Committee on Occupational Exposure Limits (SCOEL)—
Following the UK OES, in 2007 the European SCOEL recommended setting the 8-hr TWA and the STEL to 5 and 10 ppm, respectively, based on experimental studies of nasal lesions in rats (SCOEL 2007). Their report discussed studies examining eye irritation and lung function impairment, but concluded that workers in the occupational studies examined were also exposed to CS_2 gas, and that effects could not be attributed to H_2S alone at levels below 20 ppm.

4.2.5 Dutch Expert Committee on Occupational Standards (DECOS)—
The Dutch set standards in 2006 (DECOS 2006) and 2010 (DECOS 2010) at 1.6 ppm for long-term exposure to H_2S, substantially below the UK OES and European SCOEL. No recommendations were made for a short-term standard. Again, nasal lesions in rats served as the critical effect with a NOAEL of 10 ppm. The DECOS added an additional safety factor after considering the potential for differences among people, specifically pregnant women and asthmatics who may be more sensitive to exposure.

4.2.6 German maximum workplace concentration (MAK)—
In 2006, the German review committee recommended a Maximum Workplace Concertation (MAK) of 5 ppm, stipulated as the highest concentration assessed that will not interfere with occupational activity or cause adverse effects. This recommendation was based on a review of toxicity data (including ATSDR 2006; DECOS 2006), and included studies on skin irritation, lung function impairment, and cardiovascular effects.

4.3 U.S. Emergency response guidelines

Like the occupational limits, emergency response guidelines are not intended as general community standards. Several sets of guidelines are listed here for completeness and reference.

4.3.1 Emergency Response Planning Guidelines—Existing short-term exposure guidelines include the American Industrial Hygiene Association (AIHA 1991) Emergency Response Planning Guidelines (ERPGs), which are defined as concentration ranges where adverse health effects could be observed. Three ERPGs are available for many substances, with the definitions are provided below (Cavender et al. 2008).

- The ERPG-1 is the maximum airborne concentration below which nearly all individuals could be exposed for 1 hr without experiencing other than mild transient adverse health effects or perceiving a clearly defined, objectionable odor, which is set to 0.1 ppm for H_2S (60 min peak).
- The ERPG-2 is the maximum airborne concentration below which nearly all individuals could be exposed for 1 hr without experiencing or developing irreversible or other severe health effects which could impair an individual's ability to take protective action, which is 30 ppm (60 min peak).
- The ERPG-3 is the maximum airborne concentration below which nearly all individuals could be exposed for 1 hr without experiencing or developing life-threatening health effects, which is 100 ppm (60 min peak).

4.3.2 U.S. Acute Exposure Guideline Levels (AEGLs).—AEGLs are a second set of emergency response guidelines developed through a collaborative and worldwide effort involving the public and private sectors. AEGLs describe risks to humans resulting from once-in-a-lifetime, or rare, exposure to airborne chemicals. The National Advisory Committee for the Development of Acute Exposure Guideline Levels for Hazardous Substances (AEGL Committee) is involved in developing these guidelines to help both national and local authorities, as well as private companies, deal with emergencies involving spills, or other catastrophic exposures (NRC 2001). AEGLs represent threshold exposure limits for the general public and are applicable to emergency exposure periods ranging from 10 min to 8 hrs.

AEGLs are used for emergency planning and response, often in combination with computer-assisted air dispersion models to estimate "vulnerability zones" associated with releases of chemical substances, e.g., as stipulated under the U.S. EPA Risk Management Program (section 112(r) of the Clean Air Act Amendments for eligible sources (Section 1.3). Then, human health risks associated with a chemical release can be estimated by comparing the projected airborne concentrations of the chemical with the exposed populations and AEGL values to determine appropriate responses. Three levels (AEGL-1, AEGL-2 and AEGL-3) have been developed for each of five exposure periods (10 and 30 min, 1 hr, 4 hr, and 8 hr) and are distinguished by varying degrees of severity of toxic effects. The three AEGLs are defined as follows:

- AEGL-1 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic, non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure. AEGL-1 ranges from 0.33 ppm to 0.75 ppm for averaging times ranging from 8 hr to 10 min, respectively. These values are derived from a human study of headaches among asthmatics (Jappinen et al. 1990).

- AEGL-2 is the airborne concentration above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape. AEGL-2 ranges from 17 ppm to 41 ppm for averaging times ranging from 8 hr to 10 min, respectively. These values are derived from rat studies of perivascular edema (Khan et al.1991; Green et al. 1991).
- AEGL-3 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death. AEGL-3 ranges from 31 ppm to 76 ppm for averaging times ranging from 8 hr to 10 min, respectively. These values are derived from a rat study of mortality following a 1-hour exposure (MacEwen and Vernot 1972).

As the AEGL program notes, "AEGLs have been developed primarily to provide guidance in situations where there can be a rare, typically accidental exposure to a particular chemical that can involve the general public. They, therefore, differ from PELs, TLVs, WEELs, RELs or MAK values, etc. in that they are based primarily on acute toxicology data and not subchronic or chronic data. The guidance therefore does not reflect the effects that could result from frequent exposure. Also, they are designed to protect the general population including the elderly and children, groups that are generally not considered in the development of workplace exposure levels." An advantage of AEGLs is that they account for exposure time. AEGL values represent threshold levels for the general public, including susceptible subpopulations, such as infants, children, the elderly, persons with asthma, and those with other illnesses. It is recognized that individuals, subject to unique or idiosyncratic responses, could experience the effects described at concentrations below the corresponding AEGL.

The current AEGLs for H_2S were published on April 11, 2002, and remained "interim" AEGLs until 2012 when they were accepted by the AEGL Subcommittee to become "Final" for use by public and private organizations. The Subcommittee states that interim AEGLs represent "the best efforts of the AEGL Committee to establish exposure limits, and the values are available for use as deemed appropriate on an interim basis by federal and state regulatory agencies and the private sector" (NRC 2001). Shortly after approving the AEGLs, the Subcommittee disbanded. The AEGLs have not been revised subsequently.

4.4 Summary of Exposure Recommendations and Regulatory Levels

Guidelines and standards for continuous exposure to H_2S in community and occupational settings address short-term, intermediate, and long-term duration of exposure to a range of concentrations that, for the most part, exceed the background levels that communities experience on a regular basis. For shorter term exposures, the ATSDR has recommended a MRL of 0.07 ppm with a LOAEL of 2 ppm for exposures lasting ≤14 days and the WHO published a guidance value of 0.1 ppm with a LOAEL of 15 ppm for exposures lasting 24 hrs. For intermediate exposure duration (15 – 365 days), the ATSDR set a MRL of

0.02 ppm with a NOAEL of 30.5 ppm. For long-term, even lifetime, exposure duration, the EPA set an RfC of 0.0015 ppm with a LOAEL of 30 ppm and a NOAEL of 10 ppm. The California OEHHA set an inhalation REL of 0.008 ppm with a NOAEL of 30.5 ppm. In terms of occupational guidelines and standards, STELs of 5 ppm, 10 ppm, and 50 ppm were established by ACGIH, U.K. OES, and OSHA, respectively; TWAs of 1 ppm, 5 ppm, and 10 ppm were set by ACGIH, U.K. OES, and OSHA, respectively; Ceilings of 10 ppm and 20 ppm were established by OSHA and NIOSH, respectively. The OSHA exposure limits are higher than those set by other agencies and have not been updated in 40 years. Additional standards for emergency response situations (AEGLs and ERPGs) exist but are not intended to address chronic, low-level exposures. As previously discussed, occupational and community air standards are different for valid reasons. Workers are, on average, healthier and exposed to less toxic agents than would be a community member. Protective community standards must consider people of all ages with underlying health conditions, odor sensitivities, or other vulnerabilities, and who are likely exposed to a more complex mixture of agents.

For short, intermediate, and long-term exposures, community standards identify exposure to H_2S concentrations between 0.0015 and 0.1 ppm and above as potentially dangerous to human health. At first glance, a long term community standard set in the vicinity of 0.01 ppm may seem protective of public health given the H_2S levels reported in most of the epidemiological studies that used objective measures of H_2S concentrations. Most of these studies used an averaging period of at least one year, notably longer than the time period considered by all of the occupational standards, as well as by most of the community standards. However, local sources of H_2S in community settings that result in low (<0.01 ppm) long term exposure can and frequently do produce much higher concentration short-term peaks (lasting minutes to hours); these peaks may far exceed the odor detection threshold and may be associated with irritation and other adverse health effects. This highlights the need for both chronic and acute exposure limits.

Finally, as noted throughout this review, community exposure to H_2S typically occurs as a mixture of pollutants that depends on the source (e.g., CAFO, wastewater, landfill, oil and gas facility). Given the difficulty and expense of monitoring all components in the mixture, the H_2S (or total reduced sulfur) concentration may serve as a surrogate or indicator of exposure. While this does not affect the H_2S-health response relationship, it may require additional interpretation and adjustment as a community standard. Specifically, a lower standard may be required if the co-pollutants in the mixture have synergistic effects or increase the toxicity when H_2S is at low levels. Unfortunately, relatively few studies adequately characterize co-pollutants, much less their interactions.

5 Conclusion

Increased large scale food production and shifts in the fossil fuel sector, specifically the development and expansion of CAFOs and hydraulic fracturing, have spurred the growth of industries that emit H_2S. In turn, elevated emissions of H_2S in the U.S. and elsewhere has increased the likelihood of low level but widespread and chronic community exposure to this toxic gas. Acute exposure to high H_2S concentrations can produce morbidity and death with a well-understood dose-response relationship, based primarily on a large body of occupational studies. In contrast, effects of chronic and low-level exposure of H_2S, defined here as concentrations below 0.1 ppm, in both occupational and community settings is much less well understood.

This review has synthesized the literature since 2004, which includes over 100 studies addressing toxicology, controlled human studies, and observational human studies, with a focus on community impacts. We have not attempted a risk assessment of H_2S exposure. Most of the recent literature continues to focus on naturally occurring geothermal and volcanic H_2S sources and on industrial sources such as CAFOs, pulp and paper mills, and wastewater treatment facilities. The epidemiological studies in these settings are limited by several challenges. First, the exposure assessments have frequently used spatial proxies of H_2S, or spatially and temporally sparse point measurements, both with potentially large and generally unknown exposure measurement error. This is significant given considerable uncertainty and variability in H_2S emissions and concentrations, perhaps especially around CAFOs. Second, H_2S emitted by both natural and industrial sources typically occurs as part of a mixture with other pollutants; this mixture can include other reduced sulfur compounds released from many sources, as well as ammonia, dust, bacteria, insecticides, and mold from CAFOs, and SO_2, other combustion products and VOCs from industrial sources such as paper and pulp mills and oil and gas facilities. This leads to the potential for confounding by co-pollutants, particularly in chronic studies where the spatial and temporal variation of exposures is large. Third, the epidemiological literature is not conducive to formal meta-analyses given its diversity in terms of population studied, exposure conditions, and study design. However, it is primarily the potential for exposure measurement errors and confounding that limits the strength of the association between low level H_2S exposure and adverse health effects. Despite such limitations, chronic community exposure to H_2S at average concentrations below 0.01 ppm and peak (short-term) exposures roughly an order of magnitude higher has been associated with a spectrum of adverse health effects, most notably odor aversion, irritation, and ocular, nasal, respiratory, and neurological effects. It is likely that susceptible and vulnerable populations, including individuals with underlying health conditions such as asthma, may be particularly at risk. Several of the observational studies, particularly those with larger sample sizes and longitudinal designs, have greater sensitivity and have shown effects for changes in H_2S levels in the 0.001 ppm range. While the possibility of confounding by co-pollutants cannot be completely ruled out in each study, effects of low level chronic exposure are seen in different settings and across H_2S sources (CAFOs, landfills, geothermal, volcanic, pulp mills) where pollutant mixtures will vary significantly. Collectively, the epidemiological evidence supports the finding that adverse health impacts are caused by exposure to H_2S at low levels, defined here as below 0.1 ppm.

Our findings should be confirmed and extended by larger and more comprehensive epidemiological studies that incorporate susceptible populations, address a wider variety of industrial sectors, and assess multiple outcomes, including neurological, cardiovascular, reproductive/developmental, immune, and carcinogenic endpoints. These studies should be methodologically robust, measuring co-pollutants, accounting for multicollinearity, and employing objective exposure assessment techniques that include long-term continuous sampling to determine annual, daily and hourly average H_2S concentrations, mapping of exposures, hybrid modeling. Study designs using larger samples sizes, longitudinal models with repeated observations or using case-crossover techniques may prove particularly sensitive and robust. In addition, researchers should consider measuring indoor air concentrations or individual exposures using personal air monitors, while weighing the feasibility of associated costs and participant burdens.

To date, few studies have focused on the oil and gas extractive industries, or the chemical and petroleum industries, which collectively emit about one-third of total U.S. H_2S emissions. Understanding the health impacts of fracking is particularly important given its recent and rapid growth and its potential to emit significant levels of H_2S during well development and potentially other phases, though we recognize the potential for co-exposure to diesel particulate matter, NO_x and potentially other pollutants in such studies. National or state H_2S emissions tracking programs can help to identify the relative contributions of industrial sectors and the potential impact of imposing stricter regulations. Industry emissions data can help inform the design of community-based exposure assessment and health studies, although these data may not be adequate and reliable.

Long-term epidemiological studies with large sample sizes and objective exposure measures also are needed to confirm and expand upon findings of neurological effects starting at long-term mean concentrations of 0.007 ppm, and eye irritation, nasal irritation and harmful respiratory effects starting at 0.0003 ppm. As research expands to include susceptible populations and a wide range of adverse health effects, agencies will need to ensure that their guidelines are sufficiently protective of community-wide releases of H_2S.

The adverse health impacts associated with low-level chronic exposure shown in many of the reviewed studies, combined with the continuing and possibly increasing emissions in some sectors, suggest the need for additional emission standards, administrative and/or engineering controls on agricultural and industrial facilities, and enforcement of protective exposure standards or guidelines. In the USA, community guidelines of 0.0015 and 0.020 ppm were set by the EPA (RfC) and ATSDR (Intermediate MRL) in 2003 and 2006, respectively. The lower EPA guideline is more protective in part as it considers subchronic and lifetime exposures; the intermediate ATSDR guideline considers exposure durations up to one year. Although both agencies stated that these levels consider sensitive populations, they were developed from rat inhalation studies that may not be sufficiently protective to protect susceptible populations, even after adjusting for uncertainty factors. Further, these guidelines do not account for odor aversion, irritation, and ocular, nasal, respiratory and neurological effects that epidemiological studies suggest can occur at low exposure levels. Compared to community guidelines, occupational guidelines permit considerably higher exposure concentrations, namely, 1 and 10 ppm, as established by the ACGIH (TLV-TWA) and OSHA (PEL-TWA) in 2010 and 1989, respectively, and should not be applied as community guidelines.

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List of abbreviations and acronyms

This report uses the following abbreviations:

ACGIH	American Conference of Governmental Industrial Hygienists
AEGL	Acute Exposure Guideline Level
AER	Alberta Energy Regulator
AEUB	Alberta Energy and Utility Board
AH	Alberta Health
AIHA	American Industrial Hygiene Association
ATSDR	Agency for Toxic Substances and Disease Registry
BDI	Beck’s depression inventory
BHS	Beck’s hopelessness
CAAQS	California Ambient Air Quality Standard
CAFO	confined animal feeding operation
CC16	club cell protein 16
CDC	Centers for Disease Control and Prevention
CIIT	Chemical Industry Institute of Toxicology
COPD	chronic obstructive pulmonary disease
CRP	C-reactive protein
CT	computed tomography
EPA	Environmental Protection Agency
EPCRA	Emergency Planning and Community Right-to-Know Act
ERPG	emergency response planning guideline
FEV_1	forced expiratory volume
FNBH	Finnish National Board of Health

FR	Federal Register
FVC	forced vital capacity (measure of lung volume)
H_2S	hydrogen sulfide (gaseous air pollutant)
HEC	human equivalent concentration
ICAM-1	intercellular adhesion molecule 1
IDLH	Immediately Dangerous to Life and Health
IL-8	interleukin 8
IQR	interquartile range
JEM	job-exposure matrix
LOAEL	lowest observed effects level
MIP	macrophage inflammatory protein
MRI	magnetic resonance imaging
MRL	minimal risk levels
NIOSH	National Institute for Occupational Safety and Health
NOAEL	no observed adverse effects level
NO_x	nitrogen oxides (gaseous air pollutant)
NRC	National Research Council
O_3	ozone
OEHHA	California Office of Environmental Health Hazard Assessment
OEL	Occupational Exposure Limit
OES	Occupational Exposure Standard
OR	odds ratio
OSHA	Occupational Safety and Health Administration
PEL	permissible exposure limit
PK-CFD	pharmacokinetic computational fluid dynamics
$PM_{2.5}$	particulate matter under 2.5 µm dia. Also, PM_{10} for 10 µm diameter
ppb	parts per billion (volume-type pollutant concentration unit)
ppm	parts per million (volume-type pollutant concentration unit)
R_{aw}	airway resistance

RADS	reactive airways distress syndrome
RBC	red blood cell
REF	reference exposure level
REL	reference exposure levels (used by State of California)
RfC	reference concentration
SG_{aw}	specific airway conductance
sIgA	secretory immunoglobulin A
SO_2	sulfur dioxide (gaseous air pollutant)
SpD	surfactant protein D
TLV	Threshold Limit Values
TRI	Toxic Release Inventory, part of the Emergency Planning and Community Right-to-Know Act (EPCRA) Section 313 toxic chemical release reporting requirements
TRS	total reduced sulfur (gaseous air pollutant)
TSP	total suspended particulate (particulate air pollutant)
TWA	time weighted average
$\mu g/m^3$	micrograms per cubic meter (density type pollutant concentration unit)
WHO	World Health Organization
WTP	water treatment plant
WWTP	wastewater treatment plant

References

ACGIH American Conference of Governmental Industrial Hygienists, 2001. Threshold Limit Values for Chemical Substances and Physical Agents & Biological Exposure Indices, Hydrogen Sulfide (7783-06-4). Cincinnati, OH, 2010. [accessed 2022 Oct 1]. https://www.acgih.org/science/tlv-bei-guidelines/.

AER Alberta Energy Regulator, 2022. Directive 60: Upstream Petroleum Industry Flaring, Incinerating, and Venting; Calgary, AB. [accessed 2022 Oct 1]. https://www.aer.ca/documents/directives/Directive060_2020.pdf.

AEUB Alberta Energy and Utility Board, 2007. Pipeline Performance in Alberta, 1990–2005 Alberta, Canada: Alberta Energy and Utility Board. [accessed 2022 Oct 1]. https://static.aer.ca/prd/documents/reports/r2007-A.pdf.

AH Alberta Health, 2020. Odor Thresholds in Emergency Management: A jurisdictional Review [accessed 2022 Oct 1]. https://open.alberta.ca/publications/9781460147368.

AIHA American Industrial Hygiene Association, 1991. Emergency Response Planning Guidelines for Hydrogen Sulfide Akron, OH: AIHA Press. [accessed 2022 Oct 1]. https://www.aiha.org/get-involved/aiha-guideline-foundation/erpgs.

Al-Batanony MA, El-Shafie MK, 2011. Work-related health effects among wastewater treatment plants workers. Int. J. Occup. Environ. Med 2, 237–244. [PubMed: 23022842]

Environment Alberta, 2004. Assessment Report on Reduced Sulphur Compounds for Developing and Ambient Air Quality Objectives. Alberta, Canada: Alberta Environment. [accessed 2022 Oct 1]. https://open.alberta.ca/publications/0778532062.

Almeida AF, Guidotti TL, 1999. Differential sensitivity of lung and brain to sulfide exposure: A peripheral mechanism for apnea. Toxicol. Sci 50, 287–293. [PubMed: 10478866]

Amaral AFS, Rodrigues AS, 2007. Chronic exposure to volcanic environments and chronic bronchitis incidence in the Azores, Portugal. Environ. Res 103, 419–423. [PubMed: 16916511]

Ammann HM, 1986. A new look at physiologic respiratory response to H_2S poisoning. J. Hazard. Mater 13, 369–374.

Amoore JE, 1985. The Perception of Hydrogen Sulfide Odor in Relation to Setting an Ambient Standard. Prepared for California Air Resources Board ARB Contract A4-046-33. [accessed 2022 Oct 1]. http://www.arb.ca.gov/research/apr/past/a4-046-33.pdf.

Amoore JE, Hautala E, 1983. Odor as an ald to chemical safety: Odor thresholds compared with threshold limit values and volatilities for 214 industrial chemicals in air and water dilution. J. Appl. Toxicol 3, 272–290. [PubMed: 6376602]

Armstrong SR, Ames MR, Green LC, 2004. Is ambient hydrogen sulfide a risk to human health? Presented at the WEF/A&WMA Odors and Air Emissions Conference, April 2004. [accessed 2022 Oct 1]. http://cambridgeenvironmental.com/blog/wp-content/uploads/2011/11/Hydrogen%20Sulfide%20Ambient%20Air%20Health%20Risk.pdf.

Aslami H, Schultz M, Juffermans N, 2009. Potential Applications of Hydrogen Sulfide-Induced Suspended Animation. Curr. Med. Chem 16, 1295–1303. [PubMed: 19355886]

ATSDR Agency for Toxic Substances and Disease Registry, 2016. Toxicological Profile for Hydrogen Sulfide and Carbonyl Sulfide Atlanta, GA: Agency for Toxic Substances and Disease Registry. [accessed 2022 Oct 1]. https://www.atsdr.cdc.gov/toxprofiles/tp114.pdf.

ATSDR Agency for Toxic Substances and Disease Registry, 2006. Toxicological Profile for Hydrogen Sulfide Atlanta, GA: Agency for Toxic Substances and Disease Registry. [accessed 2022 Oct 1]. http://www.atsdr.cdc.gov/toxprofiles/index.asp.

ATSDR Agency for Toxic Substances and Disease Registry, 2002. Hazardous Substances Emergency Events Surveillance Database Atlanta, GA: Agency for Toxic Substances and Disease Registry. [accessed 2022 Oct 1]. https://www.atsdr.cdc.gov/hs/hsees/public_use_file.html.

ATSDR Agency for Toxic Substances and Disease Registry, 1997. Exposure Investigation for Dakota City/South Sioux City: Hydrogen sulfide in Ambient Air Atlanta, GA: Agency for Toxic Substances and Disease Registry. [accessed 2022 Oct 1]. http://www.atsdr.cdc.gov/HAC/PHA/dakcity/dak_toc.html.

Attene-Ramos MS, Wagner ED, Gaskins HR, Plewa MJ, 2007. Hydrogen sulfide induces direct radical-associated DNA damage. Mol. Cancer Res 5, 455–459. [PubMed: 17475672]

Austigard ÅD, Svendsen K, Heldal KK, 2018. Hydrogen sulphide exposure in waste water treatment. J. Occup. Med. Toxicol 13, 1–10. [PubMed: 29321805]

Avery RC, Wing S, Marshall SW, Schiffman SS, 2004. Odor from industrial hog farming operations and mucosal immune function in neighbors. Arch. Environ. Health 59, 101–108. [PubMed: 16075904]

Bardana EJ, 1999. Reactive airways dysfunction syndrome (RADS): Guidelines for diagnosis and treatment and insight into likely prognosis. Ann. Allergy, Asthma Immunol 83, 583–586. [PubMed: 10619325]

Bates MN, Garrett N, Crane J, Balmes JR, 2013. Associations of ambient hydrogen sulfide exposure with self-reported asthma and asthma symptoms. Environ. Res 122, 81–87. [PubMed: 23453847]

Bates MN, Garrett N, Graham B, Read D, 1998. Cancer incidence, morbidity and geothermal air pollution in Rotorua, New Zealand. Int. J. Epidemiol 27, 10–14. [PubMed: 9563687]

Bates MN, Garrett N, Graham B, Read D, 1997. Air pollution and mortality in the Rotorua geothermal area. Aust. N. Z. J. Public Health 21, 581–586. [PubMed: 9470262]

Bates MN, Garrett N, Shoemack P, 2002. Investigation of Health Effects of Hydrogen Sulfide from a Geothermal Source. Arch. Environ. Health 57, 405–411. [PubMed: 12641180]

Baxter PJ, Baubron J-C, Coutinho R, 1999. Health hazards and disaster potential of ground gas emissions at Furnas volcano, São Miguel, Azores. J. Volcanol. Geotherm. Res 92, 95–106.

Beauchamp RO, Bus JS, Popp JA, Boreiko CJ, Andjelkovich DA, Leber P, 1984. A critical review of the literature on hydrogen sulfide toxicity. Crit. Rev. Toxicol 13, 25–97. [PubMed: 6378532]

Bechtel D, Waldner C, Wickstrom M, 2009. Associations between immune function in yearling beef cattle and airborne emissions of sulfur dioxide, hydrogen sulfide, and VOCs from oil and natural gas facilities. Arch. Environ. Occup. Heal 64, 73–86.

Bhagavan NV, 2002. Medical Biochemistry, 4th ed. London: Academic Press. [accessed 2022 Oct 1]. https://www.elsevier.com/books/medical-biochemistry/bhagavan/978-0-12-095440-7.

Bhambhani Y, Burnham R, Snydmiller G, MacLean I, Martin T, 1996. Effects of 5 ppm Hydrogen Sulfide Inhalation on Biochemical Properties of Skeletal Muscle in Exercising Men and Women. Am. Ind. Hyg. Assoc. J 57, 464–468. [PubMed: 8638517]

Bhambhani Y, Singh M, 1991. Physiological effects of hydrogen sulfide inhalation during exercise in healthy men. J. Appl. Physiol 71, 1872–1877. [PubMed: 1761485]

Blackstone E, Morrison M, Roth MB, 2005. H_2S Induces a Suspended Animation-Like State in Mice. Science 308, 518. [PubMed: 15845845]

Blanes-vidal V, Hansen MN, Adamsen APS, Feilberg A, Petersen SO, Jensen BB, 2009. Characterization of odor released during handling of swine slurry : Part I. Relationship between odorants and perceived odor concentrations. Atmos. Environ 43, 2997–3005.

Brancher M, Griffiths KD, Franco D, de Melo Lisboa H, 2017. A review of odour impact criteria in selected countries around the world. Chemosphere 168, 1531–1570. [PubMed: 27939667]

Brenneman KA, James RA, Gross EA, Dorman DC, 2000. Olfactory neuron loss in adult male cd rats following subchronic inhalation exposure to hydrogen sulfide. Toxicol. Pathol 28, 326–333. [PubMed: 10805151]

Bullers S, 2005. Environmental stressors, perceived control, and health: The case of residents near large-scale hog farms in Eastern North Carolina. Hum. Ecol 33, 1–16.

Bustaffa E, Cori L, Manzella A, Nuvolone D, Minichilli F, Bianchi F, Gorini F, 2020. The health of communities living in proximity of geothermal plants generating heat and electricity: A review. Sci. Total Environ 706, 135998. [PubMed: 31862594]

Campagna D, Kathman SJ, Pierson R, Inserra SG, Phifer BL, Middleton DC, Zarus GM, White MC, 2004. Ambient hydrogen sulfide, total reduced sulfur, and hospital visits for respiratory diseases in northeast Nebraska, 1998–2000. J. Expo. Anal. Environ. Epidemiol 14, 180–187. [PubMed: 15014549]

Cantox Environmental, 2009. ERCBH2S: A Model for Calculating Emergency Response and Planning Zones for Sour Gas Facilities. Vol. 2: Emergency Response Planning Endpoints [accessed 2022 Oct 1]. https://static.aer.ca/prd/documents/directives/ERCBH2S_VOLUME_2.pdf.

Carlsen HK, Zoëga H, Valdimarsdóttir U, Gíslason T, Hrafnkelsson B, 2012. Hydrogen sulfide and particle matter levels associated with increased dispensing of anti-asthma drugs in Iceland's capital. Environ. Res 113, 33–39. [PubMed: 22264878]

Carroll RJ, Ruppert D, Stefanski LA, Crainiceanu CM, 2006. Measurement error in nonlinear models: a modern perspective. 2nd ed. Boca Raton, Florida: Chapman and Hall/CRC [accessed 2022 Oct 1]. 10.1201/9781420010138.

Cavender F, Phillips S, Holland M, 2008. Development of Emergency Response Planning Guidelines (ERPGs). J. Med. Toxicol 4, 127–131. [PubMed: 18570174]

CDC Centers for Disease Control and Prevention, 1993. Fatalities attributed to entering manure waste pits, Minnesota, 1992. JAMA 269, 3098–3102. [accessed 2022 Oct 1]. https://www.cdc.gov/mmwr/preview/mmwrhtml/00020468.htm. [PubMed: 8505805]

Chastain JP, Henry S, 2002. Chepter 4: Management of lagoons and storage structures for swine manure. Clemson Univerisity. In Cooperative Extension. In Livestock and forage. In CAMM, In swine training manual [accessed 2022 Oct 1]. https://www.clemson.edu/extension/camm/manuals/swine/sch4_03.pdf.

CIIT Chemical Industry Institute of Toxicology, 1983. 90-Day vapor inhalation toxicity study of hydrogen sulfide in B6C3F1 mice. EPA/OTS 0883–0255. Chemical Industry Institute of Toxicology, Research Triangle Park, NC. [accessed 2022 Oct 1]. http://www.ciit.org/AboutCIIT/About.

Collins J, Lewis D, 2000. Hydrogen sulfide: evaluation of current California air quality standards with respect to protection of children, Air Toxicology and Epidemiology Section, California Office of Environmental Health Hazard Assessment., Air Toxicology and Epidemiology Section, California Office of Environmental Health Hazard Assessment [accessed 2022 Oct 1]. https://www.arborhillsmonitoring.com/References/REF_CAL-EPA%20OEHHA%202000.pdf.

Colón J, Alvarez C, Vinot M, Lafuente FJ, Ponsá S, Sánchez A, Gabriel D, 2017. Characterization of odorous compounds and odor load in indoor air of modern complex MBT facilities. Chem. Eng. J 313, 1311–1319.

Costigan MG, 2003. Hydrogen sulfide: UK occupational exposure limits. Occup. Environ. Med 60, 918–928. [PubMed: 14634182]

DECOS Dutch Expert Committee on Occupational Standards, 2010. Health Council of the Netherlands. Presentation of Advisory Letter: Comparison of Recommended Exposure Limits for Hydrogen Sulphide [accessed 2023 Mar 28]. https://www.healthcouncil.nl/documents/advisory-reports/2010/07/15/comparison-of-recommended-exposure-limits-for-hydrogen-sulphide.

DECOS Dutch Expert Committee on Occupational Standards, 2006. Health Council of the Netherlands, Hydrogen Sulphide. Health-Based Recommended Occupational Exposure Limit in The Netherlands [accessed 2023 Mar 28]. http://werkgroepterlinden.be/H2SC.pdf.

Dominici F, Peng RD, Barr CD, Bell ML, 2010. Protecting human health from air pollution: Shifting from a single-pollutant to a multipollutant approach. Epidemiology 21, 187–194. [PubMed: 20160561]

Donham KJ, 2010. Community and occupational health concerns in pork production: a review. J. Anim. Sci 88, 102–111. [PubMed: 19820064]

Donham KJ, Knapp LW, Monson R, Kim Gustafson, 1982. Acute toxic exposure to gases from liquid manure. J. Occup. Med 24, 142–145. [PubMed: 7057283]

Donham KJ, Lee JA, Thu K, Reynolds SJ, 2006. Assessment of air quality at neighbor residences in the vicinity of swine production facilities. J. Agromedicine 11, 15–24. [PubMed: 19274894]

Donham KJ, Wing S, Osterberg D, Flora JL, Hodne C, Thu KM, Thorne PS, 2007. Community health and socioeconomic issues surrounding concentrated animal feeding operations. Environ. Health Perspect 115, 317–320. [PubMed: 17384786]

Dorman DC, Struve MF, Gross EA, Brenneman KA, 2004. Respiratory tract toxicity of inhaled hydrogen sulfide in Fischer-344 rats, Sprague-Dawley rats, and B6C3F1 mice following subchronic (90-day) exposure. Toxicol. Appl. Pharmacol 198, 29–39. [PubMed: 15207646]

Drewnoski ME, Richter EL, Hansen SL, 2012. Dietary sulfur concentration affects rumen hydrogen sulfide concentrations in feed-lot steers during transition and finishing. J. Anim. Sci 90, 4478–4486. [PubMed: 23255818]

Drimal M, Koppová K, Klöslová Z, Fabiánová E, 2010. Environmental exposure to hydrogen sulfide in central Slovakia (Ružomberok area) in context of health risk assessment. Cent. Eur. J. Public Health 18, 224–229. [PubMed: 21361108]

Dubyk ST, Mustafa S, 2002. Trip Report: H2S Survey, March 18–22, 2002. State of New Mexico: Environment Department 38 [accessed 2022 Oct 1]. https://www.env.nm.gov/air-quality/.

Durand M, Scott BJ, 2005. Geothermal ground gas emissions and indoor air pollution in Rotorua, New Zealand. Sci. Total Environ 345, 69–80. [PubMed: 15919529]

Durand M, Weinstein P, 2007. Thiosulfate in human urine following minor exposure to hydrogen sulfide: Implications for forensic analysis of poisoning. Forensic Toxicol 25, 92–95.

Durand M, Wilson JG, 2006. Spatial analysis of respiratory disease on an urbanized geothermal field. Environ. Res 101, 238–245. [PubMed: 16169550]

Eduard W, Pearce N, Douwes J, 2009. Chronic bronchitis, COPD, and lung function in farmers: The role of biological agents. Chest 136, 716–725. [PubMed: 19318669]

Elovaara E, Tossavainen A, Savolainen H, 1978. Effects of subclinical hydrogen sulfide intoxication on mouse brain protein metabolism. Exp. Neurol 62, 93–98. [PubMed: 729679]

Ensabella F, Spirito A, Duprè S, Leoni V, Schinina ME, Strinati F, Amiconi G, 2004. Measurement of sulfhemoglobin (S-Hb) blood levels to determine individual hydrogen sulfide exposure in thermal baths in Italy. Ig. Sanita. Pubbl 60, 201–217. [PubMed: 15583709]

EPA United States Environmental Protection Agency, 2020. Toxics Release Inventory (TRI) Program National Analysis: Releases of Chemicals [accessed 2022 Oct 1]. https://www.epa.gov/toxics-release-inventory-tri-program.

EPA United States Environmental Protection Agency, 2017. Final Report of the Integrated Science Assessment (ISA) for Sulfur Oxides – Health Criteria EPA/600/R-17/451. [accessed 2022 Oct 1]. https://www.epa.gov/isa/integrated-science-assessment-isa-sulfur-oxides-health-criteria.

EPA United States Environmental Protection Agency, 2016. Hydrogen Sulfide Monitoring on the Gulf Coastline. Web Archive [accessed 2022 Oct 1]. https://archive.epa.gov/emergency/bpspill/web/html/h2s.html.

EPA United States Environmental Protection Agency, 2012. National Ambient Air Quality Standards (NAAQS) for Particulate Matter (PM): Proposed Rule, 40 CFR Parts 50, 51, 52, 53 and 58 [accessed 2022 Oct 1]. https://www.epa.gov/pm-pollution/2012-national-ambient-air-quality-standards-naaqs-particulate-matter-pm.

EPA United States Environmental Protection Agency, 2011. Hydrogen Sulfide: Community Right to Know Toxic Chemical Release Reporting. 40 CFR Part 372, U.S. Environmental Protection Agency, Federal Register, 76. [accessed 2022 Oct 1]. https://www.govinfo.gov/content/pkg/FR-2011-10-17/pdf/2011-23534.pdf.

EPA United States Environmental Protection Agency, 2010a. Hydrogen Sulfide: Community Right to Know Toxic Chemical Release Reporting. 40 CFR Part 372, U.S. Environmental Protection Agency, Federal Register, 75. [accessed 2022 Oct 1]. https://www.govinfo.gov/content/pkg/FR-2010-02-26/pdf/2010-4084.pdf.

EPA United States Environmental Protection Agency, 2010b. Sulfur Dioxide (2010) Designated Area/State Information. Green Book [accessed 2022 Oct 1]. https://www.epa.gov/green-book/green-book-sulfur-dioxide-2010-area-information.

EPA United States Environmental Protection Agency, 2005. Guidelines for Carcinogen Risk Assessment EPA/630/P-03/001B. [accessed 2022 Oct 1]. https://www.epa.gov/sites/default/files/2013-09/documents/cancer_guidelines_final_3-25-05.pdf.

EPA United States Environmental Protection Agency, 2003. Toxicological Review of Hydrogen Sulfide in Support of Summary Information on the Integrated Risk Information System (IRIS) EPA/635/R-03/005. [accessed 2022 Oct 1]. https://iris.epa.gov/static/pdfs/0061tr.pdf.

EPA United States Environmental Protection Agency, 1993a. Report to Congress on Hydrogen Sulfide Air Emissions Associated with the Extraction of Oil and Natural Gas [accessed 2023 May 31]. https://www.energyindepth.org/wp-content/uploads/2011/03/EPA-H2S-Oil-and-Gas-Study-10-93.pdf.

EPA United States Environmental Protection Agency, 1993b. Health Assessment Document for Hydrogen Sulfide EPA/600/8–86/026F. Research Triangle Park, NC:. [accessed 2022 Oct 1]. https://nepis.epa.gov/Exe/ZyPDF.cgi/30001FYP.PDF?Dockey=30001FYP.pdf.

EPA United States Environmental Protection Agency, 1989. Glossary of Terms Related to Health, Exposure, and Risk Assessment. EPA/450/3–88/016. Washington, DC: U.S. Environmental Protection Agency, Air Risk Information Support Center. [accessed 2022 Oct 1]. https://nepis.epa.gov/Exe/ZyPDF.cgi/00002F5S.PDF?Dockey=00002F5S.pdf.

Farahat SA, Kishk NA, 2010. Cognitive functions changes among Egyptian sewage network workers. Toxicol. Ind. Health 26, 229–238. [PubMed: 20237195]

Fiedler N, Kipen H, Ohman-Strickland P, Zhang J, Weisel C, Laumbach R, Kelly-McNeil K, Olejeme K, Lioy P, 2008. Sensory and cognitive effects of acute exposure to hydrogen sulfide. Environ. Health Perspect 116, 78–85. [PubMed: 18197303]

Finnbjornsdottir RG, Carlsen HK, Thorsteinsson T, Oudin A, Lund SH, Gislason T, Rafnsson V, 2016. Association between daily hydrogen sulfide exposure and incidence of emergency hospital visits: A population-based study. PLoS One 11, 1–19.

Fisher GW, 1999. Natural levels of hydrogen sulphide in New Zealand. Atmos. Environ 33, 3078–3079.

FNBH Finnish National Board of Health, 1982. Valkeankosken ilma ja terveys. Epidemiologinen tutkimus yhdyskuntailman ja terveyden välisistä suhteista rekistereistä saatavien tietojen valossa [Ambient air and health status in Valkeankoski]. Helsinki, Government Printing Centre [accessed 2022 Oct 1]. https://nepis.epa.gov/Exe/ZyPDF.cgi/00002F5S.PDF?Dockey=00002F5S.pdf.

Fuller DC, Suruda AJ, 2000. Occupationally Related Hydrogen Sulfide Deaths in the United States From 1984 to 1994. J. Occup. Environ. Med 42, 939–942. [PubMed: 10998771]

Ganguly R, Batterman S, Isakov V, Snyder M, Breen M, Brakefield-Caldwell W, 2015. Effect of geocoding errors on traffic-related air pollutant exposure and concentration estimates. J. Expo. Sci. Environ. Epidemiol 25, 490–498. [PubMed: 25670023]

Gharahbaghian L, Massoudian B, Dimassa G, 2009. Methemoglobinemia and sulfhemoglobinemia in two pediatric patients after ingestion of hydroxylamine sulfate. West. J. Emerg. Med 10, 197–201. [PubMed: 19718385]

Glass DC, 1990. A review of the health effects of hydrogen sulphide exposure. Ann. Occup. Hyg 34, 323. [PubMed: 2196846]

Götschi T, Heinrich J, Sunyer J, Künzli N, 2008. Long-term effects of ambient air pollution on lung function: A review. Epidemiology 19, 690–701. [PubMed: 18703932]

Grant RH, Boehm MT, Lawrence AJ, Heber AJ, 2013. Hydrogen Sulfide Emissions from Sow Farm Lagoons across Climates Zones. J. Environ. Qual 42, 1674–1683. [PubMed: 25602408]

Greenbaum D, Shaikh R, 2010. First steps toward multipollutant science for air quality decisions. Epidemiology 21, 195–197. [PubMed: 20160562]

Guidotti T, 2009. The western Canada study: Effective management of a high-profile study of risk. Arch. Environ. Occup. Heal 64, 3–5.

Guidotti TL, 2010. Hydrogen sulfide: Advances in understanding human toxicity. Int. J. Toxicol 29, 569–581. [PubMed: 21076123]

Guidotti TL, 1996. Hydrogen sulfide. Occup. Med 46, 367–371.

Haahtela T, Marttila O, Vikka V, Jappinen P, Jaakkola JJK, 1992. The South Karelia air pollution study: Acute health effects of malodorous sulfur air pollutants released by a pulp mill. Am. J. Public Health 82, 603–605. [PubMed: 1546787]

Haider SS, Hasan M, Islam F, 1980. Effect of air pollutant hydrogen sulfide on the levels of total lipids, phospholipids & cholesterol in different regions of the guineapig brain. Indian J. Exp. Biol 18, 418–420. [PubMed: 7399614]

Häkkinen AJ, Jokinen J, Kauppinen H, 1985. Imatran ilman rikkidioksidin ja keskeisten hajurikkiyhdisteiden pitoisuustasot sekä alueen havupuuvauriot. Ilmatieteen laitos. [Concentration levels of sulfur dioxide and main odorous sulfur compounds in Imatra, and damage to the coniferous trees of the area] Helsinki, Finland: Meteorological Institute. [accessed 2022 Oct 1]. https://en.ilmatieteenlaitos.fi/.

Hansell A, Oppenheimer C, 2004. Health Hazards from Volcanic Gases: A Systematic Literature Review. Arch. Environ. Health 59, 628–639. [PubMed: 16789471]

Hayden LJ, Goeden H, Roth SH, 1990. Growth and development in the rat during sub-chronic exposure to low levels of hydrogen sulfide. Toxicol. Ind. Health 6, 389–401. [PubMed: 2237925]

Heaney CD, Wing S, Campbell RL, Caldwell D, Hopkins B, Richardson D, Yeatts K, 2011. Relation between malodor, ambient hydrogen sulfide, and health in a community bordering a landfill. Environ. Res 111, 847–852. [PubMed: 21679938]

Heederik D, Sigsgaard T, Thorne PS, Kline JN, Avery R, Bønløkke JH, Chrischilles EA, Dosman JA, Duchaine C, Kirkhorn SR, Kulhankova K, Merchant JA, 2007. Health effects of airborne exposures from concentrated animal feeding operations. Environ. Health Perspect 115, 298–302. [PubMed: 17384782]

Heldal KK, Austigard ÅD, Svendsen KH, Einarsdottir E, Goffeng LO, Sikkeland LI, Nordby KC, 2019. Endotoxin and Hydrogen Sulphide Exposure and Effects on the Airways among Waste Water Workers in Sewage Treatment Plants and Sewer Net System. Ann. Work Expo. Heal 63, 437–447.

Higashi TM, Kazuyuki T, Toyama N, Sakurai HT, Medicine P, Health P, August R, 1983. School of Medicine, Keio University, 35 281–292.

Hirsch AR, 2002. Hydrogen sulfide exposure without loss of consciousness: Chronic effects in four cases. Toxicol. Ind. Health 18, 51–61. [PubMed: 12868793]

Ho C-FH, Jolis D, Tansel B, 2008. Gaseous Emissions from Wastewater Facilities. Water Environ. Res 80, 1262–1280.

Horton R, 2007. Malodor from industrial hog operations, stress, negative mood, and secretory immune function nearby residents Chapel Hill, NC: University of North Carolina-Chapel Hill. [accessed 2022 Oct 1]. https://core.ac.uk/reader/210598950.

Horton RA, Wing S, Marshall SW, Brownley KA, 2009. Malodor as a trigger of stress and negative mood in neighbors of industrial hog operations. Am. J. Public Health 99 Suppl 3, 610–615.

Horwell CJ, Patterson JE, Gamble JA, Allen AG, 2005. Monitoring and mapping of hydrogen sulphide emissions across an active geothermal field: Rotorua, New Zealand. J. Volcanol. Geotherm. Res 139, 259–269.

Huang YL, Batterman S, 2000. Residence location as a measure of environmental exposure: A review of air pollution epidemiology studies. J. Expo. Anal. Environ. Epidemiol 10, 66–85. [PubMed: 10703849]

Inserra S, Phifer B, Pierson R, Campagna D, 2002. Community-based exposure estimate for hydrogen sulfide. J. Expo. Anal. Environ. Epidemiol 12, 124–129. [PubMed: 11965529]

Inserra SG, Phifer BL, Anger WK, Lewin M, Hilsdon R, White MC, 2004. Neurobehavioral evaluation for a community with chronic exposure to hydrogen sulfide gas. Environ. Res 95, 53–61. [PubMed: 15068930]

Jaakkola JJ, Vilkka V, Marttila O, Jäppinen P, Haahtela T, 1990. The South Karelia Air Pollution Study: the effects of malodorous sulfur compounds from pulp mills on respiratory and other symptoms. Am. Rev. Resp. Dis 142, 1344–1350. [PubMed: 2252252]

Jappinen P, Vilkka V, Marttila O, Haahtela T, 1990. Exposure to hydrogen sulphide and respiratory function. Br. J. Ind. Med 47, 824–828. [PubMed: 2271389]

Kangas J, Jäppinen P, Savolainen H, 1984. Exposure to hydrogen sulphide, mercaptans and sulphur dioxide in pulp industry. Am. Ind. Hyg. Assoc. J 45, 787–790. [PubMed: 6517022]

Khan AA, Yong S, Prior MG, Lillie LE, 1991. Cytotoxic effects of hydrogen sulfide on pulmonary alveolar macrophages in rats. J. Toxicol. Environ. Health 33, 57–64. [PubMed: 2033644]

Kilburn KH, 2012. Human impairment from living near confined animal (Hog) feeding operations. J. Environ. Public Health 2012, 565690. [PubMed: 22496706]

Kilburn KH, 2003. Effects of hydrogen sulfide on neurobehavioral function. South. Med. J 96, 639–646. [PubMed: 12940311]

Kilburn KH, 1999. Evaluating health effects from exposure to hydrogen sulfide: central nervous system dysfunction. Environ. Epidemiol. Toxicol 1, 207–216.

Kilburn KH, 1997. Exposure to reduced sulfur gases impairs neurobehavioral function. South. Med. J 90, 997–1006. [PubMed: 9347810]

Kilburn KH, 1993. Case report: profound neurobehavioral deficit in an oil field worker overcome by hydrogen sulfide. Am. J. Med. Sci 306, 301–305. [PubMed: 8238084]

Kilburn KH, Thrasher JD, Gray MR, 2010. Low-level hydrogen sulfide and central nervous system dysfunction. Toxicol. Ind. Health 26, 387–405. [PubMed: 20504829]

Kilburn KH, Warshaw RH, 1995. Hydrogen sulfide and reduced-sulfur gases adversely affect neurophysiological functions. Toxicol. Ind. Health 11, 185–197. [PubMed: 7491634]

Kioumourtzoglou MA, Spiegelman D, Szpiro AA, Sheppard L, Kaufman JD, Yanosky JD, Williams R, Laden F, Hong B, Suh H, 2014. Exposure measurement error in PM2.5 health effects studies: A pooled analysis of eight personal exposure validation studies. Environ. Heal. A Glob. Access Sci. Source 13, 1–11.

Knight LD, Presnell SE, 2005. Death by sewer gas: Case report of a double fatality and review of the literature. Am. J. Forensic Med. Pathol 26, 181–185. [PubMed: 15894856]

Ko JH, Xu Q, Jang YC, 2015. Emissions and Control of Hydrogen Sulfide at Landfills: A Review. Crit. Rev. Environ. Sci. Technol 45, 2043–2083.

Korhonen K, Liukkonen T, Ahrens W, Astrakianakis G, Boffetta P, Burdorf A, Heederik D, Kauppinen T, Kogevinas M, Osvoll P, Rix BA, Saalo A, Sunyer J, Szadkowska-Stanczyk I, Teschke K, Westberg H, Widerkiewicz K, 2004. Occupational exposure to chemical agents in the paper industry. Int. Arch. Occup. Environ. Health 77, 451–460. [PubMed: 15368059]

Kristbjornsdottir A, Rafnsson V, 2012. Incidence of cancer among residents of high temperature geothermal areas in Iceland: A census based study 1981 to 2010. Environ. Heal. A Glob. Access Sci. Source 11, 1–12.

Kumar S, 2011. Occupational, environmental and lifestyle factors associated with spontaneous abortion. Reprod. Sci 18, 915–930. [PubMed: 21960507]

Kurzban GP, Chu L, Ebersole JL, Holt SC, 1999. Sulfhemoglobin formation in human erythrocytes by cystalysin, an L-cysteine desulfhydrase from Treponema denticola. Oral Microbiol. Immunol 14, 153–164. [PubMed: 10495709]

Lambert TW, Goodwin VM, Stefani D, Strosher L, 2006. Hydrogen sulfide (H2S) and sour gas effects on the eye. A historical perspective. Sci. Total Environ 367, 1–22. [PubMed: 16650463]

Lee JA, Thorne PS, Reynolds SJ, O'Shaughnessy PT, 2007. Monitoring risks in association with exposure levels among wastewater treatment plant workers. J. Occup. Environ. Med 49, 1235–1248. [PubMed: 17993928]

Legator MS, Morris DL, Philips DL, Singleton CR, 2001. Health Effects from Chronic Low-Level Exposure to Hydrogen Sulfide. Arch. Environ. Health 56, 123–131. [PubMed: 11339675]

Leifer I, Melton C, Tratt DM, Buckland KN, Chang CS, Clarisse L, Franklin M, Hall JL, Brian Leen J, Lundquist T, Van Damme M, Vigil S, Whitburn S, 2020. Estimating exposure to hydrogen sulfide from animal husbandry operations using satellite ammonia as a proxy: Methodology demonstration. Sci. Total Environ 709, 134508. [PubMed: 31927425]

Lewis RJ, Schnatter AR, Drummond I, Murray N, Thompson FS, Katz AM, Jorgensen G, Nicolich MJ, Dahlman D, Theriault G, 2003. Mortality and cancer morbidity in a cohort of Canadian petroleum workers. Occup. Environ. Med 60, 918–929. [PubMed: 14634182]

Lewis RJ, Copley GB, 2015. Chronic low-level hydrogen sulfide exposure and potential effects on human health: A review of the epidemiological evidence. Crit. Rev. Toxicol 45, 93–123. [PubMed: 25430508]

Lewkowska P, Cieślik B, Dymerski T, Konieczka P, Namieśnik J, 2016. Characteristics of odors emitted from municipal wastewater treatment plant and methods for their identification and deodorization techniques. Environ. Res 151, 573–586. [PubMed: 27591529]

Lim E, Mbowe O, Lee ASW, Davis J, 2016. Effect of environmental exposure to hydrogen sulfide on central nervous system and respiratory function: a systematic review of human studies. Int. J. Occup. Environ. Health 22, 80–90. [PubMed: 27128692]

Lindvall T, 1970. On sensory evaluation of odorous air pollutant intensities. Measurements of odor intensity in the laboratory and in the field, with special reference to effluents of sulfate pulp factories. Nord. Hyg. Tidskr 51, 36–39.

Lipfert FW, Wyzga RE, 2008. On exposure and response relationships for health effects associated with exposure to vehicular traffic. J. Expo. Sci. Environ. Epidemiol 18, 588–599. [PubMed: 18322450]

Lococo KH, Staplin L, Schultz MW, 2018. The effects of medical conditions on driving performance: A literature review and synthesis Report No. DOT HS 812 526. Washington, DC: National Highway Traffic Safety Administration. [accessed 2022 Oct 1]. https://rosap.ntl.bts.gov/view/dot/38687.

Logue JN, Ramaswamy K, Hersh JH, 2001. Investigation of illness associated with exposure to hydrogen sulfide among Pennsylvania school students. J. Environ. Heal 63, 9–13.

Lusk JD, Kraft WA, 2010. Hydrogen Sulfide Monitoring Near Oil and Gas Production Facilities in Southeastern New Mexico and Potential Effects of Hydrogen Sulfide to Migratory Birds and Other Wildlife Albuquerque NM: U.S. Fish & Wildlife Service, New Mexico Ecological Services and Field Offices. Project identifier FFS 2, F41–200220006.

Ma X, Zheng G, Liang M, Xie D, Martinelli G, Sajjad W, Xu W, Fan Q, Li L, Du L, Zhao Y, 2019. Occurrence and origin of H_2S from volcanic reservoirs in niudong area of the Santanghu Basin, NW China. Geofluids 2019.

MacEwen JD, Vernot EH, 1972. Toxic Hazards Research Unit Annual Technical Report: 1972. AMRL-TR-72-62 Wright-Patterson AFB, OH: Aerospace Medical Research Laboratory. [accessed 2022 Oct 1]. https://apps.dtic.mil/sti/citations/AD0755358.

Marttila O, Jaakkola JJK, Partti-Pellinen K, Vilkka V, Haahtela T, 1995. South Karelia air pollution study: Daily symptom intensity in relation to exposure levels of malodorous sulfur compounds from pulp mills. Environ. Res 71, 122–127. [PubMed: 8977620]

Marttila O, Jaakkola JJK, Vilkka V, Jäppinen P, Haahtela T, 1994. The south karelia air pollution study: The effects of malodorous sulfur compounds from pulp mills on respiratory and other symptoms in children. Environ. Res 66, 152–159. [PubMed: 8055837]

Mauderly JL, Burnett RT, Castillejos M, Özkaynak H, Samet JM, Stieb DM, Vedal S, Wyzga RE, 2010. Is the air pollution health research community prepared to support a multipollutant air quality management framework. Inhal. Toxicol 22, 1–19.

MDHHS Michigan Department of Health and Human Services, 2023. Evaluation of Reduced Sulfur Compounds (RSCs) and Volatile Organic Compounds (VOCs) in Communities Near Graphic Packaging International, LLC. and Kalamazoo Water Reclamation Plant [accessed 2023 May 31]. https://www.michigan.gov/mdhhs/-/media/Project/Websites/mdhhs/Safety-and-Injury-Prevention/Environmental-Health/Health-Assessments/Documents/Kalamazoo-Air-Quality-Health-Consultation.pdf.

Merchant JA, Naleway AL, Svendsen ER, Kelly KM, Burmeister LF, Stromquist AM, Taylor CD, Thorne PS, Reynolds SJ, Sanderson WT, Chrischilles EA, 2005. Asthma and farm exposures in a cohort of rural Iowa children. Environ. Health Perspect 113, 350–356. [PubMed: 15743727]

Milby TH, Baselt RC, 1999. Hydrogen sulfide poisoning: Clarification of some controversial issues. Am. J. Ind. Med 35, 192–195. [PubMed: 9894543]

Mirabelli MC, Wing S, 2006. Proximity to pulp and paper mills and wheezing symptoms among adolescents in North Carolina. Environ. Res 102, 96–100. [PubMed: 16457803]

Mirabelli MC, Wing S, Marshall SW, Wilcosky TC, 2006a. Asthma symptoms among adolescents who attend public schools that are located near confined swine feeding operations. Pediatrics 118, 66–75.

Mirabelli MC, Wing S, Marshall SW, Wilcosky TC, 2006b. Race, poverty, and potential exposure of middle-school students to air emissions from confined swine feeding operations. Environ. Health Perspect 114, 591–596. [PubMed: 16581551]

Morii D, Miyagatani Y, Nakamae N, Murao M, Taniyama K, 2010. Japanese experience of hydrogen sulfide: The suicide craze in 2008. J. Occup. Med. Toxicol 5, 2–4. [PubMed: 20925908]

Morris J, 1997. The Brimstone Battles; Lost Opportunity; EPA Had Its Chance to Regulate Hydrogen Sulfide. The Houston Chronicle, November 9. [accessed 2022 Oct 1]. http://www.chron.com/chronicle/nationa/h2s/lostop.html.

Mousa HAL, 2015. Short-term effects of subchronic low-level hydrogen sulfide exposure on oil field workers. Environ. Health Prev. Med 20, 12–17. [PubMed: 25315268]

NIOSH National Institute for Occupational Safety and Health, 1978. Occupational Health Guideline for Hydrogen Sulfide Washington, DC: National Institute for Occupational Safety and Health. [accessed 2022 Oct 1]. https://www.cdc.gov/niosh/docs/81-123/pdfs/0337.pdf.

Niu ZG, Xu SY, Gong QC, 2014. Health risk assessment of odors emitted from urban wastewater pump stations in Tianjin, China. Environ. Sci. Pollut. Res 21, 10349–10360.

NRC National Research Council, 2003. Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs Washington, DC: The National Academies Press. [accessed 2022 Oct 1]. https://nap.nationalacademies.org/login.php?record_id=10586.

NRC National Research Council, 2001. Standing Operating Procedures for Developing Acute Exposure Guideline Levels for Hazardous Chemicals Washington, DC: The National Academies Press. [accessed 2022 Oct 1]. https://nap.nationalacademies.org/login.php?record_id=10122.

NRC National Research Council, 1979. Odors from Stationary and Mobile Sources Washington, DC: The National Academies Press. [accessed 2022 Oct 1]. https://nap.nationalacademies.org/login.php?record_id=19818.

Nunes MI, Kalinowski C, Godoi AFL, Gomes AP, Cerqueira M, 2021. Hydrogen sulfide levels in the ambient air of municipal solid waste management facilities: A case study in Portugal. Case Stud. Chem. Environ. Eng 4, 100152.

Nuvolone D, Petri D, Pepe P, Voller F, 2019. Health effects associated with chronic exposure to low-level hydrogen sulfide from geothermoelectric power plants. A residential cohort study in the geothermal area of Mt. Amiata in Tuscany. Sci. Total Environ 659, 973–982. [PubMed: 31096427]

OEHHA California Office of Environmental Health Hazard Assessment, 2008. Acute toxicity Summary: TSD for Noncancer RELs: Hydrogen Sulfide Sacramento, CA: Office of Environmental Health Hazard Assessment. [accessed 2022 Oct 1]. https://oehha.ca.gov/air/air-toxics-hot-spots.

OEHHA California Office of Environmental Health Hazard Assessment, 2000. Determination of Noncancer Chronic Reference Exposure Levels: Chronic Toxicity Summary: Hydrogen Sulfide Sacramento, CA: Office of Environmental Health Hazard Assessment. [accessed 2022 Oct 1]. http://www.oehha.ca.gov/air/chronic_rels/index.html.

OEHHA California Office of Environmental Health Hazard Assessment, 1999. Determination of Acute Reference Exposure Levels for Airborne Toxicants Sacramento, CA: Office of Environmental Health Hazard Assessment, Air Toxicology and Epidemiology Section. [accessed 2022 Oct 1]. https://oehha.ca.gov/media/downloads/crnr/acuterel.pdf.

Olson KR, 2011. The therapeutic potential of hydrogen sulfide: Separating hype from hope. Am. J. Physiol. - Regul. Integr. Comp. Physiol 301, 297–312.

Partlo LA, Sainsbury RS, Roth SH, 2001. Effects of repeated hydrogen sulphide (H2S) exposure on learning and memory in the adult rat. Neurotoxicology 22, 177–189. [PubMed: 11405250]

Partti-Pellinen K, Marttila O, Vilkka V, Jaakkola JJK, Jäppinen P, Haahtela T, 1996. The south karelia air pollution study: Effects of low-level exposure to malodorous sulfur compounds on symptoms. Arch. Environ. Health 51, 315–320. [PubMed: 8757412]

Pavilonis BT, O'Shaughnessy PT, Altmaier R, Metwali N, Thorne PS, 2013. Passive monitors to measure hydrogen sulfide near concentrated animal feeding operations. Environ. Sci. Process. Impacts 15, 1271–1278. [PubMed: 23681048]

Polhemus DJ, Lefer DJ, 2014. Emergence of hydrogen sulfide as an endogenous gaseous signaling molecule in cardiovascular disease. Circ. Res 114, 730–737. [PubMed: 24526678]

Pope K, So YT, Crane J, Bates MN, 2017. Ambient geothermal hydrogen sulfide exposure and peripheral neuropathy. Neurotoxicology 60, 10–15. [PubMed: 28223159]

Qu K, Lee SW, Bian JS, Low CM, Wong PTH, 2008. Hydrogen sulfide: Neurochemistry and neurobiology. Neurochem. Int 52, 155–165. [PubMed: 17629356]

Radon K, Schulze A, van Strien R, Ehrenstein V, Praml G, Nowak D, 2005. Atemwegsgesundheit und Allergiestatus bei jungen Erwachsenen in ländlichen Regionen Niedersachsens [Respiratory health and allergy among young adults from rural areas of Lower Saxony], In: Proceedings of 50th Annual Meeting of the German Society for Medical Informatics, Biometrics and Epidemiology, Freiburg, Germany [accessed 2022 Oct 1]. https://www.thieme-connect.de/products/ejournals/html/10.1055/s-2005-915572.

Radon K, Schulze A, Ehrenstein V, Van Strien RT, Praml G, Nowak D, 2007. Environmental exposure to confined animal feeding operations and respiratory health of neighboring residents. Epidemiology 18, 300–308. [PubMed: 17435437]

Reed BR, Crane J, Garrett N, Woods DL, Bates MN, 2014. Chronic ambient hydrogen sulfide exposure and cognitive function. Neurotoxicol. Teratol 42, 68–76. [PubMed: 24548790]

Reynolds RL, Kamper RL, 1984. Review of the State of California Ambient Air Quality Standard for Hydrogen Sulfide (H2S) Lakeport, CA: Lake County Air Quality Management District. [accessed 2022 Oct 1]. https://ww2.arb.ca.gov/resources/california-ambient-air-quality-standards.

Ríos-González BB, Román-Morales EM, Pietri R, López-Garriga J, 2014. Hydrogen sulfide activation in hemeproteins: The sulfheme scenario. J. Inorg. Biochem 133, 78–86. [PubMed: 24513534]

Roth S, Goodwin V, 2003. Health Effects of Hydrogen Sulphide: Knowledge Gaps Alberta, Canada: Alberta Environment. [accessed 2022 Oct 1]. https://www.osti.gov/etdeweb/biblio/20388483.

Roth SH, Skrajny B, Bennington R, Brookes J, 1997. Neurotoxicity of hydrogen sulfide may result from inhibition of respiratory enzymes. Proc. West Pharmacol. Soc 40, 41–43. [PubMed: 9436209]

Rumsey IC, Aneja VP, 2014. Measurement and modeling of hydrogen sulfide lagoon emissions from a swine concentrated animal feeding operation. Environ. Sci. Technol 48, 1609–1617. [PubMed: 24387076]

Saadat M, Bahaoddini A, Mohabatkar H, Noemani K, 2004. High incidence of suicide by burning in Masjid-i-Sulaiman (southwest of Iran), a polluted area with natural sour gas leakage. Burns 30, 829–832. [PubMed: 15555796]

Saadat M, Zendeh-Boodi Z, Ali Goodarzi M, 2006. Environmental exposure to natural sour gas containing sulfur compounds results in elevated depression and hopelessness scores. Ecotoxicol. Environ. Saf 65, 288–291. [PubMed: 16169081]

Saeedi A, Najibi A, Mohammadi-Bardbori A, 2015. Effects of long-term exposure to hydrogen sulfide on human red blood cells. Int. J. Occup. Environ. Med 6, 20–25. [PubMed: 25588222]

Savolainen K, Riihimäki V, Laine A, 1982. Biphasic Effects of Inhaled Solvents on Human Equilibrium. Acta Pharmacol. Toxicol. (Copenh) 51, 237–242. [PubMed: 7136729]

Schiffman SS, Studwell CE, Landerman LR, Berman K, Sundy JS, 2005. Symptomatic effects of exposure to diluted air sampled from a swine confinement atmosphere on healthy human subjects. Environ. Health Perspect 113, 567–576. [PubMed: 15866765]

Schinasi L, Horton RA, Guidry VT, Wing S, Marshall SW, Morland K, 2011. Air pollution, lung function, and physical symptoms in communities near concentrated swine feeding operations. Epidemiol 22, 208–215.

Schroeter JD, Garcia GJM, Kimbell JS, 2010. A computational fluid dynamics approach to assess interhuman variability in hydrogen sulfide nasal dosimetry. Inhal. Toxicol 22, 277–286. [PubMed: 20064104]

Schroeter JD, Kimbell JS, Andersen ME, Dorman DC, 2006. Use of a pharmacokinetic-driven computational fluid dynamics model to predict nasal extraction of hydrogen sulfide in rats and humans. Toxicol. Sci 94, 359–367. [PubMed: 16984956]

SCOEL Scientific Committee on Occupational Exposure Limits, 2007. Recommendation from the Scientific Committee on Occupational Exposure Limits for Hydrogen Sulphide [accessed 2023 Mar 28]. https://ec.europa.eu/social/search.jsp?advSearchKey=hydrogen+sulphide&mode=advancedSubmit&langId=en.

Shafran-Nathan R, Levy I, Levin N, Broday DM, 2017. Ecological bias in environmental health studies: the problem of aggregation of multiple data sources. Air Qual. Atmos. Heal 10, 411–420.

Sheppard L, Burnett RT, Szpiro AA, Kim S, Jerrett M, 2012. Confounding and exposure measurement error in air pollution epidemiology. Air Qual. Atmos. Heal 5, 203–216.

Shimonovich M, Pearce A, Thomson H, Keyes K, Katikireddi SV, 2021. Assessing causality in epidemiology: revisiting Bradford Hill to incorporate developments in causal thinking. Eur. J. Epidemiol 36, 873–887. [PubMed: 33324996]

Shusterman D, 2001. Odor-associated health complaints: Competing explanatory models. Chem. Senses 26, 339–343. [PubMed: 11287393]

Sigurdarson ST, Kline JN, 2006. School proximity to concentrated animal feeding operations and prevalence of asthma in students. Chest 129, 1486–1491. [PubMed: 16778265]

Silva M, 2013. A Review of Developmental and Reproductive Toxicity of CS2 and H_2S Generated by the Pesticide Sodium Tetrathiocarbonate. Birth Defects Res. Part B - Dev. Reprod. Toxicol 98, 119–138.

Simonton DS, King S, 2013. Hydrogen Sulfide Formation and Potential Health Consequences in Coal Mining Regions. Water Qual. Expo. Heal 5, 85–92.

Sjaastad O, Bakketeig LS, 2006. Hydrogen sulphide headache and other rare, global headaches: Vågå study. Cephalalgia 26, 466–476. [PubMed: 16556249]

Skrajny B, Hannah RS, Roth SH, 1992. Low concentrations of hydrogen sulphide alter monoamine levels in the developing rat central nervous system. Can. J. Physiol. Pharmacol 70, 1515–1518. [PubMed: 1296865]

Skrtic L, 2006. Hydrogen sulfide, oil and gas, and people's health (MS Thesis) Berkeley, CA: University of California., Energy. [accessed 2022 Oct 1]. https://earthworks.org/files/publications/hydrogensulfide_oilgas_health.pdf.

Skúladóttir B, Þórðarson H, 2003. Environmental Evaluation of Air Quality Midterm report [accessed 2022 Oct 1]. https://www.iti.is/files/%7Bfa8f9b4d-c451-4b2e-9ca9-e78b536ffddb%7D_ectos_delivery7-enviro-midtermreport.pdf.

Snyder JW, Safir EF, Summerville GP, Middleberg RA, 1995. Occupational fatality and persistent neurological sequelae after mass exposure to hydrogen sulfide. Am. J. Emerg. Med 13, 199–203. [PubMed: 7893309]

Solnyshkova TG, 2003. Demyelination of Nerve Fibers in the Central Nervous System Caused by Chronic… 136, 328–332.

Solnyshkova TG, Shakhlamov VA, 2002. Ultrastructural and morphometric characteristics of nerve cells and myelinated fibers in the cerebral cortex after chronic exposure to natural gas containing hydrogen sulfide in low concentrations. Bull. Exp. Biol. Med 134, 411–413. [PubMed: 12533774]

Szpiro AA, Paciorek CJ, 2013. Measurement error in two-stage analyses, with application to air pollution epidemiology. Environmetrics 24, 501–517. [PubMed: 24764691]

Tajik M, Muhammad N, Lowman A, Thu K, Wing S, Grant GR, 2008. Impact of odor from industrial hog operations on daily living activities. New Solut 18, 193–205. [PubMed: 18511396]

Tenhunen R, Savolainen H, Jäppinen P, 1983. Changes in haem synthesis associated with occupational exposure to organic and inorganic sulphides. Clin. Sci. (London, Engl. 1979) 64, 187–191.

Thorn J, Beijer L, Rylander R, 2002. Work related symptoms among sewage workers: A nationwide survey in Sweden. Occup. Environ. Med 59, 562–566. [PubMed: 12151615]

Thorne PS, Ansley AC, Perry SS, 2009. Concentrations of bioaerosols, odors, and hydrogen sulfide inside and downwind from two types of swine livestock operations. J. Occup. Environ. Hyg 6, 211–220. [PubMed: 19177273]

Ulutaş K, Kaskun S, Demir S, Dinçer F, Pekey H, 2021. Assessment of H_2S and BTEX concentrations in ambient air using passive sampling method and the health risks. Environ. Monit. Assess 193, 1–10.

USDA United States Department of Agriculture, 2022. United States hog inventory down 2% [accessed 2022 Oct 1]. https://www.nass.usda.gov/Newsroom/2022/09-29-2022.php.

van Gemert LJ, Nettenbreijer AH, 1984. Compilation of odour threshold values in air and water. Zeist: Central Institute for Nutrition and Food Research TNO. [accessed 2022 Oct 1]. https://cir.nii.ac.jp/crid/1570854175609650304.

Varaksin AA, Puschina EV, 2011. Hydrogen sulfide as a regulator of systemic functions in vertebrates. Neurophysiology 43, 62–72.

Vasiljeva IA, 1973. Effect of low concentrations of carbon disulfide and hydrogen sulfide on the menstrual function in women and on the estrous cycle under experimental conditions. Gig Sanit 38, 24–27.

Villeneuve PJ, Ali A, Challacombe L, Hebert S, 2009. Intensive hog farming operations and self-reported health among nearby rural residents in Ottawa, Canada. BMC Public Health 9, 1–10. [PubMed: 19121216]

Volpato GP, Searles R, Yu B, Scherrer-Crosbie M, Bloch KD, Ichinose F, Zapol WM, 2008. Inhaled hydrogen sulfide: A rapidly reversible inhibitor of cardiac and metabolic function in the mouse. Anesthesiology 108, 659–668. [PubMed: 18362598]

Waldner C, 2009. Risk of abortion and stillbirth in cow-calf herds exposed to the oil and gas industry in western canada. Arch. Environ. Occup. Heal 64, 29–45.

Waldner C, 2008a. Western Canada study of animal health effects associated with exposure to emissions from oil and natural gas field facilities. Study design and data collection I. Herd performance records and management. Arch. Environ. Occup. Heal 63, 167–184.

Waldner C, 2008b. Western Canada study of animal health effects associated with exposure to emissions from oil and natural gas field facilities. Study design and data collection II. Location of study herds relative to the oil and gas industry in Western Canada. Arch. Environ. Occup. Heal 63, 187–199.

Waldner C, 2008c. Western Canada study of animal health effects associated with exposure to emissions from oil and natural gas field facilities. Study design and data collection III. Methods of assessing animal exposure to contaminants from the oil and gas industry. Arch. Environ. Occup. Heal 63, 201–219.

Waldner C, 2008d. The association between exposure to the oil and gas industry and beef calf mortality in Western Canada. Arch. Environ. Occup. Heal 63, 220–240.

Waldner C, Clark E, 2009. Association between exposure to emissions from the oil and gas industry and pathology of the immune, nervous, and respiratory systems, and skeletal and cardiac muscle in beef calves. Arch. Environ. Occup. Heal 64, 6–27.

Wang P, Zhang G, Wondimu T, Ross B, Wang R, 2011. Hydrogen sulfide and asthma. Exp. Physiol 96, 847–852. [PubMed: 21666034]

Wasch HH, Yip P, Bowler R, Cone JE, Estrin WJ, 1989. Prolongation of the P-300 Latency Associated With Hydrogen Sulfide Exposure. Arch. Neurol 46, 902–904. [PubMed: 2757531]

White MC, Inserra SG, Berger SA, Campagna D, Phifer BL, Lybarber JA, 1999. Health concerns for communities exposed to hydrogen sulfide. A perspective from two communities. Environ. Epidemiol. Toxicol 1, 236–240.

WHO World Health Organization, 2018. Falls: Key Facts Geneva, Switzerland: World Health Organization. [accessed 2022 Oct 1]. https://www.who.int/news-room/fact-sheets/detail/falls.

WHO World Health Organization, 2006. Hydrogen Sulfide. Chap. 6.6 in Air Quality Guidelines for Europe 2nd ed. Geneva, Switzerland: World Health Organization. [accessed 2022 Oct 1]. https://apps.who.int/iris/bitstream/handle/10665/107335/9789289013581-eng.pdf?sequence=1&isAllowed=y.

WHO World Health Organization, 2003. Hydrogen Sulfide: Human Health Aspects. Concise International Chemical Assessment Document 53 Geneva, Switzerland: World Health Organization. [accessed 2022 Oct 1]. https://apps.who.int/iris/bitstream/handle/10665/42638/9241530537.pdf?sequence=1&isAllowed=y.

WHO World Health Organization, 1981. Environmental Health Criteria 19: Hydrogen Sulfide Geneva, Switzerland: World Health Organization. [accessed 2022 Oct 1]. https://wedocs.unep.org/20.500.11822/29305.

WHO World Health Organization, 1948. Preamble to the Constitution of the World Health Organization as adopted by the International Health Conference, New York, 19–22 June, 1946 ; signed on 22 July 1946 by the representatives of 61 States and entered into force on 7 April 1948 [accessed 2022 Oct 1]. http://www.who.int/governance/eb/whoconstitution_en.pdf.

Wing S, Horton RA, Marshall SW, Thu K, Tajik M, Schinasi L, Schiffman SS, 2008. Air pollution and odor in communities near industrial swine operations. Environ. Health Perspect 116, 1362–1368. [PubMed: 18941579]

Winneke G, Kotalik J, Keldenich HO, Kastka J, 1979. Zur Wahrnehmung von Schwefelwasserstoff unter Labor-und Feldbedingungen [Determination of hydrogen sulfide in laboratory and field conditions]. Staub Reinh. der Luft 39, 156–159.

Woodall GM, Smith RL, Granville GC, 2005. Proceedings of the Hydrogen Sulfide Health Research and Risk Assessment Symposium, October 31-November 2, 2000. Inhal. Toxicol 17, 593–639. [PubMed: 16033755]

Xu X, Cho S Il, Sammel M, You L, Cui S, Huang Y, Ma G, Padungtod C, Pothier L, Niu T, Christiani D, Smith T, Ryan L, Wang L, 1998. Association of petrochemical exposure with spontaneous abortion. Occup. Environ. Med 55, 31–36. [PubMed: 9536160]

Zelensky M, 2009. Appendix 2: Overview of Hydrogen Sulphide Lethality Data and Exposure Criteria. Alberta, Canada, 2004. In: ERCBH2S, A Model for Calculating Emergency Response and Planning Zones for Sour Gas Facilities Vol. 2: Emergency Response Planning Endpoints. [accessed 2022 Oct 1]. https://static.aer.ca/prd/documents/directives/ERCBH2S_VOLUME_1.pdf.

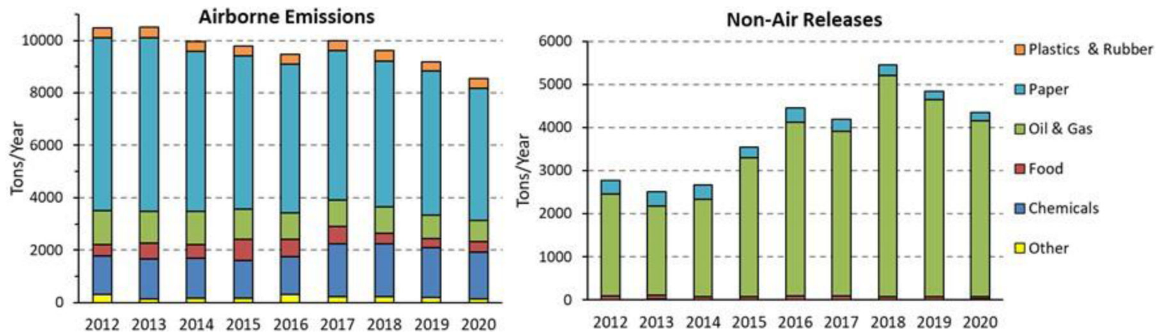

Figure 1.

H_2S emissions reported in the U.S. Toxics Release Inventory (TRI) to air and other media by the top emitting industry sectors, 2012–2020. "Oil & gas" includes releases from petroleum refineries, bulk plants and terminals, and NAICS industry code 999 (primarily oil and gas extraction); "Paper" includes pulp mills; "Other" includes primary metals, nonmetallic mineral products, water, wastewater, beverages, electric utilities, hazardous waste, wood products, leather, poultry and egg production, machinery, furniture, transportation equipment, and metal mining.

Table 1.

Summary of health symptoms and effects for concentrations and exposure durations of H_2S reported in the cited studies. Co-exposures and concentration range and study population size shown, when available. Adapted in part from ACGIH (2001) and Skrtic (2006).

Concentration (ppm)	Exposure Duration	Effect	Source	Exposure group	H_2S exposure range	Co-exposure (average, range, SD)
5000 ppm	Immediate	Death	Fuller and Suruda 2000	Occupational	0.2–5000 ppm	None
1000 – 2000 ppm	NA but very short term	Loss of consciousness, collapse, paralysis of respiration, possible death	ACGIH 2001	Occupational based on rat and human studies	0.0002–2000 ppm	None
			Fuller and Suruda 2000	Occupational	0.2–5000 ppm	None
			Milby and Baselt 1999	Occupational	0.25–1000 ppm	Cl, NH_3, SO_2 noted, but not as co-exposures
500 – 1000 ppm	Acute	Serious respiratory, central nervous, and cardiovascular system effects, e.g., stimulation of respiratory response, hyperpnea, apnea, unconsciousness, death	ACGIH 2001	Occupational based on rat and human studies	0.0002–2000 ppm	None
			EPA 1993	Oil & gas production	0–2000 ppm	Reduced sulfur gases, organic sulfides noted
			Fuller and Suruda 2000	Occupational	0.2–5000 ppm	None
250 ppm	Acute and Intermediate	Pulmonary edema, risk of death	Milby and Baselt 1999	Occupational	0.25–1000 ppm	Cl, NH_3, SO_2 noted, but not as co-exposures
		Damage to organs, nervous system, depression of cellular metabolism	EPA 1993	Oil & gas production	0–2000 ppm	None
150 – 200 ppm	NA	Olfactory fatigue, paralysis	ACGIH 2001	Occupational based on rat and human studies	0.0002–2000 ppm	None
			EPA 1993	Oil & gas production	0–2000 ppm	None
100 ppm	NA	Headaches, dizziness, lethargy	ACGIH 2001	Occupational based on rat and human studies	0.0002–2000 ppm	None
50 – 100 ppm	Prolonged	Intense eye irritation, conjunctivitis, cornea scarring, olfactory fatigue	EPA 1993	Oil & gas production	0–2000 ppm	None
			Milby and Baselt 1999	Industrial	0.25–1000 ppm	Cl, NH_3, SO_2 noted, but not as co-exposures
50 ppm	Prolonged	Olfactory fatigue, ocular pain	OEHHA 2008	Workplace	0.00007–1000 ppm	None
4–50 ppm	Prolonged	Nasal bleeding, headaches, fatigue	Mousa 2015	Oil field workers	4–50 ppm	None
30 ppm	NA	Olfactory paralysis	Snyder et al. 1995	Occupational	30 - >700 ppm	None

Concentration (ppm)	Exposure Duration	Effect	Source	Exposure group	H_2S exposure range	Co-exposure (average, range, SD)
5 – 50 ppm	NA	Moderate irritation of the eyes, risk of pulmonary edema	ACGIH 2001	Occupational based on rat and human studies	0.0002–2000 ppm	Carbon disulfide
5 ppm	Immediate	Increase in anxiety	ATSDR 2006	Inhalation	0->500 ppm	NO_X, SO_2, CO, NH_3, methyl mercaptan, methyl sulfide
5 – 10 ppm	Immediate	Relatively minor metabolic changes in exercising individuals during short-term exposures.	ACGIH 2001	Occupational based on rat and human studies	0.0002–2000 ppm	None
<10 ppm	Various	Slowed development in infants, irritability, headache, fatigue.	EPA 1993	Oil & gas production	0–2000 ppm	None
5 ppm	Acute	Increase in anxiety symptoms (single exposure)	ACGIH 2001	Occupational based on rat and human studies	0.0002–2000 ppm	None
5 ppm	NA	Start of the dose-response curve (short term exposure’:	ACGIH 2001	Occupational based on rat and human studies	0.0002–2000 ppm	None
<5 ppm	NA	Metabolic changes observed in exercising individuals, but not clinically significant	ACGIH 2001	Occupational based on rat and human studies	0.0002–2000 ppm	Methyl mercaptan, dimethyl sulfide
2 – 5 ppm	Acute	Higher oxygen intake	Bhambhani et al. 1996;	Inhalation with exercise	0–5 ppm	None
			Bhambhani and M. Singh 1991	Inhalation with exercise	0–5 ppm	SO_2, CO_2 noted, but not as co-exposures
			Jappinen et al. 1990	Pulp mill workers	1–11 ppm	SO_2 (0.03 ppm)
1 – 5 ppm	Acute to intermediate	Balance issues, delayed verbal recall, impaired color discrimination, decreased grip strength, reaction time impacts, recall issues	Kilburn 1999	4 exposure groups: (1) residents with soil gas exposure in California (N-24); (2) residents near refinery (N=35); (3) residents near refinery explosion (N=48); (4) refinery workers (N=16); Controls from 4 towns (N=357)	0.1 – 8.8 ppm (24-hr), other measurements to 20 ppm reported	Group 2: carbon oxide sulfide (2.6–52 ppm), mercaptans (1–21.1 ppm)
0.25 – 0.30 ppm	Chronic	Odor nuisance, nausea, disturbance to sleep	Milby and Baselt 1999	Industrial	0.25–1000 ppm	Cl, NH_3, SO_2 noted, but not as co-exposures
0.17 ppm	Chronic	Increase in mortality from transportation accidents	Lewis et al. 2003	Petroleum workers(N=25,292; Transportation accidents with N=15)	H_2S estimated for workers with transportation accidents (N=15); 0.01–0.60 ppm for larger group	Fuels (0.01–48 ppm), lubricants (0.1 – 289 ppm), coke/catalyst (0.03–84 μg/m^3), vinyl chloride monomer, asbestos; smoking status
0.020–0.027 ppm	Chronic	Slightly reduced prevalence of wheeze; no other effects on asthma or respiratory symptoms	Bates et al. 2013	Adults in Rotorua at residential & workplace locations (N=1637)	0–0.064 ppm	None

Concentration (ppm)	Exposure Duration	Effect	Source	Exposure group	H_2S exposure range	Co-exposure (average, range, SD)
0.02–0.13 ppm	Acute	Odor recognition	Costigan 2003	Oil and water treatment industry - review of studies	0–2000 ppm	SO_2, CS_2, H_2SO_4
0.03 ppm	Chronic	Aggravation of respiratory disease noted by increased hospital visits	Campagna et al. 2004	Unscheduled hospital visits for respiratory disease in Nebraska, USA near agricultural and tanning sources (Visits N=455 for asthma, N=5009 for all respiratory disease)	0.03 ppm	TRS, SO_2 (0.03 ppm)
0.03–0.05 ppm	Acute	Odor nuisance, headaches, nausea	Fiedler et al. 2008	Individuals exposed to low concentrations	0.05–5 ppm	None
			OEHHA 2008	Panel study (N=16)	0.00007–1,000 ppm	none - controlled study
			Reynolds and Kamper 1984	Sensitive population	0.012–0.069 ppm	CO_2, NO
0.008 ppm	Intermediate	Nasal histological change in mice	OEHHA 2008	90-day mouse exposure; N=10–12 for each of 4 exposure groups	0 – 80 ppm for 6 hr/day, 5 day/week for animals; 100-fold adjustments for humans	none - controlled study
0.007–0.027 ppm	Chronic	Neurophysiological abnormalities	Legator et al. 2001	Groups in Odessa, Texas (N=126) and Puna, Hawaii (N=97) compared to 170 controls	0.007–0.027 ppm (average); 0.5 ppm for max 8-hr in Odessa; 0.5 ppm for max 1-hr in Puna	None
0.007–0.096 ppm	Acute & Chronic	Eye irritation	Haahtela et al. 1992	Group near pulp mill during upset (N=60) and reference group (N=66)	0–0.096 ppm (4-hr)	SO_2 (2–3 μg/m^3, average); mesityl oxide
			Heaney et al. 2011	Adults living within 0.75 mile of landfills (N=23)	0–0.0023 ppm	None
			Kilburn 2012	Residents within 2.2 km of CAFO hog lagoons (N=25) in Ohio and unexposed individuals (N=22)	0–0.03 ppm (average); several measurements from 1–2.1 ppm	CO in expired air (0–27 ppm)
			Marttila et al. 1994	Children living near pulp mill (N=134)	0.0007–0.053 ppm average; 0.01–0.067 ppm 24-hr peaks (modeled)	CH_3HS (2–5 μg/m^3 average), SO_2 (2–3 μg/m^3 average)
			Schiffman et al. 2005	Volunteers in controlled tests (N=48)	0–0.024 ppm	NH_3 (0.046–0.817 ppm), PM_{10} (24 μg/m^3), endotoxin (7.4 EU/m^3)
			Schinasi et al. 2011	see Horton below	see Horton below	see Horton below
0.002 ppm (TRS)	Intermediate	Eye and nasal symptoms, cough, headache/migraine	Partti-Pellinen et al. 1996	Residents near pulp & paper mill and controls (N=336)	0.002 ppm average; 0–0.038 ppm for 24-hr; 0.104 ppm for 1-hr max (all as TRS)	SO_2 (average 1 μg/m^3; 24-hr from 0–24 μg/m^3; 1-hr maximum of 152 μg/m^3)

Concentration (ppm)	Exposure Duration	Effect	Source	Exposure group	H_2S exposure range	Co-exposure (average, range, SD)
Δ0.0067 ppm	Chronic	Asthma exacerbation, indicated by increase in medication dispensed	Carlsen et al. 2012	Adults in Rotorua, Iceland dispensed anti-asthma drugs (N=up to 192 per day)	0–0.062 ppm (24-hr)	PM_{10} (24-hr 23.2 ±17.8 μg/m^3); NO_2 (24-hr 21.9 ±14.5 μg/m^3); O^3 (8-hr 42.9 ±15.2 μg/m^3)
Δ0.005 ppm	Chronic	Respiratory hospitalizations and mortality	Nuvolone et al. 2019	Residents near geothermal electric power plants (N=33,804)	Model predicted 90-day maximum	PM, NO_2, O_3 noted as below limits
0.005 ppm	Acute effects (7.5 year long study)	Emergency room visits associated with heart disease	Finnbjornsdottir et al. 2016	Residents exposed to geothermal power plant plume in Reykjavik, Iceland (N=13,381 hospital patients)	0.005 ppm average: 0–0.047 ppm for 24-hr; plume model estimates	NO_2, O_3, PM_{10}, SO_2 noted; values not given
0.00022 ppb	Acute	Emergency room visits associated with heart disease	Heaney et al. 2011	Residents within 0.75 mile of municipal waste landfills (N=23)	0–2.3 ppb (1-hr)	None
0.0003–0.001 ppm *	Chronic (2-yr)	Stress and negative mood	Horton 2007	Residents within 0.2 – 1.4 miles of CAFO (swine) facility (N=101)	0.0003 ±0.00186 ppm (1-hr average); 0–0.0015 ppb (2-yr average across 16 areas)	Odor (1.3 ±1.88); $PM_{2.5}$ (10.9 ±5.6 μg/m^3); PM_{10} (19.4±11.8 μg/m^3), endotoxin
		Nose and eye irritation, difficulty breathing, wheezing	Schinasi et al. 2011			

'NA' means not available (not provided).'Δ' means change in concentration;

* analyzed a 0.001 ppm change in the exposure concentration.

Table 2.

Summary of existing H_2S exposure recommendations for the general public in the U.S. Derived and updated from Armstrong et al. (2004).

Parameter	EPA	California OEHHA	ATSDR	ATSDR	WHO
Standard or guideline	RfC	REL (inhalation)	Acute MRL	Intermediate MRL	Guidance value
Concentration (ug/m^3)	2	10	100	30	150
Concentration (ppm)	0.0015	0.008	0.070	0.020	0.101
Exposure period	continuous (lifetime)	continuous (i.e., 8 yrs)	continuous, acute duration (≤ 2 wks)	continuous, intermediate duration (≤1 yr)	24 hr
Target population	general population, including sensitive groups	general population	general population, including sensitive groups	general population, including sensitive groups	general population
LOAEL (ppm)	30	-	2	-	15
NOAEL (ppm)	10	30.5	-	30.5	NA
Critical study	subchronic rat study by Brenneman et al. 2000	subchronic mouse study by CIIT 1983	acute experimental human study by Jappinen et al. 1990	subchronic rat study by Brenneman et al. 2000	Savolainen et al. 1982 for ocular effects; Tenhunen et al. 1983 for haem synthesis
Critical effects	no destruction of olfactory neurons or inflammation/necrosis of nasal epithelium	no inflammation of nasal epithelium	increase in airway resistance	no inflammation of nasal epithelium	ocular irritation
Adjustments	intermittent = continuous exposure, rat = human, dosimetry, interspecies, sensitive humans, subchronic = chronic exposure	intermittent = continuous exposure, rat = human, dosimetry, interspecies, sensitive humans, subchronic = chronic exposure	LOAEL= NOAEL, interspecies sensitivity	intermittent = continuous exposure, rat = human, dosimetry, interspecies, sensitive humans	uncertainty factor due to steep dose-effect curve; also single report of haem synthesis impacts at 1.5 mg/m^3
Year developed	2003	2000, maintained in 2008	1999, maintained in 2016	2006, maintained in 2016	2000, maintained in 2003
Comments	RfCs can be derived for non-carcinogenic effects of known carcinogens and for non-inhalation routes.	same as ATSDR except for subchronic, chronic factor and rounding differences			Also recommends a 30-min mean exposure limit of 0.005 ppm or 7 µg/m^3 for odor annoyance.