ATSDR
Health Consultation

Evaluation of Hydrogen Sulfide in Outdoor Air
Environmental Contamination in the Tijuana River

Tijuana River Valley, California

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and Disease Registry

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Health Consultation

Evaluation of Hydrogen Sulfide in Outdoor Air

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Tijuana River Valley, California

U.S. Department of Health and Human Services
Agency for Toxic Substances and Disease Registry
Office of Community Health Hazard Assessment
Atlanta, Georgia, 30333

About ATSDR

The Agency for Toxic Substances and Disease Registry (ATSDR) is a federal public health agency of the U.S. Department of Health and Human Services (HHS). ATSDR works with other agencies and tribal, state, and local governments to study possible health risks in communities where people could come in contact with dangerous chemicals. For more information about ATSDR, visit the ATSDR website at www.atsdr.cdc.gov/.

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Acronyms and Abbreviations

95UCL	95 percent upper confidence limit of the arithmetic mean
ACE	Assessment of Chemical Exposure
ADF	Augmented Dickey-Fuller
ATSDR	Agency for Toxic Substances and Disease Registry
CASPER	Community Assessment for Public Health Emergency Response
CDC	Centers for Disease Control and Prevention
CO	Carbon monoxide
CV	Comparison value
DPW	Department of Public Works
ED	Emergency Department
EMEG	Environmental Media Evaluation Guide
EPA	Environmental Protection Agency
EPC	Exposure Point Concentration
ESS	Effective sample size
GRASP	Geospatial Research, Analysis, and Services Program
H_2S	Hydrogen sulfide
HEPA	High efficiency particulate air
HHE	Health Hazard Evaluation
HHSA	County of San Diego Health and Human Services Agency
HQ	Hazard quotient
IARC	International Agency for Research on Cancer
IBWC	International Boundary and Water Commission, United States and Mexico
LOAEL	Lowest observable adverse effect level
$LOAEL_{Adj}$	Adjusted LOAEL
$LOAEL_{HEC}$	Human equivalent concentration LOAEL
MOE	Margin of exposure
MRL	Minimal risk level
n.d.	No date
NIOSH	National Institute for Occupational Safety and Health
NO_2	Nitrogen dioxide
NOAA	National Oceanic and Atmospheric Administration
NOAEL	No observable adverse effect level
$NOAEL_{Adj}$	Adjusted NOAEL
$NOAEL_{HEC}$	Human equivalent concentration NOAEL
NTP	National Toxicology Program
OCDAPS	Office of Capacity Development and Applied Prevention Science
OCHHA	Office of Community Health Hazard Assessment
PB CILA	*Planta de Bombeo Comisión Internacional de Límites y Aguas (*PB CILA) Pump Station
PHA	Public health assessment
PPB	Parts per billion
PPE	Personal protective equipment

PPM	Parts per million
RfC	Reference concentration
RMEG	Reference Dose Media Evaluation Guide
SBIWTP	South Bay International Wastewater Treatment Plant
SDAPCD	San Diego Air Pollution Control District
SO_2	Sulfur dioxide
TeledyneT101	Model T101 UV Fluorescence H_2S Analyzer by Teledyne AP
TVOC	Total volatile organic compounds
UCSD	University of California San Diego

1. Summary

In May 2024, the Centers for Disease Control and Prevention (CDC)/Agency for Toxic Substances and Disease Registry (ATSDR) received a petition from members of the California congressional delegation to investigate the public health impacts of Tijuana wastewater contamination, both in the Tijuana River and in the surrounding communities of Imperial Beach, Coronado, and San Diego. The congressional delegation requested that CDC/ATSDR assess the presence of contaminants in the communities' water, soil, and air. CDC/ATSDR was also asked to investigate any potential connection between these contaminants and the reported increases in gastrointestinal illnesses and other symptoms.

In July 2024, the CDC/ATSDR director responded that ATSDR would start the petition process to investigate specific environmental health concerns. ATSDR gathered air, surface water, sediment, and biota data from federal, state, local, and academic partners, determining that there were enough data to accept the petition. On January 7, 2025, the CDC/ATSDR director notified the congressional delegation that ATSDR would conduct a public health assessment of hydrogen sulfide in the air [CDC/ATSDR 2025].

ATSDR will release the findings of the public health assessment activities in two reports. This is the first, focusing on potential exposures to contaminants in air in the Tijuana River Valley. A second report will address other potential exposure pathways, like surface water, sediment, and soil. In this health consultation, ATSDR evaluated exposures to air contaminants via outdoor air in the Tijuana River Valley following the agency's public health assessment (PHA) process, as summarized in Appendix A, and detailed in ATSDR's Explanation of ATSDR's PHA Process [ATSDR 2022].

ATSDR reached the following conclusions from our evaluation of Tijuana River Valley air data and associated health risks:

Conclusion 1	**Environmental odors in the Tijuana River Valley can negatively affect people's health and well-being.**
Basis for Conclusion	• Hydrogen sulfide levels in outdoor air were measured above the hydrogen sulfide odor threshold in 30-minute samples at all four air monitoring sites in the Tijuana River Valley up to 93% of the time. • As a result, people in the Tijuana River Valley may experience environmental-odor-related health symptoms such as headaches, nausea, stress or annoyance, nasal congestion, eye, nose, and throat irritation, hoarseness and sore throat, cough, chest tightness, and shortness of breath [ATSDR 2014, ATSDR 2016]. • Some of the symptoms people experience from environmental odors are like those observed in toxicological studies of hydrogen sulfide at higher concentrations (for example, 2,000 ppb, the lowest level where health effects

	have been observed in toxicological studies). However, hydrogen sulfide can be smelled at much lower levels (as low as about 0.5 ppb). This means that symptoms can occur in response to the odor itself, even at levels far below those used in toxicological studies. In this way, environmental odors can affect how people feel, even when measured chemical levels are low.
Conclusion 2	**Hydrogen sulfide in outdoor air at the Leon Avenue monitoring site, and likely the Berry Elementary monitoring site, has reached a level for short periods of time that could harm people's health. Exposure to hydrogen sulfide at this level is a public health hazard.**
Basis for Conclusion	• One-minute readings for hydrogen sulfide were collected at four monitoring locations in the Tijuana River Valley. ATSDR calculated 30-minute rolling averages of these data to compare the results to the air concentrations in the toxicological literature examining hydrogen sulfide health effects from short-term exposure. • The highest exposure point concentration (EPC; a maximum 30-minute rolling average) came from the Leon Avenue monitoring location in September 2024; the 30-minute rolling average was 3,021.5 parts per billion (ppb). This EPC is above the 2,000 ppb lowest observable adverse effect level (LOAEL) identified in the Jäppinen et al. (1990) study used to develop ATSDR's acute minimal risk level (MRL). • This means that people who breathed hydrogen sulfide in this location were sometimes exposed to concentrations higher than those demonstrated to cause health effects in humans. These health effects include headaches, dryness of the nose and throat, and possibly difficulty breathing in sensitive people. • Rolling 30-minute hydrogen sulfide concentrations exceeded the 2,000 ppb LOAEL 0.04% of the time at Leon Avenue. EPCs for the remaining locations were below 2,000 ppb. Berry Elementary School is across the street from the Leon Avenue monitoring site. Monitoring at Berry did not begin until October 2024 (after the highest hydrogen sulfide concentrations were measured at Leon Avenue). It is likely that hydrogen sulfide levels were also high at Berry Elementary because the two locations are very close to each other, but ATSDR does not have air data for Berry Elementary before monitoring began. However, ATSDR did demonstrate that hydrogen sulfide levels at the two locations are significantly correlated.

Conclusion 3	**Longer-term hydrogen sulfide exposures (14 days or more) at the four monitoring locations are not expected to pose a public health hazard or result in additional health effects beyond those linked to short-term elevated exposures. However, they may still be associated with odor-related symptoms.**
Basis for Conclusion	• **Intermediate duration (more than 14 to 364 days):** ATSDR calculated 14-day rolling averages as the EPC for each monitoring location as a conservative estimate of intermediate exposures. The highest EPC came from Leon Avenue (151.9 ppb). The next highest EPC came from Berry Elementary (31.6 ppb). • The EPCs at both locations exceeded ATSDR's intermediate MRL (20 ppb). However, these levels were nine times lower (at Leon Avenue) and 44 times lower (at Berry) than the level shown to cause health effects in the toxicological literature (1,380 ppb). Therefore, ATSDR does not expect that intermediate exposures to hydrogen sulfide in the Tijuana River Valley will harm people's health. • **Chronic duration (1 year or more):** ATSDR averaged between four to seven months of monitoring data from each monitoring location as EPCs for chronic exposures. Air monitoring began at different times at the sites, which explains the variation in the length of time that data are available for each site. • The highest EPC came from Leon Avenue (23.6 ppb). The next highest EPC came from Berry Elementary (9.2 ppb). These levels were 58 and 150 times lower than the levels shown to cause health effects in the toxicological literature (1,380 ppb). Therefore, ATSDR does not expect that chronic exposures to hydrogen sulfide in the Tijuana River Valley will harm people's health.
Conclusion 4	**ATSDR cannot conclude whether breathing hydrogen sulfide in outdoor air in the Tijuana River Valley before September 2024 could have harmed people's health. Sufficient data were not collected before this time.**
Basis for Conclusion	• In September 2024, air monitoring began in the Tijuana River Valley, with instruments adequate for public health assessment. Data before this time are not available to assess health risks. • ATSDR understands that the Tijuana River sewage issue has persisted for many years and exposures to hydrogen sulfide in outdoor air have almost certainly occurred as a result. We

are unable to quantify and characterize these past exposures without data.

Next Steps

ATSDR will release these findings to the public. We will later publish a second report that will address other potential exposure pathways in the Tijuana River Valley, like exposures to chemicals in surface water, sediment, and soil.

ATSDR has the following public health recommendations based on our evaluation of hydrogen sulfide in outdoor air at four monitoring locations around the Tijuana River Valley:

Recommendations for federal and state agencies:

- Prevent transboundary sewage flows into the Tijuana River Valley so that hydrogen sulfide levels remain as low as possible, ideally below the odor threshold of 0.5 ppb.
- Improve and maintain wastewater treatment infrastructure to manage flows in the Tijuana River Valley.
- Continue collaborating with local agencies to implement measures that reduce hydrogen sulfide releases at the location where the Tijuana River flows under Saturn Boulevard.

Recommendations for local agencies:

- Continue monitoring hydrogen sulfide in air. Notify community members, businesses, daycares, and schools when levels exceed thresholds set by the state or local agencies to be health protective. Use multiple methods to reach community members (e.g. text messages and emails).
- Maintain signage throughout the Tijuana River Valley to alert visitors to the possible presence of hydrogen sulfide.
- Continue to offer air purifiers and filters through the Air Improvement Relief Effort Program.
- Continue to collect and monitor odor complaints. Consider ways to precisely identify the location of odor complaints to target hotspots for air monitoring and better understand the geographic distribution of odors.
- Conduct air monitoring to determine hydrogen sulfide levels beyond the locations with fixed monitors. Consider expanding air monitoring to other contaminants that may be released from the Tijuana River, including volatile organic compounds.

- Continue collaborating with federal and state agencies to reduce hydrogen sulfide releases at the location where the Tijuana River flows under Saturn Boulevard.
- Verify that interventions that address the hydrogen sulfide problem in the Tijuana River Valley do not cause continued or additional harmful exposures.
- Maintain the Community Hydrogen Sulfide Guidance: https://www.sdapcd.org/content/sdapcd/about/tj-river-valley/tjrv-air-quality-monitoring.html. Consider engaging appropriate state and federal agencies to develop and incorporate recommendations for workers who cannot leave the area or go indoors during their work shift.

Recommendations for schools:

- Monitor hydrogen sulfide levels in the Tijuana River Valley by visiting San Diego Air Pollution Control District's (SDAPCD) Air Monitoring website: https://www.sdapcd.org/content/sdapcd/about/tj-river-valley/tjrv-air-quality-monitoring.html. Follow SDAPCD and San Diego County's Community Hydrogen Sulfide Guidance.
- Follow San Diego County's Resources for Schools materials to make informed decisions about daily activities: https://www.sandiegocounty.gov/content/sdc/hhsa/programs/phs/community_epidemiology/south-region-health-concerns/schools.html

Recommendations for community members

- Monitor hydrogen sulfide levels in the Tijuana River Valley by visiting SDAPCD's Air Monitoring website: https://www.sdapcd.org/content/sdapcd/about/tj-river-valley/tjrv-air-quality-monitoring.html. Follow SDAPCD and San Diego County's Community Hydrogen Sulfide Guidance.
- People who are sensitive to environmental odors can reduce exposure by using air purifiers, limiting outdoor activities when odors are bothersome, keeping windows and doors closed when odors outside are bothersome, or leaving the area as needed when monitoring indicates hydrogen sulfide levels are elevated. Avoid using candles and incense in homes to mask hydrogen sulfide odors. Candles and incense themselves can be irritants.
- Eligible residents are encouraged to obtain a free air purifier from the SDAPCD Air Improvement Relief Effort Program. Information about the program can be found here:

	https://www.sdapcd.org/content/sdapcd/about/tj-river-valley/aire.html. Guidance on the best use of air purifiers can be found here: https://www.sdapcd.org/content/dam/sdapcd/documents/tjrv/aire/CARB-CleanAirSpace-Infographic.pdf. Air purifying filters are most effective when maintained and replaced based on manufacturers' guidelines. • Report odors in the Tijuana River Valley to the SDAPCD by calling (858) 586-2650 or emailing apcdcomp@sdapcd.org. After hours, call (858) 586-2650 and select option 2. An app for reporting odors is also available for download on SDAPCD's air quality concerns website: https://www.sdapcd.org/content/sdapcd/compliance/air-quality-complaints.html. • People concerned about health effects from hydrogen sulfide exposure are encouraged to speak to their doctor. Consider providing a copy of the fact sheet summarizing this report.
For More Information	Community members can contact ATSDR's Region 9 office to learn more about hydrogen sulfide levels and health risks in the Tijuana River Valley. You can get ATSDR region 9 staff contact information here: https://www.atsdr.cdc.gov/regional-offices/index.html or by calling 800-CDC-INFO (800-232-4636).

2. Background

2.1. Statement of Issue and Purpose

Untreated wastewater has flowed for decades from Tijuana, Mexico into the Tijuana River Valley and Pacific Ocean owing to challenges in wastewater infrastructure. Hydrogen sulfide "sewer gas," which has a foul rotten egg odor, and other contaminants are released from these wastewater flows, producing air quality and odor issues in nearby communities. Hydrogen sulfide forms in the Tijuana River as bacteria break down organic materials in the river [OSHA 2005]. Multiple federal, state, and local agencies, universities, community organizations, and elected officials are engaged in efforts to improve the wastewater infrastructure and address environmental and health concerns.

In May 2024, CDC/ATSDR received a request from California congressional members to investigate the public health impacts of wastewater contamination in the Tijuana River and nearby communities. In response, ATSDR initiated the agency's petition review process [ATSDR 2024a] and decided in January 2025 to conduct public health assessment activities. ATSDR evaluated whether exposure to hydrogen sulfide in air near the Tijuana River in southern San Diego County, California, could harm people's health.

Both biological contaminants (e.g., bacteria like E. Coli) and chemical contaminants (e.g., hydrogen sulfide) are present in wastewater flows affecting the Tijuana River Valley and Pacific Ocean waters [CRWQCB 2024]. **However, consistent with ATSDR's congressional mandate, the Tijuana River Valley public health assessment activities focus on potentially harmful chemical exposures [ATSDR 2024b]. ATSDR's evaluation will be shared in two reports.** This is the first report, focusing on exposure to hydrogen sulfide in the air. A future report will address potential exposures to chemicals in surface water, sediment, and soil.

2.2. Site Description and Timeline

The Tijuana River Valley, located along the U.S.-Mexico border in San Diego County, California, is an ecologically significant 8-square-mile natural floodplain with mixed land uses [City of San Diego n.d., CSLC 2025] (n.d. = no date). The valley supports recreation (e.g., horseback riding, hiking, camping, and surfing), conservation, agriculture, military activities, and commercial and residential areas. Imperial Beach and Coronado are among the nearby communities. Most of the land in the Tijuana River Valley is managed by various binational, federal, state, and local government agencies.

The Tijuana River Valley is a small part of the 1,700-square-mile Tijuana River watershed, most of which is in northern Baja California, Mexico [City of San Diego n.d.]. The Tijuana River flows northward from Mexico, through the city of Tijuana and into the United States, eventually emptying into the Pacific Ocean. The river's flow is highly variable, with significant seasonal fluctuations due to rainfall patterns.

Transboundary flow refers to movement of water across an international boundary. During the rainy season, the river can experience rapid increases in transboundary flow, contributing to flooding in certain areas. Wet weather events also deposit large quantities of trash, debris, and sediment in the Valley.

In addition to seasonal wet weather flows, dry weather transboundary flows are a significant concern in the Tijuana River Valley. These flows occur during dry periods, when untreated wastewater (e.g., sewage and industrial waste) from Tijuana enters the river system. Rapid population growth in Tijuana and challenges with wastewater treatment infrastructure has compounded longstanding transboundary pollution problems.

There are three main ways that transboundary pollution enters California waters in this area [CSLC 2025, EPA 2021a]:

1. Polluted water flows through the main channel of the Tijuana River, through the Tijuana River Valley and to the Pacific Ocean.
2. Polluted water flows into the Valley through tributary canyons along the border.
3. Untreated wastewater is discharged into the ocean in Mexico, five miles south of the border, and then carried north by ocean currents to the coastal waters off San Diego County.

Wastewater management in the Tijuana River Valley is complex, in part due to the cross-border nature of the region. The schematic in Figure 1 explains the wastewater infrastructure in both the United States and Mexico. The International Boundary and Water Commission (IBWC) manages water-related issues along the border. The U.S. section of the IBWC operates the South Bay International Wastewater Treatment Plant (SBIWTP), located in the United States near the border [IBWC 2023]. The SBIWTP treats wastewater originating in Tijuana [SDRWQCB n.d.]. IBWC also owns five canyon collectors that are intended to capture dry weather transboundary flows that occur in tributary canyons along the border. Water captured by the canyon collectors is pumped for treatment at the SBIWTP [SDRWQCB n.d.]. Treated water from the SBIWTP is then pumped to the South Bay Ocean Outfall in the Pacific Ocean, about 3.5 miles offshore. Wastewater infrastructure in Tijuana River Valley includes the main pump station in Mexico (Planta de Bombeo Comisión Internacional de Límites y Aguas [“PB CILA”]) and several other pump stations intended to divert dry weather river flows to the SBIWTP or the San Antonio de los Buenos Treatment Plant in Mexico.

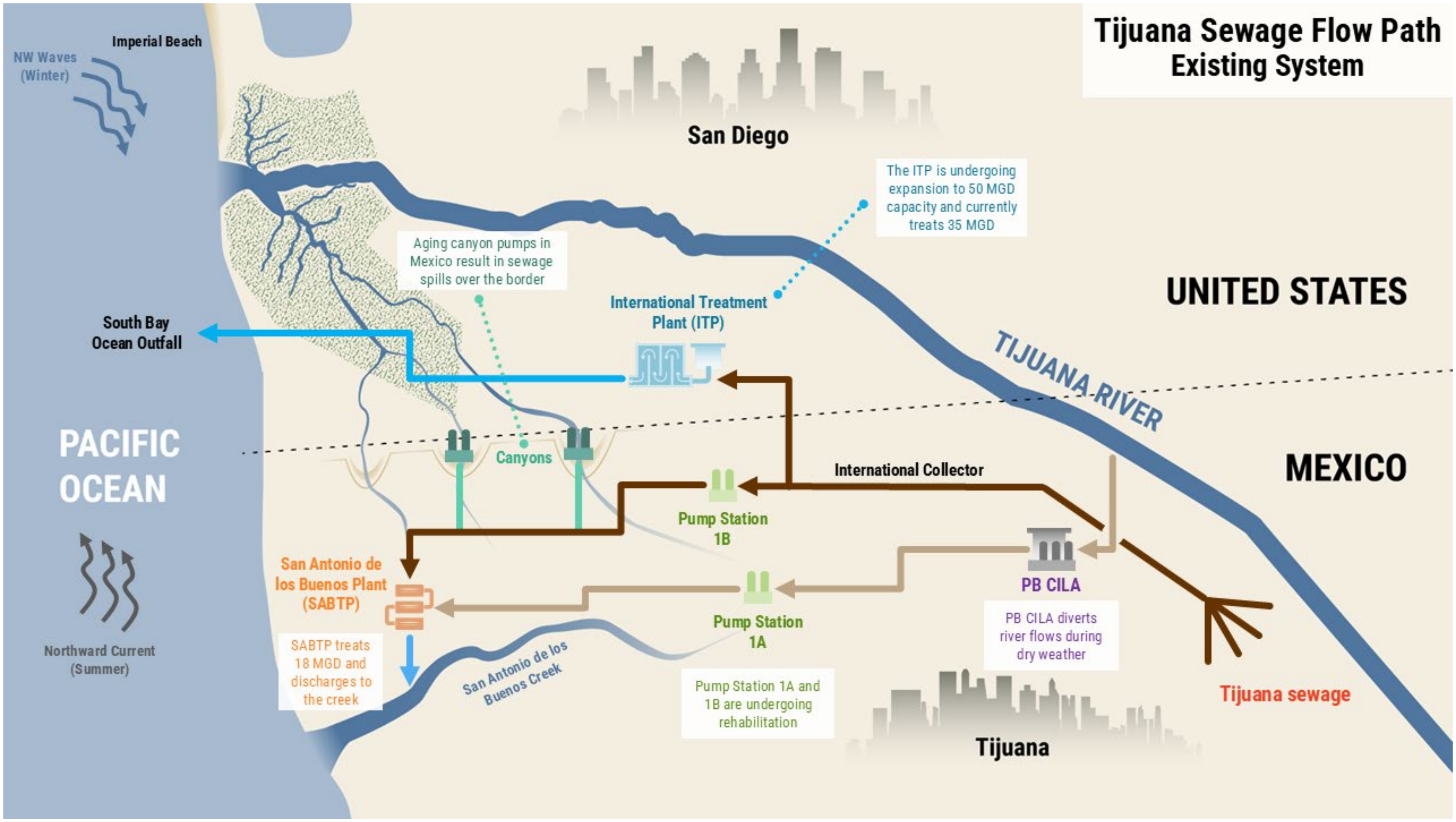


Figure 1: Tijuana Wastewater and River Flow Schematic

Source: [EPA 2021a]

Binational efforts to improve the infrastructure to capture and treat wastewater have been ongoing for decades, but challenges persist. The volume of wastewater originating from Tijuana often exceeds capacity of the International Treatment Plant. Further, both wet and dry weather transboundary flows sometimes exceed the capacity of the canyon collectors, releasing untreated wastewater into the Tijuana River Valley. There have also been many spills and releases of untreated wastewater from aging wastewater facilities.

As outlined in a July 2025 agreement between the United States and Mexico, there have been many ongoing efforts to reduce and prevent wastewater pollution in the Tijuana-San Diego region [EPA 2025]. Among them was a recent increase in the International Treatment Plant's capacity, from 25 million gallons per day to 35 million gallons per day.

Many agencies and organizations are working to better understand and address concerns about hydrogen sulfide exposures. An overview of recent activities is presented in Table 1. In 2024, the County of San Diego released a Health Advisory [HHSA 2024a] and partnered with CDC and ATSDR to conduct two community health surveys [HHSA 2024b, HHSA 2024c], which are further described in Section 3.3. The San Diego County Air Pollution Control District (SDAPCD) monitors hydrogen sulfide levels in air at three locations in the Tijuana River Valley (Figure 2). SDAPCD shares these monitoring results on a public website and issues community notifications when levels exceed the California Ambient Air Quality Standard of 30 ppb [SDAPCD 2024].

SDAPCD also collaborated with the County of San Diego and other agencies, including ATSDR, to develop public health recommendations for community members. These recommendations are also available on the SDAPCD hydrogen sulfide air monitoring website. Additionally, SDAPCD distributes air purifiers to eligible households in areas affected by hydrogen sulfide odors [SDAPCD 2025b]. As of July 31, 2025, 4,752 households had received an air purifier through the program, and only a small portion of users (17%) reported no health improvement [SDAPCD 2025a].

University of California San Diego researchers leveraged community member knowledge to help identify a hydrogen sulfide release hotspot caused by river turbulence [Rico, et al. 2025]. The hotspot is located where the Tijuana River flows under Saturn Boulevard (Figure 2). IBWC and local agencies are exploring solutions to reduce hydrogen sulfide levels at that location [SDPR 2026, Soto 2025]. The County of San Diego also posted hydrogen sulfide exposure warning signs in parts of the Tijuana River Valley in August 2025 [Lightfoot 2025].

As part of ATSDR's public health assessment process, ATSDR staff visited the Tijuana River Valley in June 2025 to learn about the geography of the area and ways that people may be exposed to chemicals in the environment. Over two days, they toured environmental sampling sites, observed how people use the area, experienced hydrogen sulfide odors, and met with multiple agencies and organizations.

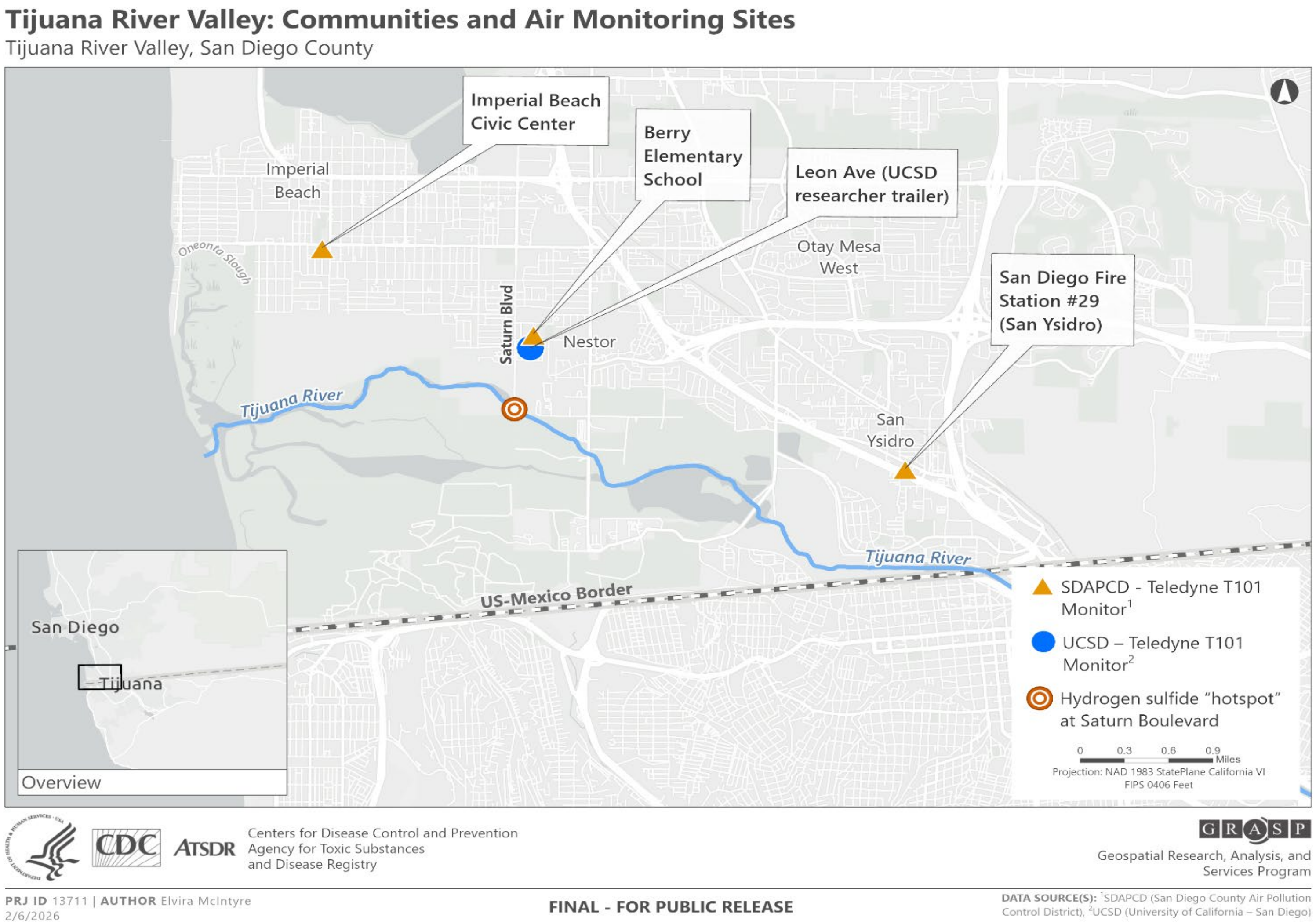


Figure 1: Tijuana River Valley: Communities and Air Monitoring Sites

Table 1. Timeline of recent events related to hydrogen sulfide in the Tijuana River Valley

Date/Year	Event
March 2023	UCSD researchers document bacteria and chemicals in sea spray aerosols [Pendergraft, et al. 2023].
September 2023	SDAPCD begins monitoring hydrogen sulfide and other contaminants using AQMesh sensors.
May 2024	CDC/ATSDR receives a petition from members of the California congressional delegation to investigate the public health impacts of Tijuana wastewater contamination, both in the Tijuana River and in the surrounding communities of Imperial Beach, Coronado, and San Diego.
September 2024	Unusual dry season river flows increase odor complaints. UCSD researchers and San Diego County measure elevated hydrogen sulfide levels. SDAPCD begins hydrogen sulfide monitoring with a Model T101 UV Fluorescence Hydrogen Sulfide (Teledyne T101) Analyzer at San Ysidro. UCSD researchers begin monitoring hydrogen sulfide with a Teledyne T101 at Leon Avenue (Figure 2, Figure 4).
October 2024	County of San Diego and CDC conduct Community Assessment for Public Health Emergency Response (CASPER) survey. County of San Diego and ATSDR conduct Assessment of Chemical Exposure (ACE) survey.
October– December 2024	SDAPCD begins hydrogen sulfide monitoring with Teledyne T101 analyzers at Berry Elementary School and Imperial Beach Civic Center (Figure 2, Figure 4). SDAPCD publishes web-based dashboard with hydrogen sulfide monitoring data. SDAPCD and San Diego County issue community hydrogen sulfide guidance.
January 2025	CDC/ATSDR accepts the petition requests and begins conducting a public health assessment of hydrogen sulfide in the air.
February 2025	SDAPCD begins distributing free air purifiers with High Efficiency Particulate Air (HEPA) filters with activated carbon and potassium permanganate in areas affected by hydrogen sulfide odors.
March 2025	The National Institute for Occupational Safety and Health (NIOSH) completes a Health Hazard Evaluation (HHE), which the City of Imperial Beach requested in August 2024 [Shi 2025].
June 2025	ATSDR conducts site visit for Tijuana River Valley public health assessment.
August 2025	County of San Diego posts hydrogen sulfide exposure warning signs in parts of the Tijuana River Valley.
September – November 2025	IBWC completes a pilot project using ozone nanobubble technology to reduce hydrogen sulfide levels in Tijuana River water [IBWC 2025b].

3. Community Description and Concerns

3.1. Community Demographics

San Diego County, California, spans approximately 4,526 square miles [DPW n.d.]. It includes 18 incorporated cities and several unincorporated areas, featuring a mix of urban and rural communities [HHSA n.d.]. A significant portion of the area is rural, with agriculture playing a vital role in the local economy. Other key economic sectors include aerospace, cybersecurity, life sciences, software, tourism, defense, and manufacturing [SDREDC 2024].

About 10% of the county's population lives below the poverty line [Bureau n.d.]. The five census tracts (6073010009, 6073010109, 6073010104, 6073010110, and 6073010200) surrounding the Tijuana River rank between the 50th and 93rd percentiles for percent of the population living below two times the federal poverty level [OEHHA 2021]. Approximately 45% of the county's population holds a bachelor's degree or higher [Bureau n.d.]. The five census tracts near the river rank between the 25th and 85th percentiles for the percentage of the population older than age 25 years with less than a high school education [OEHHA 2021].

ATSDR's Geospatial Research, Analysis, and Services Program (GRASP) mapped and calculated demographic data in San Diego County within two and five miles of the Tijuana River (Figure 3). The population within two miles of the river totals 104,781. This includes 78,161 individuals identified as Hispanic or Latino, 27,125 as White, 3,002 as Black, 1,662 as American Indian/Alaskan Native, 6,592 as Asian, 373 as Native Hawaiian or Other Pacific Islander, 38,198 as some other race, and 27,830 as two or more races.

In the neighboring resort town of Coronado, which also houses a Navy base, the population totals 18,288 and includes 13,912 individuals identified as White, 3,029 as Hispanic or Latino, 2,225 as two or more races, 820 as some other race alone, 637 as Black, 548 as Asian, 99 as American Indian/Alaskan Native, and 46 as Native Hawaiian & Other Pacific Islander.

A significant portion of the population is classified as socially vulnerable to disasters and ranks at medium to high percentiles for overall social vulnerability [GRASP 2022], raising concerns about the burden of environmental exposures to the community. The five census tracts surrounding the river rank between the 47th and 77th percentiles for age-adjusted rate of emergency department (ED) visits for asthma per 10,000 (averaged over 2015 – 2017) [OEHHA 2021].

Spanish is the most spoken language other than English in San Diego County within a two-mile radius of the Tijuana River. Among those that speak English less than very well, approximately 89% speak Spanish. Other notable languages spoken in the area include Tagalog, Chinese, Vietnamese, African languages, and Japanese [U.S. Census Bureau 2012].

Tijuana River

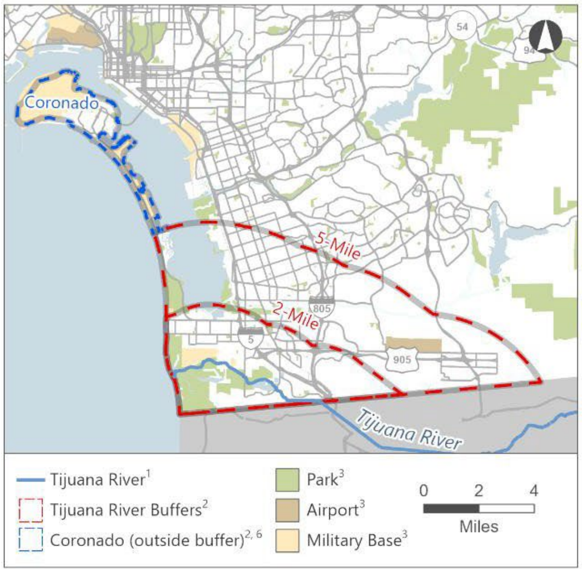
Tijuana River, San Diego County, CA

INTRODUCTORY MAP SERIES

GENERAL SITE PROFILE

EPA FACILITY ID NA

Site Vicinity Map



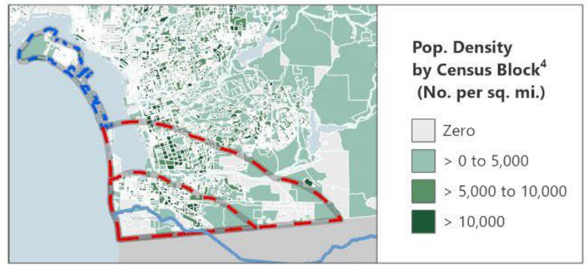
The **General Site Profile Map** depicts the site of interest, along with any airport, industrial, military, or park land uses. It also provides community demographic and housing statistics.

Demographic Statistics[4,5]

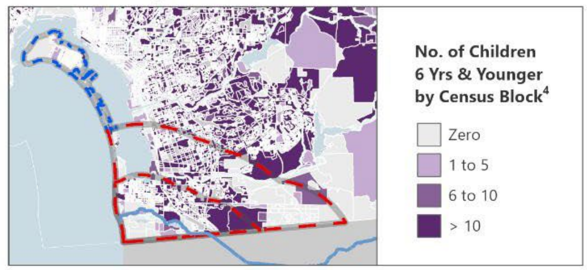
Within specified buffer distances and Coronado[6]

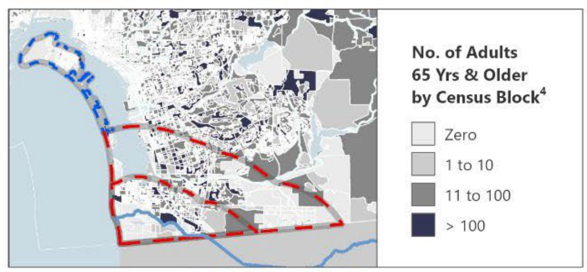
Measure	2-Mile Buffer	5-Mile Buffer	Coronado (outside buffer)
Total Population	104,781	228,975	18,288
White Alone	27,125	55,925	13,912
Black Alone	3,002	8,275	637
Am. Indian/AK Native Alone	1,662	3,720	99
Asian Alone	6,592	18,818	548
Native Hawaiian & Other Pacific Islander Alone	373	1,052	46
Some Other Race Alone	38,198	80,510	820
Two or More Races	27,830	60,681	2,225
Hispanic or Latino[6]	78,161	166,813	3,029
Children Aged 6 and Younger	8,500	18,589	1,090
Adults Aged 65 and Older	13,996	31,570	3,602
Females Aged 15 to 44	22,410	48,622	3,226
Housing Units	32,494	70,352	8,525
Housing Units Pre 1950	1,365	2,981	2,187

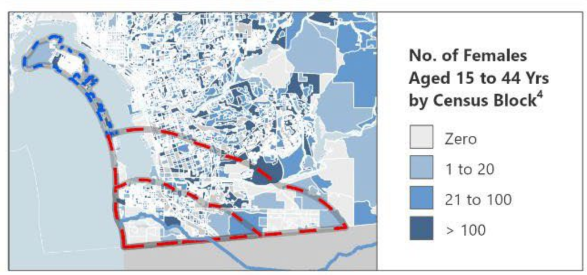
General Population Density



Sensitive Populations







Data Sources: [1]USGS, [2]ATSDR GRASP, [3]TomTom 2021Q3, [4]US Census 2020 Demographic and Housing Characteristics, **Notes:** [5]Calculated using area-proportion spatial analysis method, [6]Individuals identifying origin as Hispanic or Latino may be of any race. [7]Portion of Coronado Census Designated Place located beyond the 5-mile buffer
Coordinate System: Coordinate System used for all map panels is NAD 1983 StatePlane California VI FIPS 0406 Feet

ATSDR Agency for Toxic Substances and Disease Registry

GRASP Geospatial Research, Analysis, and Services Program

PRJ ID 15765 | **AUTHOR** Elvira McIntyre

FINAL - FOR PUBLIC RELEASE

12/10/2025

Figure 3: Demographic Information Within 5-Miles of the Site and Coronado

3.2. Community Concerns

ATSDR sought to understand community views on air quality and odor issues in the Tijuana River Valley through various sources. We used CDC CASPER and ATSDR ACE surveys, news reports, documentary videos, social media comments, and a site visit by ATSDR staff members in 2025. Based on the review and conversations, community members in the south county area are concerned about hydrogen sulfide's effects on human health, animal health, quality of life, and the local economy. On a local news program one resident stated, "The smell some days is so strong it leaves you nauseous with a headache" (NBC 7 San Diego, 00:53 – 00:57) [NBC 7 San Diego 2025].

ATSDR noted the following community concerns:

- Unpleasant odors and health risks from poor air quality caused by hydrogen sulfide, and possibly other contaminants
- Physical health symptoms such as eye irritation, headache, nausea, allergies, and asthma
- Children's unique exposures, and deciding when to cancel outdoor activities such as recess or organized sports practices, or postpone youth sports events
- Reduced enjoyment or use of home, yards, or outdoor recreation areas
- Changed behaviors at home (keeping windows closed, purchasing and maintaining air cleaning devices)
- The health of animals, such as horses boarded near the river and dogs
- Negative impacts of odors on local businesses and tourism
- Frustration over the pace of progress in addressing odors and their root cause
- The quality of drinking water and beach water

ATSDR responses to these concerns are outlined in Section 5.4, Addressing Community Concerns (Table 14).

3.3. Summary of CDC/ATSDR Health Surveys and Investigations

This section summarizes the results of Tijuana River Valley health surveys and evaluations that CDC and ATSDR conducted in response to requests from the County of San Diego and that the NIOSH conducted in response to a request from the City of Imperial Beach.

In June 2024, the County of San Diego Public Health Services requested epidemiological assistance from CDC and ATSDR to assess community health concerns related to the Tijuana River Valley sewage crisis. In response, CDC/ATSDR partnered with the county to conduct two separate health surveys.

- CDC conducted a Community Assessment for Public Health Emergency Response (CASPER) from October 17–19, 2024 [HHSA 2024c]. It assessed health status, experiences, and needs of residents of the South Region of San Diego County, including individual information and community estimates.

- An ATSDR Assessment of Chemical Exposure (ACE) investigation from October 21–November 25, 2024 [HHSA 2024b] collected self-reported exposure and health information. It used an online survey open to people living, working, or visiting the communities of Imperial Beach, Nestor, San Ysidro, Otay Mesa West, Silver Strand, and Coronado.

In addition, in August 2024 the City of Imperial Beach requested a NIOSH Health Hazard Evaluation (HHE), which was completed in March 2025 [Shi 2025]. The HHE evaluated health hazards to City of Imperial Beach workers in the Tijuana River valley and beach by reviewing existing environmental data and health outcomes in conjunction with employee interviews.

3.3.1. Water Exposures

All three assessments (CASPER, ACE, and HHE) evaluated water exposure among different populations in the affected area.

3.3.1.1. CASPER

The CASPER estimated that 8% of households had direct contact with water from the Tijuana River and 16% had contact with water at Imperial Beach, Tijuana Slough, or Silver Strand during closures. These were the lowest exposure estimates, likely because residents were aware of the contamination and took steps to reduce risk. Many households reported decreasing beach visits (66%) and time spent outdoors (61%). The CASPER reported bottled water to be the main drinking source for 67% of households.

3.3.1.2. ACE

The ACE found that 24% of respondents had direct contact with contaminated river or beach water while beaches were officially closed. It also assessed recreational activities near affected areas, with 31% of respondents reporting such activities, including swimming (16%), surfing (7%), boating (6%), and fishing (5%). Among 35 respondents who were City of Imperial Beach employees, 43% reported direct contact with beach or river water at work in the past 30 days. Overall, higher exposure estimates in ACE may reflect that it included non-residents, such as workers and visitors, and used a convenience sample. The ACE reported high use of bottled (70%) and filtered (63%) drinking water among respondents when in the affected area.

3.3.1.3. HHE

The HHE included meetings with employee representatives, who reported frequent water exposure while working, particularly among Marine Safety (e.g., lifeguards) and Public Works (e.g., maintenance staff). Inconsistent use of protective measures and sanitation practices were reported following exposure.

3.3.2. Air Exposures

The CASPER reported that a high percentage (94%) of households noticed a sewage smell in the past month, with most (69%) reporting the smell was strongest in the evening or at night. Among ACE respondents, 95% reported a sewage smell within the last 30 days, with the intensity of the smell correlating with the reported frequency.

3.3.3. Health Outcomes

The CASPER reported that 45% of households had at least one health symptom in the last month. Headache (80%), GI issues (76%), cough (62%), and dry or irritated throat (61%), and dizziness (51%) were most common. Seventy percent of ACE respondents with direct contaminated river or beach water contact reported symptoms. The most common were headache (58%), runny nose (54%), eye irritation (52%), congestion (50%), coughing (50%), and nausea (46%). Symptoms were more common among ACE respondents with direct water exposure and also included GI symptoms and skin related symptoms. Workers with direct water exposure reported symptoms including headache (73%), runny or stuffy nose (80%), eye irritation (73%), coughing (80%), and burning nose or throat (60%). Reported physical symptoms were consistent across all three evaluations. Symptoms, while general, are consistent with exposure to contaminated water (bacteria, viruses, heavy metals, persistent organic pollutants) and hydrogen sulfide [EPA 2021b, HHSA 2024a, Szczęsna, et al. 2023].

3.3.4. Mental Health

Sixty-five percent of ACE respondents reported mental health symptoms they felt were related to the sewage contamination, with 28% of respondents reporting anxiety and 21% reporting depression symptoms. In the CASPER, over half of households reported increased stress (58%), trouble sleeping (56%), or signs of emotional distress (63%) due to the sewage contamination. Community estimates from the CASPER indicate 14% of residents screened positive for depression using the PHQ-2 scale and 12% of residents screened positive for anxiety using the GAD-2 scale. Additionally, the HHE identified that 60% of workers with direct water exposure and 30% of workers without direct water exposure reported experiencing mental health symptoms due to sewage contamination. The number of households indicating they have changed their daily routines (35%) likely contributes to the high household awareness (85%) and increase in mental health symptoms.

3.3.5. Health Surveys: Conclusion

Despite a small proportion of the population having direct contact with contaminated water, the community is experiencing impacts on both physical and mental health. Physical symptoms appear to be mild, as evidenced by the lack of healthcare-seeking behavior among both CASPER (18% of households) and ACE (21% of respondents), but still have significant impact on the community. Respondents to the CASPER (70% of households with symptoms) believed their symptoms improved when outside the Tijuana River valley area. The ACE consistently demonstrated a greater prevalence of physical and mental symptoms among those exposed to contaminated water in the past 30 days. Employees interviewed during the HHE expressed concerns about increased risk due to exposure related to inconsistent access to PPE, limited decontamination resources, and inconsistent sanitation practices. Ongoing communication about prevention measures, including consistent PPE use, may reduce exposure.

4. Sampling Data

This section describes the data that ATSDR used for this report. Only air exposures are evaluated in this report, thus we focus on air data here. A separate report will be released later that evaluates additional exposure pathways.

4.1. Outdoor Air Data

In late 2024, ATSDR began requesting environmental sampling data from academic, local, state, and federal partners. ATSDR received responses from the San Diego County Air Pollution Control District (SDAPCD) and University of California San Diego (UCSD) researchers indicating that they had potentially relevant air data. ATSDR requested air data through April 2025 from both organizations to ensure that the data spanned the area's typical November to March rainy season.

ATSDR also received electrochemical device sampling data from the San Diego County Environmental Health and Quality, but these data were not of sufficient quality for use in a public health assessment. In general, field screening results from these devices can be considered in the PHA process, but more refined sampling techniques are needed to provide the type of data needed to make public health conclusions [ATSDR 2022].

Additional information about the air datasets ATSDR received from SDAPCD and UCSD are provided below.

4.1.1. SDAPCD Outdoor Air Data:

SDAPCD provided data collected between September 25, 2023, and May 5, 2025, that consisted of the following:

- 1-minute data from Model T101 UV Fluorescence H_2S Analyzer by Teledyne API (TeledyneT101) equipment monitoring for hydrogen sulfide
- 15-minute data from AQMesh equipment monitoring for hydrogen sulfide (H_2S), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and total volatile organic compounds (TVOC)
- Meteorological data collected at the U.S. Navy's Imperial Beach Outlying Landing Field

4.1.1.1. Data Quality and Monitoring Locations

SDAPCD identified data quality issues with the AQMesh equipment when comparing the AQMesh monitoring data to their Teledyne101 air monitors. A correction factor could not be calculated for the AQMesh monitors measuring hydrogen sulfide. Further communication with SDAPCD indicated that data for other contaminants that ATSDR could evaluate that were measured using the AQMesh were not of sufficient quality when analyzed in an informal sensor-to-sensor comparison, and so SDAPCD advised ATSDR to not use the AQMesh data as part of the consultation.

Therefore, ATSDR excluded data from AQMesh monitors from this analysis. As a result, the AQMesh monitoring sites excluded in this analysis are the Tijuana River Valley Campground, International Wastewater Treatment Plant, and Imperial Beach Pier. The contaminants excluded from this analysis are CO, NO_2, SO_2, and TVOC. Therefore, only hydrogen sulfide exposures are evaluated in this health consultation.

SDAPCD's TeledyneT101 monitoring data were deemed to be of sufficient quality for this analysis. SDAPCD began collecting hydrogen sulfide monitoring data with TeledyneT101 monitors at three locations at different times:

- San Diego Fire Station # 29 in San Ysidro on September 17, 2024
- Berry Elementary School on October 9, 2024
- Imperial Beach Civic Center on December 24, 2024

Monitoring locations are shown in Figure 4.

On occasion, the monitors experienced operational errors and readings were flagged for potential bias. At the San Diego Fire Station #29 site in San Ysidro, the instrument experienced calibration issues on September 12, 2024, and was recalibrated on September 16, 2024. The Teledyne T101 monitor at Berry Elementary School also produced data flagged for calibration or ambient issues. All calibration-related and otherwise flagged measurements were excluded from the final dataset. Because these problematic readings were removed, the issues were not expected to affect the quality of the valid data collected when the equipment was functioning properly.

4.1.2. UCSD Outdoor Air Data:

The data that UCSD provided was collected from September 1, 2024 to May 1, 2025 and consisted of the following:

- 1-minute data from TeledyneT101 equipment monitoring for hydrogen sulfide
- Meteorological data collected via collocated MODULAIR^{TM} air quality monitors

4.1.2.1. Data Quality and Monitoring Locations

UCSD's TeledyneT101 data were deemed to be of sufficient quality for this assessment. The UCSD TeledyneT101 monitoring site was on private property on Leon Avenue. ATSDR estimates that this monitoring site is only approximately 600 feet from SDAPCD's Berry Elementary School monitoring site. Monitoring locations are shown in Figure 4.

4.1.3. Summary of Available Outdoor Air Data

Table 2 summarizes the data sources used in this assessment and the monitoring locations.

Table 2: Outdoor Air Data Sources

Location	Data Source	Monitor
San Diego Fire Station #29 (San Ysidro)	SDAPCD	TeledyneT101
Berry Elementary School	SDAPCD	TeledyneT101
Leon Ave (UCSD researcher trailer on private property)	UCSD	TeledyneT101
Imperial Beach Civic Center	SDAPCD	TeledyneT101

Abbreviations: SDAPCD = San Diego Air Pollution Control District; UCSD = University of California San Diego

Figure 4 shows the locations of the monitoring equipment for both SDAPCD and UCSD. Figure 4 also shows the population density around the Tijuana River Valley, and where the monitoring sites are relative to the locations of the surrounding communities.

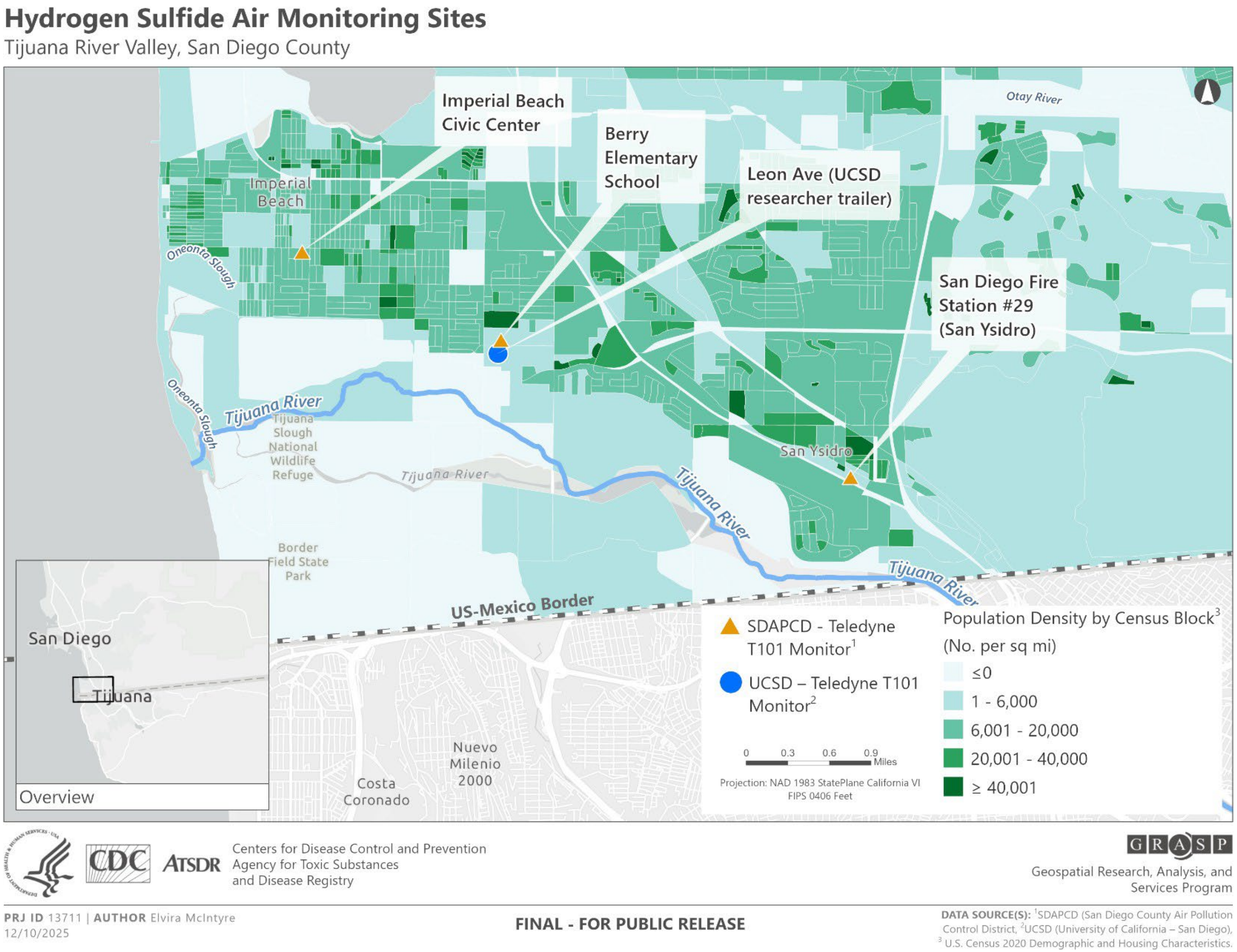


Figure 4: Air Monitoring Locations

Summary statistics of the air data ATSDR used in this evaluation are provided in Table 3. Briefly, ATSDR used data collected from September 2024 to May 2025 at four monitoring locations. Data were collected at San Diego Fire Station #29 and the Leon Ave monitoring sites beginning in September 2024, but data collection did not begin at Berry Elementary School or Imperial Beach Civic Center until October 2024 and December 2024, respectively. Between 139,719 and 262,373 measurements for each monitoring site were analyzed for this report.

Hydrogen sulfide outdoor air concentrations were low enough that the equipment could not detect its presence in air 4-30% of the time depending on the monitoring location. Most of the time, the TeledyneT101 equipment was able to detect hydrogen sulfide in outdoor air. The detection limit for the TeledyneT101 is 0.4 ppb. Hydrogen sulfide concentrations in outdoor air ranged from below the detection limit to 4,513 ppb (4.513 parts per million [ppm]). Even though the San Diego Department of Environmental Health and Quality's photoionization device (PID) data is not appropriate for use in this analysis, one PID data point indicates that hydrogen sulfide levels at the location where the Tijuana River flows under Saturn Boulevard (Figure 2) reached up to 15,500 ppb (15.5 ppm) on September 9, 2024.

Table 3: Summary Statistics for Outdoor Air Data Sources

Location	Date Range	Number of Measurements	Non-detects	Range of Measurements (ppb)
San Diego Fire Station #29 (San Ysidro)	9/17/24–5/2/25	139,719	30%	<0.4–80
Berry Elementary School	10/9/24–5/5/25	262,373	4%	<0.4–1,455
Leon Ave (UCSD)	9/1/24–5/1/25	231,665	14%	<0.4–4,513
Imperial Beach Civic Center	12/24/24–5/5/25	185,195	11%	<0.4–384

Abbreviation: ppb = parts per billion; UCSD = University of California San Diego

The polar plots in Figure 5 show that hydrogen sulfide levels at the Berry Elementary and Leon Avenue monitoring locations were highest when wind speeds were low, regardless of which direction the wind was blowing. The higher concentrations appear as red, orange, and yellow shading near the center of the plots.

This finding suggests there is a hydrogen sulfide source, or sources, located close to these two monitoring sites. When winds are calm, hydrogen sulfide builds up at the monitors. When winds are stronger, the hydrogen sulfide disperses, and concentrations drop. Because high concentrations occur during low winds from all directions, not just from one specific direction, the source is likely very near these locations. The other two monitoring sites show different patterns, indicating they are not as close to a hydrogen sulfide source.

4.1.4. Correlation of Hydrogen Sulfide Concentrations Between Berry Elementary School and Leon Avenue Monitoring Sites

In September 2024, the highest hydrogen sulfide concentrations were detected at the Leon Avenue monitoring location, but monitoring had not yet begun across the street at Berry Elementary school. Outdoor air monitoring at Berry Elementary School began October 9, 2024. Because children spend many hours at the school and represent a sensitive population, ATSDR thought it was important to understand what exposure levels could have been at Berry Elementary in September 2024, given that the highest levels of hydrogen sulfide in air were detected during this time period.

To better understand Berry Elementary school exposures before monitoring began at the site, ATSDR assessed how closely related the school and Leon Avenue hydrogen sulfide concentrations were when data were available from both sites at the same time (Appendix C). Analysis showed that hydrogen sulfide concentrations at Leon Ave and Berry Elementary School were significantly correlated with each other overall, with a statistically small difference of 0.69 ppb (Table 18). When comparing different periods of time in the data, all visually matched well with each other. There was one period when the two locations were significantly different, with a difference of 1.65 ppb. These results indicate that the hydrogen sulfide concentrations at the two locations were similar but not always perfectly aligned.

4.2. Odor Complaints

SDAPCD collects odor complaints from residents in the South Bay area [SDAPCD 2025c] via an app, by telephone, or by email. The odor complaint data that ATSDR received from SDAPCD consisted of the complaint record ID, the date received, location of the odor complaint, and nature of the odor complaint. Over 1,382 odor complaints were received September 17, 2024–May 5, 2025, for zip codes 91901, 91911, 91932, 92105, 92116, 92118, 92131, and 92154.

Most, but not all, environmental odor complaints were related to hydrogen sulfide odors in the Tijuana River Valley. ATSDR removed complaints unrelated to hydrogen sulfide odors for analysis (total complaints removed=9). When a specific location was not provided by the reporting party, SDAPCD assigned the complaint a generic location. Many complaints had generic locations, preventing meaningful spatial analysis based on the specific location of complaints.

To analyze the odor complaints, ATSDR calculated two-day rolling averages from 24-hour time averages of hydrogen sulfide concentrations for each monitoring location. ATSDR selected two days to account for the fact that some people may not report a strong odor at night until the following morning. ATSDR compared the two-day hydrogen sulfide averages with the number of odor complaints by day and found that odor complaints appeared to trend with hydrogen sulfide concentrations. Results are shown in Appendix B in Figure 8 (Berry Elementary School), Figure 9 (Leon Avenue), Figure 10 (Imperial Beach Civic Center), and Figure 11 (San Diego Fire Station #29, San Ysidro).

4.3. River Flow Rates

ATSDR conducted a limited assessment of how Tijuana River flow rates affect hydrogen sulfide concentrations in the Tijuana River Valley. ATSDR compared one-hour average flow rates at the International Wastewater Treatment Plant to matching one-hour averages of hydrogen sulfide readings from the Leon Avenue monitoring location from September 1–22, 2024 (Figure 12). This was a period when high hydrogen sulfide concentrations were detected. ATSDR found that hydrogen sulfide concentrations trended higher when flow rates were higher, which aligns with a previous report that odor complaints increased when flow rates increased during the same period of time [Rico, et al. 2025]. The full relationship between river flow, both during dry-weather and wet-weather events, and hydrogen sulfide levels is not fully understood.

5. Scientific Evaluations

After examining the available site-specific information and data, ATSDR's next step is to perform a sequence of steps that include:

- Evaluating site-specific exposure scenarios and potential exposure pathways (Section 5.1)
- Comparing contaminant concentrations to media-specific screening levels (Section 5.2.2)
- Estimating exposure concentrations (Section 5.2.3)
- Analyzing toxicological information for contaminants, if warranted, to assess potential health risks (Section 5.3)

This section explains ATSDR's scientific evaluation of potential exposures and health risks due to chemicals in outdoor air in the Tijuana River Valley. This health consultation only addresses exposures to hydrogen sulfide in the air. Additional exposure pathways (i.e. exposure to chemicals in the Tijuana River, soils, sediments, etc.) will be evaluated in a separate public health assessment that ATSDR will release later.

5.1. Exposure Pathway Analysis

To evaluate whether a contaminant in outdoor air will affect human health, ATSDR must first evaluate the site's exposure pathways. An exposure pathway is the link between an environmental release or source and the point where a population might come into contact with the environmental contaminant [ATSDR 2025a].

ATSDR determines whether exposure pathways are complete, potential, or eliminated before assessing whether exposures will result in harmful health effects. For people to be exposed to a chemical contaminant, they must come into direct contact with the contaminant through a completed exposure pathway. A completed exposure pathway consists of five main parts:

1. A **source** of contamination (e.g., chemicals in the Tijuana River)
2. A method of environmental **transport** (air, water, soil, sediment, etc.) that allows the contaminants to move from the source area to a point where they contact people
3. A **point of exposure** where people come into physical contact with the contaminant

4. A **route of exposure** (ingestion, inhalation, or skin contact), which is how a contaminant enters people's bodies
5. A **population at risk**, i.e., people likely to come into contact with the contaminant

For people who live, work, recreate, go to school, or spend time doing other activities in or near the Tijuana River Valley, a completed exposure pathway exists for hydrogen sulfide in air. That is, hydrogen sulfide is present in and released from the Tijuana River (source), migrates through outdoor air (transport) to areas in the Tijuana River Valley (point of exposure) where people (populations at risk) inhale hydrogen sulfide (route of exposure).

Though a completed exposure pathway exists, physical contact with a contaminant alone does not necessarily result in harmful health effects. A contaminant's ability to affect a person's health depends on:

- How much of the contaminant a person is exposed to (dose)
- How long a person is exposed (duration)
- How often a person is exposed (frequency)
- The toxicity of the contaminant (how contaminants interact with the body to make people sick)

5.2. Outdoor Air Evaluation

This section describes how ATSDR initially evaluates, or screens, chemicals to determine if exposure to a chemical warrants further evaluation. Statistical analyses of hydrogen sulfide in outdoor air over time at each monitoring location were conducted in R version 4.5.0, using the openair package [R 2025].

5.2.1. Overview

After determining that both a completed exposure pathway exists and that there are data of sufficient quality and representativeness to conduct an assessment, the human health evaluation takes place in two steps:

- Step 1, **Screening Analysis**: Maximum contaminant concentrations are compared to screening values to determine which contaminants exceed health-based comparison levels and require further evaluation.
- Step 2, **Evaluation of Health Implications**: Detailed evaluations are completed for any contaminant that exceeds screening values.

5.2.2. Screening Analysis

5.2.2.1. Background on Comparison Values (CVs) and Minimal Risk Levels (MRLs)

To conduct a screening analysis, ATSDR compares maximum detected chemical concentrations to screening values. For screening values, ATSDR uses its chemical- and media-specific comparison values (CVs). ATSDR's CVs are always chemical concentrations in a specific medium—like water, soil, or air—that are not likely to cause harmful health effects to exposed people. If a contaminant concentration meets or exceeds a CV, it does not mean that harmful health effects will occur, but rather that further evaluation is necessary. Contaminants with detected concentrations less than CVs are not expected to result in harmful health effects and do not require further analysis.

ATSDR develops separate values, called health guidelines or Minimal Risk Levels (MRLs), that are usually expressed as doses (the amount entering the body). MRLs estimate the daily exposure level unlikely to cause adverse (noncancer) health effects and are not regulatory action levels [ATSDR 2024c]. **For inhalation, the ATSDR CVs are the same as the MRLs and are concentrations in air.**

5.2.2.2. CVs and MRLs for Hydrogen Sulfide in Air

For exposures to hydrogen sulfide in air, two types of CVs are available:

- ATSDR inhalation environmental media evaluation guides (EMEGs)
    - Estimate hydrogen sulfide air concentrations that people could breathe without harmful noncancer effects for **acute** (1-14 days) or **intermediate** (15-364 days) exposure durations.
    - Are the same as the corresponding hydrogen sulfide acute and intermediate MRLs.
- ATSDR inhalation reference dose media evaluation guides (RMEG)
    - Represents a hydrogen sulfide air concentration at which **chronic** (365 days and longer) daily hydrogen sulfide exposure is unlikely to result in noncancer health effects.
    - Is the same as the corresponding EPA reference concentration (RfC). EPA RfCs are estimates of the concentrations of pollutants that anyone could be exposed to for a lifetime without experiencing health effects [EPA 2024].

ATSDR's acute inhalation MRL, and thus the acute CV, is 70 ppb. ATSDR's intermediate inhalation MRL, and thus its intermediate air CV, and EPA's chronic RfC are derived from the same study by Brenneman, et al. 2000. In that study, 460 ppb was identified as the lowest human-equivalent adjusted concentration that did not cause health effects, and it was used to derive both the MRL and the RfC. ATSDR applied an uncertainty factor of 30 to develop its MRL to account for extrapolation from animals to humans with dosimetric adjustment and the variability between humans. Thus, ATSDR's intermediate inhalation MRL is 20 ppb (460 ppb ÷ 30 = 15 ppb, rounded to one significant figure = 20 ppb). EPA applied an uncertainty factor of 300, adding an additional factor of 10 to account for the study being a subchronic study (e.g. 10 weeks) instead of full chronic study. EPA initially conducted its calculations in mg/m^3, which resulted in an RfC of 0.002 mg/m^3 (1.4 ppb).

5.2.2.3. Conducting a Screening Analysis

For screening, ATSDR compares the maximum measured concentration of each contaminant to the appropriate CV for that contaminant (in this case, the hydrogen sulfide air CVs). This health consultation evaluates only hydrogen sulfide (see Section 4.1.1.1). Because hydrogen sulfide has not been shown to cause cancer in humans [ATSDR 2016], no cancer risk screening or evaluation was conducted.

This section discusses ATSDR's comparison of the maximum hydrogen sulfide air concentrations across monitoring sites to ATSDR's CVs for hydrogen sulfide in air. A contaminant only needs to meet or exceed the lowest CV to warrant further evaluation, but all available hydrogen sulfide air CVs are presented for comparison in Table 4.

Table 4: Screening results for hydrogen sulfide in air

Location	Maximum Hydrogen Sulfide Concentration (ppb)*,**	Acute EMEG (ppb)	Intermediate EMEG (ppb)	Chronic RMEG (ppb)
San Diego Fire Station #29 (San Ysidro)	80	**70**‡	**20**‡	**1.4**‡
Berry Elementary School	1,455	**70**‡	**20**‡	**1.4**‡
Leon Avenue	4,513	**70**‡	**20**‡	**1.4**‡
Imperial Beach Civic Center	384	**70**‡	**20**‡	**1.4**‡

Abbreviations: ppb = parts per billion; EMEG = environmental media evaluation guides; RMEG = reference dose media evaluation guides

‡**Bold text** = CV was exceeded
Acute EMEG = ATSDR Acute minimal risk level (MRL); Intermediate EMEG = ATSDR Intermediate MRL; chronic RMEG = EPA reference concentration (RfC)
*Maximum 1-minute hydrogen sulfide readings are used for this comparison
**Background levels of hydrogen sulfide in urban areas in the United States range from 0-1 ppb [ATSDR 2016].

Hydrogen sulfide concentrations in air exceeded all of ATSDR's hydrogen sulfide air CVs at all monitoring locations. Therefore, hydrogen sulfide air exposures warranted further evaluation, which is discussed in the following sections. Figure 6 shows how daily average hydrogen sulfide concentrations compared to the acute, intermediate, and chronic screening levels. Similarly, Figure 7 shows the 30-minute averages for the four locations compared to the screening levels.

5.2.3. Exposure Point Concentrations

Chemicals that exceed CVs are further evaluated by calculating Exposure Point Concentrations (EPCs). An EPC is a conservative estimate of a chemical concentration, usually a maximum value or a 95% upper confidence limit of the arithmetic mean (95UCL). It represents the amount of chemical a person might contact over some time period, for each area of exposure and route of exposure. The EPC may be adjusted to account for the duration, frequency, and time of exposure based on the actions and habits of the exposed population. The adjusted EPCs are then compared to health guidelines (i.e. MRLs or RfCs) specific to each contaminant and exposure duration to determine if there is a health risk.

For air monitoring data, ATSDR calculates descriptive statistics to use as EPCs. Because hydrogen sulfide air concentrations (and thus EPCs) can be compared directly to hydrogen sulfide air concentrations used in scientific studies, ATSDR did not need to also calculate exposure doses for this analysis. Later in ATSDR's process, EPCs are compared to chemical concentrations used in scientific studies to determine if a health effect is likely (Section 5.3).

To complete the EPC analysis, ATSDR calculated hydrogen sulfide EPCs for each monitoring location and exposure duration (i.e. acute, intermediate, and chronic exposures). The EPCs are described in Sections 5.2.3.1-5.2.3.3.

5.2.3.1. Acute Exposure EPCs

The acute hydrogen sulfide inhalation MRL and CV (70 ppb) was based on a study that exposed adults to 2,000 ppb hydrogen sulfide for 30 minutes [ATSDR 2016, Jäppinen, et al. 1990]. To provide the best comparison to the Jäppinen et al. study, ATSDR calculated rolling 30-minute averages of measured hydrogen sulfide air concentrations. Because a true average could be calculated from the measured air data, it was not necessary to calculate a 95UCL for the EPC. Therefore, the maximum 30-minute rolling average for each location was used as the EPC.

Rolling averages smooth out data by calculating averages over a moving time window. To create 30-minute rolling averages from air measurements taken every minute, ATSDR started by averaging the first 30 minutes of data (minutes 1-30). ATSDR then shifted forward by one minute to average minutes 2-31, then shifted forward again to average minutes 3-32, and kept repeating until reaching the end of the data. Rolling averages are useful because they help people see trends by reducing moment-to-moment fluctuations in the data. Instead of seeing every spike and dip, people see the general pattern over time, making it easier to spot when levels were generally high or low throughout the day. The limit of detection for each measurement was substituted for non-detections for the analysis.

While 5.2% of 30-minute averages exceeded the MRL at the Leon Avenue monitoring location, only 0.04% of 30-minute averages exceeded 2000 ppb, which was the level shown to cause health effects in the Jäppinen, et al. 1990 study. Rolling 30-minute averages exceeded the MRL at the Imperial Beach Civic Center and Berry Elementary school 0.4% and 2.0 % of the time, respectively. The health effect level (2000 ppb) was exceeded at Leon Avenue only during periods of time from September 8–10, 2024.

Table 5: Acute EPCs

Location	Maximum 30-Min Rolling Average (ppb)*	Percent of 30-Min Rolling Averages that Exceeded Acute MRL**, Health Effect Level†
San Diego Fire Station #29 (San Ysidro)	48.2	0%, 0%
Berry Elementary School	749.2	2.0%, 0%
Leon Avenue	3,021.5	5.2%, 0.04%
Imperial Beach Civic Center	333.0	0.4%, 0%

Abbreviations: EPCs = exposure point concentrations; ppb = parts per billion; MRL = minimal risk level
*This is the EPC for each location
**Acute MRL is 70 ppb
†Health Effect Level for acute effects is 2000 ppb [ATSDR 2016], [Jäppinen, et al. 1990]

As ATSDR heard during the site visit and as indicated in the ACE survey results, hydrogen sulfide odors can seem stronger at night. To further explore this, ATSDR compared acute EPCs during the day and during the night (Appendix B, Table 15 and Figure 13). With the exception of San Diego Fire Station #29, the highest 30-minute rolling average across all sites was measured at night. This difference between daytime and nighttime EPCs was most pronounced at the Imperial Beach Civic Center, where the nighttime EPC (333 ppb) was nearly six times higher than the daytime EPC (54 ppb). The Berry Elementary School nighttime EPC (749 ppb) was twice the daytime EPC (318 ppb). The nighttime EPC was also higher at the Leon Avenue monitoring location. The most likely explanation for this is that at night, air doesn't mix upward as much as it does during the day. As a result, concentrations of chemicals like hydrogen sulfide can build up more during the nighttime hours. Other reasons could be daytime/nighttime differences in flow patterns, sewage levels, wind patterns, and any combination of these factors.

5.2.3.2. Intermediate EPCs

The intermediate MRL study, which is also the basis of EPA's chronic RfC used in this report's chronic analysis, exposed rats to hydrogen sulfide intermittently for 10 weeks and was adjusted for continuous 24-hour exposure [ATSDR 2016, Brenneman, et al. 2000]. To reflect exposure conditions in the Tijuana River Valley, which could include exposures lasting 24 hours for 7 days a week, ATSDR calculated 14-day rolling averages. Intermediate exposures are typically 15 to 364 days, so the 14-day rolling average (representing a full 14 days of exposure) is a more conservative approach to estimating intermediate exposures. Additionally, because a well-defined average could be calculated, it was not necessary to calculate a 95UCL for the EPC. The maximum 14-day rolling average for each location was used as each location's EPC (Table 6).

ATSDR's intermediate air inhalation MRL is 20 ppb. Roughly 13% of 14-day averages at Leon Avenue exceeded the intermediate hydrogen sulfide MRL, and roughly 9% of 14-day averages at Berry Elementary School exceeded the intermediate MRL (Appendix B, Figure 14). Averaged 14-day concentrations at the other two locations did not exceed the MRL. ATSDR's MRL is derived from the lowest adjusted human-equivalent hydrogen sulfide level (460 ppb) that caused no health effects in the Brenneman, et al. 2000 study. Fourteen-day rolling averages did not exceed this level (460 ppb) at any monitoring location.

Table 6: Intermediate EPCs

Location	Maximum 14-Day Rolling Average (ppb)*	Percent of 14-Day Rolling Averages Exceeded MRL**, Health Effect Level†
San Diego Fire Station #29 (San Ysidro)	3.3	0%, 0%
Berry Elementary School	31.6	8.9%, 0%
Leon Avenue	151.9	12.7%, 0%
Imperial Beach Civic Center	7.6	0%, 0%

Abbreviations: EPCs = exposure point concentrations; ppb = parts per billion; MRL = minimal risk level
*This is the EPC for each location
**Intermediate MRL is 20 ppb
†Health Effect Level for intermediate effects is 1380 ppb

5.2.3.3. Chronic EPCs

ATSDR used all data from eight months (or less depending on the location) of air monitoring to estimate chronic exposures. Per ATSDR's guidance, it is appropriate to calculate a 95UCL to estimate chronic exposures [ATSDR 2023]. However, the Tijuana River Valley air monitoring data had significant autocorrelation, which indicated that the data were not independent. To address the dependence of the data, 95UCLs were adjusted with effective sample size (ESS). Using ESS helps calculate a 95UCL for autocorrelated data as though the data were from a random sample. The ESS was calculated based on the 1-min raw data to estimate the 95UCL of the sampling period. The chronic EPCs for each of the four locations are presented in Table 7.

The same study that ATSDR used to develop the intermediate inhalation MRL (Brenneman, et al. 2000) was used by EPA to develop the chronic RfC (1.4 ppb). The RfC was exceeded at all four monitoring locations, but all chronic EPCs were much lower than the lowest adjusted human-equivalent hydrogen sulfide level (460 ppb) that caused no health effects in the Brenneman, et al. 2000 study. ATSDR discusses limitations of the chronic database in Section 5.3.6.4.

Table 7: Chronic EPCs

Location	95UCL (ppb)*
San Diego Fire Station #29 (San Ysidro)	2.8
Berry Elementary School	9.2
Leon Avenue	23.6
Imperial Beach Civic Center	4.0

Abbreviations: EPCs = exposure point concentrations; 95UCL = 95 percent upper confidence limit of the arithmetic mean; ppb = parts per billion
*This is the chronic EPC for each location

5.3. Health Effects Evaluation

This section describes how ATSDR compared the EPCs for each of the four locations to health guidance values and how ATSDR interprets the results.

5.3.1. Background on Hydrogen Sulfide and Hydrogen Sulfide Health Effects[1]

Hydrogen sulfide is a flammable, colorless gas that smells like rotten eggs. People usually can smell hydrogen sulfide at low concentrations in air, ranging from 0.5 to 300 ppb hydrogen sulfide. At high concentrations, a person might lose their ability to smell it. This is important because a person might falsely think that hydrogen sulfide is no longer present; this may increase their exposure risk to air levels that may cause serious health effects.

Hydrogen sulfide occurs both naturally and from human-made processes. It is in gases from volcanoes, sulfur springs, undersea vents, swamps, stagnant bodies of water, and in crude petroleum and natural gas. Hydrogen sulfide is also associated with municipal sewers and sewage treatment plants, swine containment and manure-handling operations, and pulp and paper operations. Other industrial sources of hydrogen sulfide include petroleum refineries, natural gas plants, petrochemical plants, coke oven plants, food processing plants, and tanneries. Bacteria found in your mouth and gastrointestinal tract produce hydrogen sulfide during the digestion of food containing vegetable or animal proteins.

Most of the hydrogen sulfide released into air comes from natural sources such as swamps, bogs, and volcanoes. Hydrogen sulfide can also be released from any of the aforementioned industrial sources. Hydrogen sulfide air concentrations from natural sources range between 0.11 and 0.33 ppb. In urban areas, the air concentrations are generally less than 1 ppb. Hydrogen sulfide remains in the atmosphere for approximately 1–42 days, depending on the season. It can change into sulfur dioxide and sulfates in the air.

[1]This information in section 5.3.1 is available in the Hydrogen Sulfide and Carbonyl Sulfide Toxicological Profile Public Health Statement and can be found here: https://www.atsdr.cdc.gov/ToxProfiles/tp114-c1.pdf.

Hydrogen sulfide might be released to water in liquid waste of an industrial facility or as the result of a natural event. It can be naturally present in well water. Hydrogen sulfide concentrations in surface water are usually very low because it readily evaporates from oxygenated water. It can also be present in groundwater. Groundwater concentrations of hydrogen sulfide are generally less than 1 ppm; however, measured sulfur concentrations in surface and waste waters have ranged from slightly less than 1 to 5 ppm. Hydrogen sulfide can enter soil through atmospheric deposition or from spills. In soil, hydrogen sulfide is consumed by bacteria, which change it to sulfur.

Hydrogen sulfide enters your body primarily through the air you breathe. Much smaller amounts can enter your body through the skin. Hydrogen sulfide is a gas, so you would not likely be exposed to it by ingestion. When you breathe air containing hydrogen sulfide or when hydrogen sulfide comes into contact with skin, it is absorbed into the blood stream and distributed throughout the body. In the body, hydrogen sulfide is primarily converted to sulfate and is excreted in the urine. Hydrogen sulfide is rapidly removed from the body.

You are not likely to have health effects if you are exposed to typical environmental concentrations of hydrogen sulfide. You can have respiratory and neurological effects if you are exposed to higher concentrations of hydrogen sulfide. The effects can include

- Eye irritation
- Nose irritation
- Throat irritation
- Difficulty breathing in people with asthma
- Headaches
- Poor memory
- Tiredness
- Balance problems

If you are exposed to very high concentrations of hydrogen sulfide, you may have severe problems breathing even if you do not have a preexisting respiratory condition. You could lose consciousness if you are briefly exposed to very high concentrations (more than 1 million times higher than the amount typically found in the environment). If this happens, you may regain consciousness without any other effects. However, some people may have longer lasting effects, such as headaches, poor attention span, poor memory, and poor motor function.

5.3.2. Overview of the Health Effects Evaluation Process

The likelihood of noncancer health effects can be evaluated by calculating hazard quotients (HQ) for individual contaminants. A hazard quotient is the ratio of the EPC to a noncancer health guideline, such as an inhalation MRL or RfC. If the HQ is less than one, noncancer adverse health effects are not expected to result from exposure to the pollutant. If the HQ is equal to or greater than one, further toxicological evaluation is warranted by reviewing the critical and supporting studies used to develop the health guideline.

ATSDR also conducts margin of exposure (MOE) calculations to further assess the effects of the hydrogen sulfide exposures. Doing these analyses allows ATSDR to draw conclusions about the potential for harmful health effects that might occur due to the chemical exposure.

In this section, ATSDR uses the hydrogen sulfide EPCs calculated for acute, intermediate, and chronic exposures to calculate hazard quotients. For the exposure scenarios with an HQ equal to or greater than 1, ATSDR then discusses the potential for health implications.

5.3.3. Cancer Risk Estimates

Hydrogen sulfide has not been shown to cause cancer in humans and is not currently classified as a carcinogen [ATSDR 2016]. The EPA, in its most recent cancer assessment, determined that available data are inadequate to assess the carcinogenic potential of hydrogen sulfide [EPA 2003a, EPA 2003b]. Neither the National Toxicology Program (NTP) nor the International Agency for Research on Cancer (IARC) have classified carcinogenicity of hydrogen sulfide. Therefore, cancer risk estimates were not calculated in this evaluation.

5.3.4. Evaluating Noncancerous Health Risks from Acute Exposures

This section describes how ATSDR quantitatively assessed the noncancer health risks of acute exposures to hydrogen sulfide in air in the Tijuana River Valley and what health effects might result from the exposures.

5.3.4.1. Hazard Quotients – Acute Exposure

Table 8 compares the acute EPC (maximum 30-minute rolling average of hydrogen sulfide concentrations) to the acute MRL by location and provides the calculated HQs. HQs exceeded one for Berry Elementary School (HQ=11), Leon Avenue (HQ=43), and Imperial Beach Civic Center (HQ=4.7). Thirty-minute rolling averages exceeded the MRL from 0.4% to 5.2% of the time at these three locations. Because the HQ was greater than one at these three locations, additional evaluation of acute exposures to hydrogen sulfide in air is warranted. The HQ did not exceed one for the San Diego Fire Station (#29 – San Ysidro).

Table 8: Hazard Quotients – Acute Exposures to Hydrogen Sulfide in Air

Location	EPC (ppb)*	Acute MRL (ppb)	% of 30-Minute Rolling Averages Exceeding the Acute MRL	Acute HQ**
San Diego Fire Station #29 (San Ysidro)	48.2	70	0%	0.69
Berry Elementary School	749.2	70	2%	**11**‡
Leon Avenue	3021.5	70	5.2%	**43**‡
Imperial Beach Civic Center	333.0	70	0.4%	**4.7**‡

Abbreviations: EPC = exposure point concentration; ppb= parts per billion; MRL = minimal risk level; HQ = hazard quotient

‡**Bold text** = HQs greater than 1
*EPC calculated as the maximum 30-minute average
**HQ = EPC/MRL

5.3.4.2. Margins of Exposure – Acute Exposures

A HQ greater than one means there is an exceedance of the noncancer health guidelines and additional evaluation is needed. When HQs are greater than one, ATSDR conducts a second, complimentary analysis that numerically compares the site-specific concentration to the health effect concentration from the original study that served as the basis for the MRL [ATSDR 2025b]. This comparison is done by dividing the critical study's lowest observable adverse effect level (LOAEL) by the site-specific exposure concentrations. The resulting value is called the margin of exposure (MOE). The LOAEL used for the basis of the acute inhalation MRL is described further in section 5.3.4.3.

An MOE equal to or below one indicates that the site-specific concentration is at or above the health effect study level, which likely indicates harmful effects are possible. A value above one means that a site-specific concentration is below the health effect study level. The MOEs for acute exposures to hydrogen sulfide in air across the four sites are presented in Table 9.

Table 9: Margins of Exposure – Acute Exposures to Hydrogen Sulfide in Air

Location	LOAEL* (ppb)	EPC (ppb)	MOE**
San Diego Fire Station #29 (San Ysidro)	2000	48.2	41.5
Berry Elementary School	2000	749.2	2.7
Leon Avenue	2000	3021.5	**0.7**‡
Imperial Beach Civic Center	2000	333.0	6.0

Abbreviations: LOAEL = lowest observable adverse effect level; ppb= parts per billion; EPC = exposure point concentration; MOE = margin of exposure
‡**Bold text** = MOE equal to or less than 1
*[ATSDR 2016], [Jäppinen, et al. 1990]; **MOE = LOAEL/EPC

Across the four sites, the MOE was below one only at the Leon Avenue location (MOE=0.7). However, the MOE for the Berry Elementary School location was 2.7, which indicates the site-specific concentration is approaching the effect level. Based on these findings, it is likely that exposures at Leon Avenue, and potentially Berry Elementary school, could result in health effects like those observed in the study used to develop ATSDR's acute MRL, which is discussed in the following section.

Notably, ATSDR does not have data for every place or time where hydrogen sulfide exposures occurred in the Tijuana River Valley, and exposures of concern may have occurred at other locations or other times unmonitored. For example, monitoring started at Berry Elementary after the highest levels of hydrogen sulfide were recorded at Leon Avenue. Though ATSDR cannot quantify exposures at Berry Elementary before monitoring began that the school, ATSDR tested for correlation between these two sites (Section 4.1.4 and Appendix C). Correlation testing results indicated there is significant correlation between the two sites, which means it is likely that high hydrogen sulfide concentrations at Leon Avenue would also correlate to high concentrations at Berry Elementary School.

5.3.4.3. Toxicological Analysis – Acute Exposures

To conduct a toxicological analysis, ATSDR reviews the studies that were used to develop the MRL (e.g. critical studies) and compares the concentrations at the site (e.g. Tijuana River Valley monitoring sites) to the concentrations in the critical studies. If the concentrations at the site exceed the concentrations in the critical studies used to develop the MRL, it indicates that health effects may occur because of site exposures.

A study by Jäppinen et al. (1990) was the basis of ATSDR's acute inhalation MRL (70 ppb) [ATSDR 2016]. In this study, 10 adults, three men (ages 33–50 years) and seven women (ages 31–61 years), were exposed to 2 ppm (2,000 ppb) hydrogen sulfide for 30 minutes in an exposure chamber. Their respiratory function in response to a histamine challenge was checked before and after the 30-minute hydrogen sulfide exposure. Each of the participants had pre-existing bronchial asthma for 1 to 13 years (mean = 3.7 years) that required medication, though none were considered to have severe asthma. Subjects with severe asthma were not included in the study because it was recommended that study subjects go two days without medication before being exposed to hydrogen sulfide.

Among the 10 adults exposed to 2 ppm hydrogen sulfide for 30 minutes, all subjects detected an unpleasant hydrogen sulfide odor and experienced dryness of the nose and throat at the start of exposure. Three subjects complained of headaches after exposure. No statistically significant changes in respiratory function occurred, though some increase in airway resistance was observed. Two of the 10 adults experienced >30% changes in airway resistance and specific airway conductance, which was suggestive of bronchial obstruction.

5.3.4.4. Summary – Acute Exposures

The highest EPC, which was measured at the Leon Avenue monitoring location in September 2024, was 3021.5 ppb (3.0 ppm). This EPC is above the LOAEL of 2 ppm identified in the Jäppinen et al. (2000) study. Additionally, the EPC from Berry Elementary School (0.7 ppm) is approaching the LOAEL. People exposed to hydrogen sulfide in the Tijuana River Valley areas of Leon Avenue, and potentially Berry Elementary School, may experience health effects like those experienced by the 10 adults exposed to 2 ppm hydrogen sulfide for 30 minutes in the Jäppinen et al. (1990) study. These health effects include dryness of the nose and throat, headaches, and airway resistance/possible signs of bronchial obstruction (e.g., difficulty breathing) in sensitive people. Additionally, people exposed to hydrogen sulfide may experience similar health effects related to smelling unpleasant environmental odors, such as headaches, nasal congestion, eye, nose, and throat irritation, hoarseness and sore throat, cough, chest tightness, and shortness of breath [ATSDR 2014]. Environmental odors and related health effects are further discussed in Section 5.3.7.

Additionally, the San Diego Department of Environmental Health and Quality evaluated hydrogen sulfide in air with PID devices and reported levels up to 15,500 ppb (15.5 ppm) where the Tijuana River flows under Saturn Boulevard. Though these data were not of sufficient quality to use in this report, it indicates that even higher levels than those included in this analysis may be present for short periods of time.

5.3.5. Evaluating Noncancerous Health Risks from Intermediate Exposures

ATSDR considers exposures lasting 15 to 364 days as intermediate exposures. For this evaluation, exposures were assumed to last 24 hours each day. ATSDR averaged 14 full days of hydrogen sulfide readings to represent intermediate-duration exposures. This was chosen as the most conservative, health-protective approach to estimating intermediate-duration exposures. This section describes how ATSDR quantitatively assessed the health risks of 14-day exposures to hydrogen sulfide in air in the Tijuana River Valley and what health effects, if any, might result from intermediate-duration exposures.

5.3.5.1. Hazard Quotients – Intermediate Exposures

Table 10 compares the intermediate EPC (maximum 14-day rolling average of hydrogen sulfide concentrations) to the intermediate MRL (20 ppb) by location and provides the calculated HQs. HQs exceeded one at Berry Elementary School (HQ=1.6) and Leon Avenue (HQ=7.6). Fourteen-day rolling averages exceeded the MRL 9% to 13% of the time at these two locations. Because the HQ was greater than one at these two locations, additional evaluation of intermediate exposures to hydrogen sulfide in air is warranted. HQs did not exceed one at the San Diego Fire Station (#29 – San Ysidro) or the Imperial Beach Civic Center.

Table 10: Hazard Quotients – Intermediate Exposures to Hydrogen Sulfide in Air

Location	EPC (ppb)*	Intermediate MRL (ppb)	% Exceeding the Intermediate MRL	Intermediate HQ**
San Diego Fire Station #29 (San Ysidro)	3.3	20	0%	0.16
Berry Elementary School	31.6	20	9%	**1.6**‡
Leon Avenue	151.9	20	13%	**7.6**‡
Imperial Beach Civic Center	7.6	20	0%	0.38

Abbreviations: EPC = exposure point concentration; ppb= parts per billion; MRL = minimal risk level; HQ = hazard quotient

‡**Bold text** = HQs equal to or greater than 1
*EPC calculated using the maximum two-week rolling average
**HQ = EPC/MRL

5.3.5.2. Margins of Exposure – Intermediate Exposures

ATSDR's intermediate inhalation MRL was derived based on a critical study's no observable adverse effect level (NOAEL), which ATSDR does not use for MOE calculations. Since the same critical study is used for the intermediate MRL and the RfC, ATSDR adopted the human equivalent concentration LOAEL ($LOAEL_{HEC}$) that EPA calculated for the derivation of the RfC. Additional information about how the adjusted $LOAEL_{HEC,ADJ}$ (1.38 ppm) was calculated is provided in Section 5.3.5.3. ATSDR then divided the $LOAEL_{HEC,ADJ}$ by the EPC from all four air monitoring locations to determine MOEs.

An MOE equal to or below one indicates that the site-specific concentration is above the health effect study level, which likely indicates harmful effects are possible. A value above one means that a site-specific concentration is below the health effect study level. The MOEs for intermediate exposures to hydrogen sulfide in air across the four sites are presented in Table 11.

Table 11: Margins of Exposure – Intermediate Exposures to Hydrogen Sulfide in Air

Location	$LOAEL_{HEC}$* (ppb)	EPC (ppb)	MOE**
San Diego Fire Station #29 (San Ysidro)	1,380	3.3	418.2
Berry Elementary School	1,380	31.6	43.7
Leon Avenue	1,380	151.9	9.1
Imperial Beach Civic Center	1,380	7.6	181.6

Abbreviations: $LOAEL_{HEC}$ = human equivalent concentration of the lowest observable adverse effect level; ppb= parts per billion; EPC = exposure point concentration; MOE = margin of exposure
*Source of LOAEL: [ATSDR 2016, Brenneman, et al. 2000]
**MOE = $LOAEL_{HEC}$/EPC

The MOE for the San Diego Fire Station #29, Berry Elementary School, and Imperial Beach Civic Center were all well above one. This means that health effects are not likely to result from exposures of intermediate durations in these areas. The MOE for Leon Avenue was 9.1. This MOE is above one, but it's low enough that it is considered to be approaching the effect level. This does not mean that any health effects will definitively occur, but it does mean that additional toxicological evaluation is warranted.

Data were not collected at Berry Elementary School at the time (September 2024) the highest hydrogen sulfide concentrations were detected at Leon Avenue. Thus, the school's Intermediate EPC may be higher if data were collected there in September 2024. However, the school's EPC would not be expected to be higher than the Leon Avenue EPC because the school is farther from the Tijuana River (See Appendix C).

5.3.5.3. Toxicological Analysis – Intermediate Exposures

ATSDR noted in its 2016 Toxicological Profile for Hydrogen Sulfide and Carbonyl Sulfide that animal studies highlight the respiratory tract and nervous system as sensitive targets for intermediate-duration exposures to hydrogen sulfide [ATSDR 2016]. A study by Brenneman et al. (2000) was the basis of ATSDR's intermediate inhalation MRL (20 ppb). In this study, groups of 12 male Sprague Dawley rats were exposed to 0, 10, 30, or 80 ppm hydrogen sulfide for six hours per day, seven days per week, for 10 weeks. An extensive exam of the exposed rats' nasal cavities was conducted to assess the toxicity of the exposures.

Only rats exposed to 30 or 80 ppm experienced nasal lesions of the olfactory mucosa. For this study, the NOAEL was 10 ppm, and the LOAEL was 30 ppm.

In developing the intermediate-duration MRL, the NOAEL was adjusted for 24-hour exposure using the equation below:

Adjusted NOAEL ($NOAEL_{Adj}$) = 10 ppm x (6 hours/24 hours) x (7 days/7 days) = 2.5 ppm

ATSDR completed additional calculations to account for the differences in the surface area of the nose and breathing rate differences between rats and humans [ATSDR 2016]. To do this, ATSDR calculated a regional gas dose ratio (RGDR) for the extrathoracic region. The calculated RGDR was 0.184.

A final human-equivalent NOAEL ($NOAEL_{HEC}$) was calculated using the following formula:

$NOAEL_{HEC}$ = $NOAEL_{Adj}$ x 0.184 = 2.5 ppm x 0.184 = 0.46 ppm

For comparison, a human equivalent LOAEL for the same study is 1.38 ppm:

$LOAEL_{HEC}$ = $LOAEL_{Adj}$ x 0.184 = 30 ppm x (6 hours/24 hours) x (7 days/7 days) x 0.184 = 1.38 ppm

5.3.5.4. Summary – Intermediate Exposures

The highest EPC, which was from the Leon Avenue monitoring location in September 2024, was 151.9 ppb (0.152 ppm). This EPC is roughly 10 times lower than the critical study's $LOAEL_{HEC}$ and three times lower than the $NOAEL_{HEC}$.

Intermediate duration exposures (i.e. 15 to 364 days) to hydrogen sulfide in air in the Tijuana River Valley at the four monitoring locations are not expected to result in adverse health effects. However, people exposed to hydrogen sulfide may experience health effects related to smelling unpleasant odors, such as headaches, nasal congestion, eye, nose, and throat irritation, hoarseness and sore throat, cough, chest tightness, and shortness of breath [ATSDR 2014]. Environmental odors are further discussed in section 5.3.7.

5.3.6. Evaluating Noncancerous Health Risks from Chronic Exposures

ATSDR considers exposures that last more than 364 days to be chronic exposures. For this evaluation, EES-adjusted 95UCLs were calculated using 1-minute hydrogen sulfide measurements collected from September 2024 to May 2025 as an estimate of chronic exposures for each monitoring location. This section describes how ATSDR quantitatively assessed the health risks of chronic exposures to hydrogen sulfide in air in the Tijuana River Valley and what health effects, if any, might result from exposures.

5.3.6.1. Hazard Quotients – Chronic Exposures

Table 12 compares chronic EPCs to the EPA RfC by location and provides calculated HQs. HQs exceeded one at San Diego Fire Station #29 (HQ=2.0), Berry Elementary School (HQ=6.4), Leon Avenue (HQ=16), and Imperial Beach Civic Center (HQ=2.8). Because the HQ was greater than one at all four locations, additional evaluation of chronic exposures to hydrogen sulfide in air is warranted.

Table 12: Hazard Quotients – Chronic Exposures to Hydrogen Sulfide in Air

Location	EPC (ppb)*	EPA RfC** (ppb)	Chronic HQ⁺
San Diego Fire Station #29 (San Ysidro)	2.8	1.4	**2.0**‡
Berry Elementary School	9.2	1.4	**6.4**‡
Leon Avenue	23.6	1.4	**16**‡
Imperial Beach Civic Center	4.0	1.4	**2.8**‡

Abbreviations: EPC = exposure point concentration; ppb= parts per billion; RfC = EPA reference concentration; HQ = hazard quotient

‡**Bold text** = HQs greater than 1

*EPC calculated using the effective sample size (ESS) of the 95 percent upper confidence limit of the arithmetic mean (95UCL)

**Source of EPA RfC: [Brenneman, et al. 2000, EPA 2003b]

⁺HQ=EPC/EPA RfC

5.3.6.2. Margins of Exposure – Chronic Exposures

As with the acute and intermediate duration assessments, ATSDR complimented the chronic HQ analysis with an MOE evaluation. ATSDR determined the MOE for chronic inhalation exposures, which are presented in Table 13.

The same study used as the basis for the intermediate MRL was used as the basis for the EPA RfC, and the process to calculate a human-equivalent LOAEL ($LOAEL_{HEC}$) based on this study is previously described in Section 5.3.5.3. Limitations of the chronic database are discussed in Section 5.3.6.4.

Table 13: Margins of Exposure – Chronic Exposures to Hydrogen Sulfide in Air

Location	$LOAEL_{HEC}$* (ppb)	EPC (ppb)	MOE**
San Diego Fire Station #29 (San Ysidro)	1,380	2.8	492.8
Berry Elementary School	1,380	9.2	150.0
Leon Avenue	1,380	23.6	58.5
Imperial Beach Civic Center	1,380	4.0	345.0

Abbreviations: $LOAEL_{HEC}$ = human equivalent concentration of the lowest observable adverse effect level; ppb= parts per billion; EPC = exposure point concentration; MOE = margin of exposure
*Source of LOAEL: [ATSDR 2016, Brenneman, et al. 2000]
**MOE = $LOAEL_{HEC}$/EPC

The MOEs for all four locations are well above one, indicating that these estimated site-specific chronic exposures are below the concentrations that caused health effects in the critical study.

5.3.6.3. Toxicological Analysis – Chronic Exposures

EPA's RfC was based on the same study used to derive the intermediate inhalation MRL, which we described in Section 5.3.5.3. Briefly, a study by Brenneman et al. (2000) exposed groups of 12 male Sprague Dawley rats to 0, 10, 30, or 80 ppm hydrogen sulfide for six hours per day, seven days per week, for 10 weeks. An exam of the exposed rats' nasal cavities was conducted to assess the toxicity of the exposures. Only rats exposed to 30 or 80 ppm experienced nasal lesions of the olfactory mucosa. For this study, the NOAEL was 10 ppm, and the LOAEL was 30 ppm.

When adjusted for continuous 24-hour exposure, differences in the surface area of the nose, and breathing rate differences between rats and humans, the human-equivalent concentrations for the NOAEL and LOAEL were 0.46 ppm and 1.38 ppm, respectively. The chronic EPCs at all four Tijuana River Valley monitoring locations were orders of magnitude below both the $NOAEL_{HEC}$ and $LOAEL_{HEC}$.

5.3.6.4. Limitations of the Chronic Database

Per ATSDR's public health assessment process, this assessment is based on the body of toxicological literature available when ATSDR's 2016 Toxicological Profile for Hydrogen Sulfide and Carbonyl Sulfide was developed. Notably, the Toxicological Profile highlighted the absence of a robust chronic-duration toxicological database for hydrogen sulfide [ATSDR 2016]. Though chronic exposure durations are typically considered to last one year or longer, the critical study for the EPA RfC was based on a 10-week (sub-chronic) exposure duration. EPA accounted for the sub-chronic study duration by applying an additional uncertainty factor of 10 when developing the RfC.

In the Toxicological Profile, ATSDR identified no studies that evaluated chronic-duration hydrogen sulfide exposures in animals. Studies of workers and residents in areas with high levels of hydrogen sulfide often have strong confounders (e.g. exposures to other chemicals are likely) or lack an adequate exposure assessment component [ATSDR 2016, Batterman, et al. 2023]. Authors have indicated that chronic-duration studies, which control for exposures to other contaminants and adequately quantify exposures, are needed to best characterize the health implications of chronic-duration exposures in both animals and humans. EPA also identified the need for chronic-duration studies in rats and mice with multiple dose groups to understand the effect of hydrogen sulfide on the developing brain [EPA 2003b].

EPA determined it had medium to high confidence in its RfC assessment; the "medium" qualifier was applied because the critical study only covered a subchronic duration. EPA's hydrogen sulfide RfC, which was used to characterize chronic exposures in this assessment, accounted for the use of a sub-chronic study to derive a chronic health guidance value [EPA 2003b]. To do so, EPA applied an uncertainty factor of 10 to the RfC, reducing the comparison concentration 10-fold as a conservative measure. Uncertainty factors help ensure a health guidance value is protective of health for even the most sensitive populations, but this only addresses the screening value. Additional chronic-duration hydrogen sulfide studies in animals and humans would increase confidence in the effect levels used for the assessment of chronic exposure risks.

5.3.6.5. Summary – Chronic Exposures

The critical study's health effect level (1,380 ppb) was much higher than the highest chronic-duration EPC (23.6 ppb) in the Tijuana River Valley. As a result, chronic duration exposures (i.e. more than 364 days) to hydrogen sulfide in air in the Tijuana River Valley at the four monitoring locations are not expected to result in adverse health effects. Additional chronic studies would further strengthen confidence in the long-term health effects assessment. People exposed to hydrogen sulfide may also experience health effects related to smelling unpleasant odors, such as headaches, nasal congestion, eye, nose, and throat irritation, hoarseness and sore throat, cough, chest tightness, and shortness of breath [ATSDR 2014]. Environmental odors are further discussed in section 5.3.7.

5.3.7. Environmental Odors[2]

5.3.7.1. Background on Environmental Odors

Chemicals with offensive odors can affect health by more than one mechanism [Schiffman and Williams 2005]. Odors are detected when the odorous chemical stimulates the olfactory nerve in the nasal passage. If odors are considered offensive, this mechanism may be associated with headache, nausea, or vomiting [Schiffman, et al. 1995]. If malodorous chemicals are present in higher concentrations (i.e., generally, 10 to 100 times higher than the odor threshold),

[2] Information in this section is taken from ATSDR's Exposure Investigation of Outdoor Air Exposures from the Port Townsend Paper Corporation that can be found here:
https://www.atsdr.cdc.gov/HAC/pha/PortTownsendPaperCorp/Port-Townsend-HC-508.pdf

stimulation of other cranial nerves may cause irritation, including a burning, stinging, or itching sensation in the eyes, nose, or throat. Irritation of the respiratory tract may be accompanied by changes in respiration, including changes in breathing rate, or increased airflow resistance in the upper or lower respiratory tract [Schiffman, et al. 2000, Schiffman and Williams 2005]. Combinations of low concentrations of malodorous chemicals may also cause irritation. The health effects of breathing mixtures of malodorous chemicals are not well understood.

With repeated exposures to a malodorous chemical, people can develop learned responses to the odor of that chemical [Schiffman and Williams 2005]. For example, if breathing malodorous sulfur-based compounds at sufficient exposure levels previously caused an asthma attack, perception of the odor of those compounds may subsequently trigger an attack. Repeated exposure to irritating, malodorous chemicals (and other environmental air pollutants including particulate matter, nitrogen oxides, and ozone) may induce chronic respiratory illnesses including asthma, especially in children and elderly adults, although the relevant pollutant mixtures and exposures are not well understood [Clark, et al. 2010, Schiffman and Williams 2005, Tétreault, et al. 2016]. Repeated exposure to offensive odors perceived as unpredictable or uncontrollable may also add significantly to individuals' stress levels and affect quality of life [Schiffman and Williams 2005]. Chronic stress can harm people's health in a variety of ways, which we will discuss in the next section.

Generally, odor-related symptoms subside once odors dissipate and do not require medical attention. However, symptoms may last longer if odors are persistent or if malodorous chemicals reach irritation levels. Respiratory symptoms that may not subside include shortness of breath, chest tightness, or breathing discomfort, especially in people with chronic cardiopulmonary disease or chronic respiratory disease such as asthma [ATSDR 2014]. ATSDR recommends that individuals seek medical advice for any persistent symptoms that do not subside when the odors dissipate.

People's perception of odors and their responses to those perceptions may vary. Genetics, sex, and age can influence olfaction and the perception of odors [Greenberg, et al. 2013]. Women tend to be more sensitive than men to odors, and younger people tend to be more sensitive than older people. Pregnant women may be more likely to experience nausea in response to offensive odors. An individual's health can also influence sensitivity to odors. Individuals with chronic respiratory diseases like asthma may be more likely to experience chest tightness or difficulty breathing in response to offensive odors [ATSDR 2014].

Numerous community studies have found that chronic exposure to malodorous sulfur emissions may cause adverse health effects, negative emotions, and decreased quality of life [Campagna, et al. 2004, Haahtela, et al. 1992, Jaakkola, et al. 1999, Kilburn and Warshaw 1995, Legator, et al. 2001, Marttila, et al. 1994, Partti-Pellinen, et al. 1996].

5.3.7.2. Stress Due to Environmental Odors

Individuals living near contaminated sites are at increased risk of experiencing stress and the negative health effects associated with chronic stress. Offensive odors that are perceived as unpredictable or uncontrollable raise individuals' stress levels. Other causes of stress can include frustration with lengthy cleanup times at sites and the perception that health threats do not diminish over time. Individuals may be stressed by uncertainties about their current or future health, the current or future health of their children, and the impact of environmental exposures on their health.

Increased stress can be accompanied by a variety of negative emotions, including anxiety, depression, anger, and confusion [Schiffman, et al. 1995, Schiffman and Williams 2005]. Because of the interaction of the central nervous, immune, and endocrine systems, stress and negative emotions can affect people's health in a variety of ways over a long period of time, due to the interaction of the central nervous, immune, and endocrine systems in the body [Glaser and Kiecolt-Glaser 2005]. Health issues induced by chronic stress can include increased susceptibility to infection, increased severity of infectious diseases, or increased inflammatory responses may be associated with many common diseases, such as coronary artery disease and irritable bowel syndrome [Glaser and Kiecolt-Glaser 2005]. Indirect effects of stress (e.g., poor sleep, poor eating habits, less exercise, increased smoking, and alcohol consumption) put people at even greater risk of developing health problems.

5.3.7.3. Hydrogen Sulfide Odors in the Tijuana River Valley

People can begin to smell hydrogen sulfide in the air when it's present at concentrations as low as 0.5 ppb. Hydrogen sulfide concentrations near the Tijuana River exceeded the hydrogen sulfide odor threshold in all four monitoring locations (Appendix B: Figure 6). Specifically, 1-minute hydrogen sulfide readings exceeded the odor threshold at the San Diego Fire Station in San Ysidro, Leon Avenue, Imperial Beach Civic Center, and Berry Elementary School monitoring sites 70%, 82%, 89%, and 96% of the time, respectively.

When hydrogen sulfide concentrations exceed the hydrogen sulfide odor threshold, people may experience odor-related health symptoms such as headaches, nausea, stress or annoyance, nasal congestion, eye, nose, and throat irritation, hoarseness and sore throat, cough, chest tightness, and shortness of breath [ATSDR 2014, ATSDR 2016]. Notably, many of respondents to the 2024 ACE and CASPER surveys reported many of these symptoms [HHSA 2024b, HHSA 2024c]. Health surveys also identified a large portion of respondents who experienced stress and other mental health symptoms attributed to the sewage contamination [HHSA 2024b, HHSA 2024c, Shi 2025].

5.4. Addressing Community Concerns

Community members have expressed concerns about the odors and poor air quality in the Tijuana River Valley for many years. Table 14 describes ATSDR's response to key community concerns.

Table 14: ATSDR's Response to Community Concerns

Community Concern	ATSDR's Response
Unpleasant odors and poor air quality from hydrogen sulfide in neighborhoods for more than one year	ATSDR's analysis found that hydrogen sulfide concentrations exceeded the odor threshold most of the time. ATSDR found that short-term exposures to hydrogen sulfide near Leon Avenue can be a public health hazard, but long-term exposures are not expected to result in additional health effects. ATSDR's recommendations for addressing acute exposures and odors are found in Section 7: Recommendations and Public Health Action Plan
Experiencing physical symptoms such as eye irritation, headache, nausea, allergies, and asthma	ATSDR's analysis found that sometimes short-term hydrogen sulfide exposures in the Tijuana River Valley near the Leon Avenue monitoring site are expected to result in headaches, dryness of the nose and throat, and possible difficulty breathing in sensitive people. People exposed to hydrogen sulfide odors in the Tijuana River Valley may also experience headaches, nasal congestion, eye, nose, and throat irritation, hoarseness and sore throat, cough, chest tightness, and shortness of breath. People may also experience nausea, vomiting, stress, and the negative health effects of chronic stress. Repeated exposures to odors can induce chronic respiratory illnesses like asthma.
Children's unique exposures, and decisions about canceling outdoor activities such as recess, organized sports practices, and youth sports events	This is addressed in Section 5.5.1: Children's Susceptibility
Reduced enjoyment or use of home, yard, or outdoor recreation in the area	ATSDR provides recommendations for people in the Tijuana River Valley in Section 7: Recommendations and Public Health Action Plan

Community Concern	**ATSDR's Response**
Changing home maintenance behaviors related to fresh air: keeping windows closed, purchasing and maintaining air cleaning devices to reduce odors	ATSDR makes recommendations, including to obtain air purifiers from SDAPCD, in Section 7: Recommendations and Public Health Action Plan. Maintaining air filters in accordance with manufacturer's recommendations is important to ensure the filters are effective.
The health of animals such as horses boarded near the river, and dogs	Although the focus of this health consultation is human health, ATSDR did not identify any hydrogen sulfide studies that showed horses or dogs are uniquely susceptible to hydrogen sulfide exposures. Efforts to reduce hydrogen sulfide exposures to humans may likely also help protect horses and dogs.
Negative impacts of odors on local businesses and tourism	ATSDR's analysis found that hydrogen sulfide concentrations exceeded the odor threshold most of the time. Recommendations to address the odors are provided in Section 7: Recommendations and Public Health Action Plan
Frustration over the slow progress in addressing odors and their root cause	Community members experiencing strong environmental odors in both private and community spaces may feel frustrated. In general, sewer gases are challenging to manage and control because they move through the air and have strong odors that people can smell at low levels. In the Tijuana River Valley, the situation is made more complex by the geography, weather patterns, proximity of different land uses, and international border. Community engagement and reporting of health concerns have contributed to increased attention from local, state, and federal officials to address aging infrastructure, monitor and communicate about air quality, and provide air cleaning devices to the most affected.

5.5. Summary of Limitations and Uncertainties

The limitations and uncertainties of this evaluation are discussed in this section.

5.5.1. Children's Susceptibility

Children represent a unique exposure population. It's important to consider their possible exposures to hydrogen sulfide in the Tijuana River Valley due to the close proximity of the Tijuana River to Berry Elementary School, daycares, residences, the Tijuana River Valley campground, baseball fields, and other places where children might visit. However, there is very little information available on possible health effects in children from hydrogen sulfide exposures, and we do not know if they are more sensitive to hydrogen sulfide than adults [ATSDR 2016]. However, Individuals spending more time outside will have a higher exposure.

5.5.2. Sampling Limitations

Data from four monitoring locations are used in this assessment. These four locations do not necessarily represent the places where the most people are exposed, nor do they necessarily represent locations of the highest exposures. Of the four locations, Leon Avenue likely has the highest outdoor air concentrations of hydrogen sulfide due to the vertical water drop under Saturn Boulevard. However, there may be other locations of concern that are not known and monitored currently. For example, monitoring at the Saturn Boulevard drop would likely produce higher concentrations of hydrogen sulfide than reported here if it is the hotspot of hydrogen sulfide in the Tijuana River Valley. This is further supported by the high hydrogen sulfide reading (15,500 ppb) measured once by the San Diego Department of Environmental Health and Quality.

Sampling did not begin at Berry Elementary School until October 2024. Outdoor air concentrations at the Leon Avenue monitoring site, across the street from the school, were the highest in September 2024. It's likely that concentrations were also high at the school in September 2024 due to the close proximity of the two monitoring sites, but the data are not available to confirm. Though ATSDR cannot quantify exposures at the school prior before October 2024, ATSDR tested for correlation between these two sites (Section 4.1.4 and Appendix C). The results indicated significant correlation.

5.5.3. Exposure Assumptions

This report relies on monitoring data from four monitoring locations. Leon Avenue and Berry Elementary School monitoring sites are thought to represent some of the highest hydrogen sulfide levels the community may be exposed to, but a larger sampling effort throughout the Tijuana River Valley would be needed to confirm.

Exposure point concentrations (EPCs) for the acute exposure assessment, which were used to determine the conclusions, largely came from the nighttime hours. During the night, people tend to be in their homes, which might reduce their exposures to outdoor air depending on their behaviors (e.g., opening windows, using air purifiers, etc.). Therefore, the exposure estimates in this report may overestimate people's true exposures in the Tijuana River Valley. To further assess acute exposures, ATSDR calculated acute EPCs for the daytime only and compared them to acute EPCs for hydrogen sulfide levels at night (Appendix B, Table 15). With the exception of the San Diego Fire Station at San Ysidro, ATSDR found that acute EPCs were consistently higher at night. Even though the Leon Avenue acute EPC was lower during the day, it still exceeded the health effect level of 2 ppm identified in the critical study [Jäppinen, et al. 1990]. Thus, ATSDR's conclusion remains that short-term hydrogen sulfide exposures in the Tijuana River Valley can be at levels that are a public health hazard.

5.5.4. Database of Literature on Chronic Exposures

The toxicological database for hydrogen sulfide lacks robust chronic-duration studies. Notably, the health effect level used for analysis of chronic effects in this report is based on a 10-week sub-chronic study rather than a chronic exposure study (typically one year or longer). For further discussion of these limitations, see Section 5.3.6.4.

6. Conclusions

6.1. Conclusion 1: Environmental Odors

Environmental odors in the Tijuana River Valley can negatively affect people's health and well-being.

Not all environmental odors in the Tijuana Valley are from hydrogen sulfide, but most likely many of them are. Hydrogen sulfide levels in outdoor air were measured above the odor threshold in 30-minute samples at all four air monitoring sites in the Tijuana River Valley up to 93% of the time. As a result, people in the Tijuana River Valley may experience environmental odor-related health symptoms such as headaches, nausea, stress or annoyance, nasal congestion, eye, nose, and throat irritation, hoarseness and sore throat, cough, chest tightness, and shortness of breath [ATSDR 2014, ATSDR 2016].

Some of the symptoms people experience from environmental odors are similar to those observed in toxicological studies of hydrogen sulfide at higher concentrations (for example, 2,000 ppb, the lowest level where health effects have been observed in toxicological studies). However, hydrogen sulfide can be smelled at much lower levels (as low as about 0.5 ppb). This means that symptoms can occur in response to the odor itself, even at levels far below those used in toxicological studies. In this way, environmental odors can affect how people feel, even when measured chemical levels are low.

6.2. Conclusion 2: Short-Term (Acute) Exposures

Hydrogen sulfide in outdoor air at the Leon Avenue monitoring site, and likely the Berry Elementary monitoring site, has reached a level for short periods of time that could harm people's health. Exposure to hydrogen sulfide at this level is a public health hazard.

One-minute readings for hydrogen sulfide were collected at four monitoring locations in the Tijuana River Valley. ATSDR calculated 30-minute rolling averages of these data to compare the results to the air concentrations in the toxicological literature examining hydrogen sulfide health effects from short-term exposure.

The highest EPC (a maximum 30-minute rolling average) came from the Leon Avenue monitoring location in September 2024; the 30-minute rolling average was 3,021.5 ppb. This

EPC is above the 2,000 ppb LOAEL identified in the Jäppinen et al. (1990) study used to develop ATSDR's acute MRL. This means that people who breathed hydrogen sulfide in this location sometimes had exposures to concentrations higher than those demonstrated to cause health effects in humans. These health effects include headaches, dryness of the nose and throat, and airway resistance/possible signs of bronchial obstruction (e.g., difficulty breathing) in sensitive people. Rolling 30-minute hydrogen sulfide concentrations exceeded the 2,000 ppb LOAEL 0.04% of the time at Leon Avenue.

EPCs for the remaining locations were below 2,000 ppb. However, monitoring at Berry Elementary School, which is across the street from the Leon Avenue monitoring site, did not begin until October 2024 (after the highest hydrogen sulfide concentrations were measured at Leon Avenue). It is likely that hydrogen sulfide levels were also high at Berry Elementary because the two locations are very close to each other, but ATSDR does not have air data for Berry Elementary before monitoring began at the school. However, ATSDR did demonstrate that hydrogen sulfide levels at the two locations are significantly correlated.

6.3. Conclusion 3: Longer-Term (Intermediate and Chronic) Exposures

Longer-term hydrogen sulfide exposures (14 days or more) at the four monitoring locations are not expected to pose a public health hazard or result in additional health effects beyond those linked to short-term elevated exposures. However, they may still be associated with odor-related symptoms.

Intermediate duration (more than 14 to 364 days): ATSDR calculated 14-day rolling averages as the EPC for each monitoring location as a conservative estimate of intermediate exposures. The highest EPC came from the Leon Avenue monitoring location (151.9 ppb). The next highest EPC came from Berry Elementary School (31.6 ppb). The EPCs at both locations exceeded ATSDR's intermediate MRL (20 ppb). However, these levels were nine and 44 times lower, respectively, than the level shown to cause health effects in the toxicological literature (1,380 ppb). Therefore, ATSDR does not expect that intermediate exposures to hydrogen sulfide in the Tijuana River Valley will harm people's health.

Chronic duration (one year or more): ATSDR averaged between four to seven months of monitoring data from each monitoring location as EPCs for chronic exposures. Air monitoring began at different times at the sites, which is why the length of time data are available for each site varies. The highest EPC came from the Leon Avenue monitoring location (23.6 ppb). The next highest EPC came from the Berry Elementary School location (9.2 ppb). These levels were 58 and 150 times lower than the levels shown to cause health effects in the toxicological literature (1,380 ppb). Therefore, ATSDR does not expect that chronic exposures to hydrogen sulfide in the Tijuana River Valley will harm people's health.

6.4. Conclusion 4: Exposures before September 2024

ATSDR cannot conclude whether breathing hydrogen sulfide in outdoor air in the Tijuana River Valley before September 2024 could have harmed people's health. Sufficient data were

not collected before this time.

Air monitoring in the Tijuana River Valley using instruments adequate for public health assessment began in September 2024. Data before this time are not available to assess health risks. Although ATSDR understands that the Tijuana River sewage issue has persisted for many years, and exposures to hydrogen sulfide in outdoor air have almost certainly occurred as a result, ATSDR is unable to quantify and characterize these past exposures without data.

7. Recommendations and Public Health Action Plan

7.1. Recommendations

ATSDR has the following public health recommendations based on our evaluation of hydrogen sulfide in outdoor air at four monitoring locations around the Tijuana River Valley:

Recommendations for federal and state agencies:

- Prevent transboundary sewage flows into the Tijuana River Valley so that hydrogen sulfide levels remain as low as possible, ideally below the odor threshold of 0.5 ppb.
- Improve and maintain wastewater treatment infrastructure to manage flows in the Tijuana River Valley.
- Continue collaborating with local agencies to implement measures that reduce hydrogen sulfide releases at the location where the Tijuana River flows under Saturn Boulevard.

Recommendations for local agencies:

- Continue monitoring hydrogen sulfide in air and notifying community members, businesses, daycares, and schools when levels exceed thresholds set by the state or local agencies to be health protective. Use multiple methods to reach community members (e.g. text messages and emails).
- Maintain signage throughout the Tijuana River Valley to alert visitors to the possible presence of hydrogen sulfide.
- Continue to offer air purifiers and filters through the Air Improvement Relief Effort Program.
- Continue to collect and monitor odor complaints. Consider ways to precisely identify the location of odor complaints to target hotspots for air monitoring and better understand the geographic distribution of odors.
- Conduct air monitoring to determine hydrogen sulfide levels beyond the locations with fixed monitors. Consider expanding air monitoring to other contaminants that may be released from the Tijuana River, including volatile organic compounds.
- Continue collaborating with federal and state agencies to reduce hydrogen sulfide releases at the location where the Tijuana River flows under Saturn Boulevard.

- Ensure air monitoring is conducted to verify that any interventions implemented to address the hydrogen sulfide problem in the Tijuana River Valley do not result in continued or additional harmful exposures.
- Maintain the Community Hydrogen Sulfide Guidance: https://www.sdapcd.org/content/sdapcd/about/tj-river-valley/tjrv-air-quality-monitoring.html. Consider engaging appropriate state and federal agencies to develop and incorporate recommendations for workers who cannot leave the area or go indoors during their work shift.

Recommendations for schools:

- Monitor hydrogen sulfide levels in the Tijuana River Valley by visiting SDAPCD's Air Monitoring website: https://www.sdapcd.org/content/sdapcd/about/tj-river-valley/tjrv-air-quality-monitoring.html. Follow SDAPCD and San Diego County's Community Hydrogen Sulfide Guidance.
- Follow San Diego County's Resources for Schools materials to make informed decisions about daily activities: https://www.sandiegocounty.gov/content/sdc/hhsa/programs/phs/community_epid em iology/south-region-health-concerns/schools.html

Recommendations for community members:

- Monitor hydrogen sulfide levels in the Tijuana River Valley by visiting SDAPCD's Air Monitoring website: https://www.sdapcd.org/content/sdapcd/about/tj-river-valley/tjrv-air-quality-monitoring.html.Follow SDAPCD and San Diego County's Community Hydrogen Sulfide Guidance.
- People who are sensitive to environmental odors can reduce exposure by using air purifiers, limiting outdoor activities when odors are bothersome, keeping windows and doors closed when odors outside are bothersome, or leaving the area as needed when monitoring indicates hydrogen sulfide levels are elevated. Avoid using candles and incense in homes to mask hydrogen sulfide odors. Candles and incense themselves can be irritants.
- Eligible residents are encouraged to obtain a free air purifier from the SDAPCD Air Improvement Relief Effort Program. Information about the program can be found here: https://www.sdapcd.org/content/sdapcd/about/tj-river-valley/aire.html. Guidance on the best use of air purifiers can be found here: https://www.sdapcd.org/content/dam/sdapcd/documents/tjrv/aire/CARB-CleanAirSpace-Infographic.pdf. Air purifying filters are most effective when maintained and replaced based on manufacturers' guidelines.
- Report odors in the Tijuana River Valley to the SDAPCD at (858) 586-2650 or apcdcomp@sdapcd.org. After hours, call (858) 586-2650 and select option 2. An app for reporting odors is also available for download on SDAPCD's air quality concerns website: https://www.sdapcd.org/content/sdapcd/compliance/air-quality- complaints.html.

- People concerned about health effects from hydrogen sulfide exposure are encouraged to speak with their doctor. Consider providing a copy of the fact sheet summarizing this report.

7.2. Public Health Action Plan

ATSDR will release these findings to the public. ATSDR will later publish a second report that will address other potential exposure pathways in the Tijuana River Valley, like exposures to chemicals in surface water, sediment, and soil.

Since 2024, HHSA, SDAPCD, and IBWC have taken many steps to reduce the impacts of hydrogen sulfide exposures in the Tijuana River Valley. UCSD researchers continue to collect air monitoring data to inform local, state, and federal agencies of the presence of contaminants in the Tijuana River Valley. In 2024, SDAPCD released an online dashboard that allows people to view hydrogen sulfide levels measured at its three monitoring stations. Additionally, SDAPCD notifies subscribers via an alert system when hydrogen sulfide levels exceed established thresholds. SDAPCD and HHSA released the “Community Hydrogen Sulfide Guidance” to provide guidance related to its monitoring results. SDAPCD continues to monitor odor complaints and provide free air purifiers and filters through its Air Improvement Relief Effort Program, which is funded with an additional $1 million for 3,500 new air purifiers [City News Service 2026].

HHSA released a Health Advisory and partnered with CDC/ATSDR to conduct two community health surveys in 2024 (ACE and CASPER). HHSA is in the early stages of conducting an exposure characterization study to further understand the extent of hydrogen sulfide exposures, along with other contaminants, in the Tijuana River Valley. The analysis and results may inform future studies. HHSA continues to provide guidance to community members and convene subject matter experts when monitoring indicates hydrogen sulfide levels are high. The County of San Diego partnered with the City of San Diego to post signs throughout the Tijuana River Valley to notify people of the possible presence of hydrogen sulfide.

IBWC continues its binational work expanding the capacity of the International Wastewater Treatment Plant, implementing engineering measures to address sediment and excessive flows, and exploring options for removing hydrogen sulfide gas in the Tijuana River flows [IBWC 2025a]. Multiple agencies are working to identify the best way to reduce hydrogen sulfide releases at the Saturn Boulevard hydrogen sulfide “hotspot”[SDPR 2026].

Community members can contact ATSDR’s Region 9 office to learn more about hydrogen sulfide levels and health risks in the Tijuana River Valley. ATSDR region 9 staff contact information is listed here: https://www.atsdr.cdc.gov/regional-offices/index.html or by calling 800-CDC-INFO (800-232-4636).

8. Authors, Site Team, and Contributors

Jona Johnson, PhD, MPH, REHS, CPH, Team Lead
Agency for Toxic Substances and Disease Registry (ATSDR)
Office of Community Health Hazard Assessment (OCHHA)

Ben Gerhardstein, MPH, Environmental Health Scientist (ATSDR/OCHHA)

Contributors: James Pyon, MS, Associate Service Fellow (ATSDR/OCHHA), Jamie Rayman, MPH, Region 9 Director (ATSDR/OCHHA), Venus Malloy, MS, NCC, LCMHC, LCAS, CCMHC, Behavioral Scientist, (ATSDR/Office of Capacity Development and Applied Prevention Science [OCDAPS]), Terrell Perry, Community Involvement Specialist (ATSDR/OCDAPS), Jessica Tomov, PhD, CPH Epidemiologist (ATSDR/OCHHA)

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Appendices

Appendix A: Brief Summary of ATSDR's Public Health Assessment (PHA) Process

ATSDR follows the PHA process to find out

- Whether people living near a hazardous waste site are being exposed to toxic substances
- Whether that exposure is harmful
- What must be done to stop or reduce exposure

The PHA process is a step-by-step consistent approach during which ATSDR

- Establishes communication mechanisms, including engaging communities at the beginning of site activities and involving them throughout the process to respond to their health concerns
- Collects many different kinds of site information
- Obtains, compiles, and evaluates the usability and quality of environmental and biological sampling data (and sometimes modeling data) to examine environmental contamination at a site
- Conducts four main, sequential scientific evaluations
    - Exposure pathways evaluations identify past, present, and future site-specific exposure situations, categorizing them as completed, potential, or eliminated.
    - Screening analyses compare the available sampling data to media-specific environmental screening levels (ATSDR comparison values [CVs] and non-ATSDR screening levels). This process identifies potential contaminants of concern that require further evaluation for completed and potential exposure pathways.
    - Exposure Point Concentrations (EPCs) and exposure calculations are for contaminants flagged as requiring further evaluation in completed and potential exposure pathways. It involves calculating EPCs, using EPCs to perform calculations that characterize exposure, and determining which site-specific exposure scenarios require an in-depth toxicological effects analysis.
    - In-depth toxicological effects evaluations, if necessary, are based on the three previous scientific evaluations. This step looks more closely at contaminant-specific toxicity information in the context of site exposures. This evaluation can also help determine if there is a potential for noncancer or cancer health effects and what those effects might be.
- Summarizes findings and next steps, while acknowledging uncertainties and limitations. Provides recommendations to site-related entities, partner agencies, and

communities to prevent and minimize harmful exposures.

The sequence of steps can differ based on site-specific factors. For instance, health assessors might define an exposure unit before or after the screening analysis or refine EPC calculations as they go through their site-specific analysis.

For more detail on the PHA process, visit Explanation of ATSDR's PHA Process Evaluation. Readers can also refer to ATSDR's Public Health Assessment Guidance Manual for all information related to the step-wise PHA process.

Appendix B: Additional Tables and Figures

Table 15 shows the differences between the 30-minute rolling averages (e.g., the acute EPC) of hydrogen sulfide concentrations during the day vs. during the night. Daytime and nighttime hours were determined using the R package openair, which uses National Oceanic and Atmospheric Administration (NOAA) methods [R 2025].

Table 15: Comparison of Daytime and Nighttime Acute EPCs

Location	Time of Day	EPC (ppb)*
San Diego Fire Station #29 (San Ysidro)	Daytime	48
San Diego Fire Station #29 (San Ysidro)	Nighttime	44
Berry Elementary School	Daytime	318
Berry Elementary School	Nighttime	749
Leon Avenue	Daytime	2245
Leon Avenue	Nighttime	3021
Imperial Beach Civic Center	Daytime	54
Imperial Beach Civic Center	Nighttime	333

Abbreviations: EPC = exposure point concentration; ppb= parts per billion
*Maximum 30-minute rolling average

Figure 5 shows polar plots for the four Teledyne T101 monitoring locations.

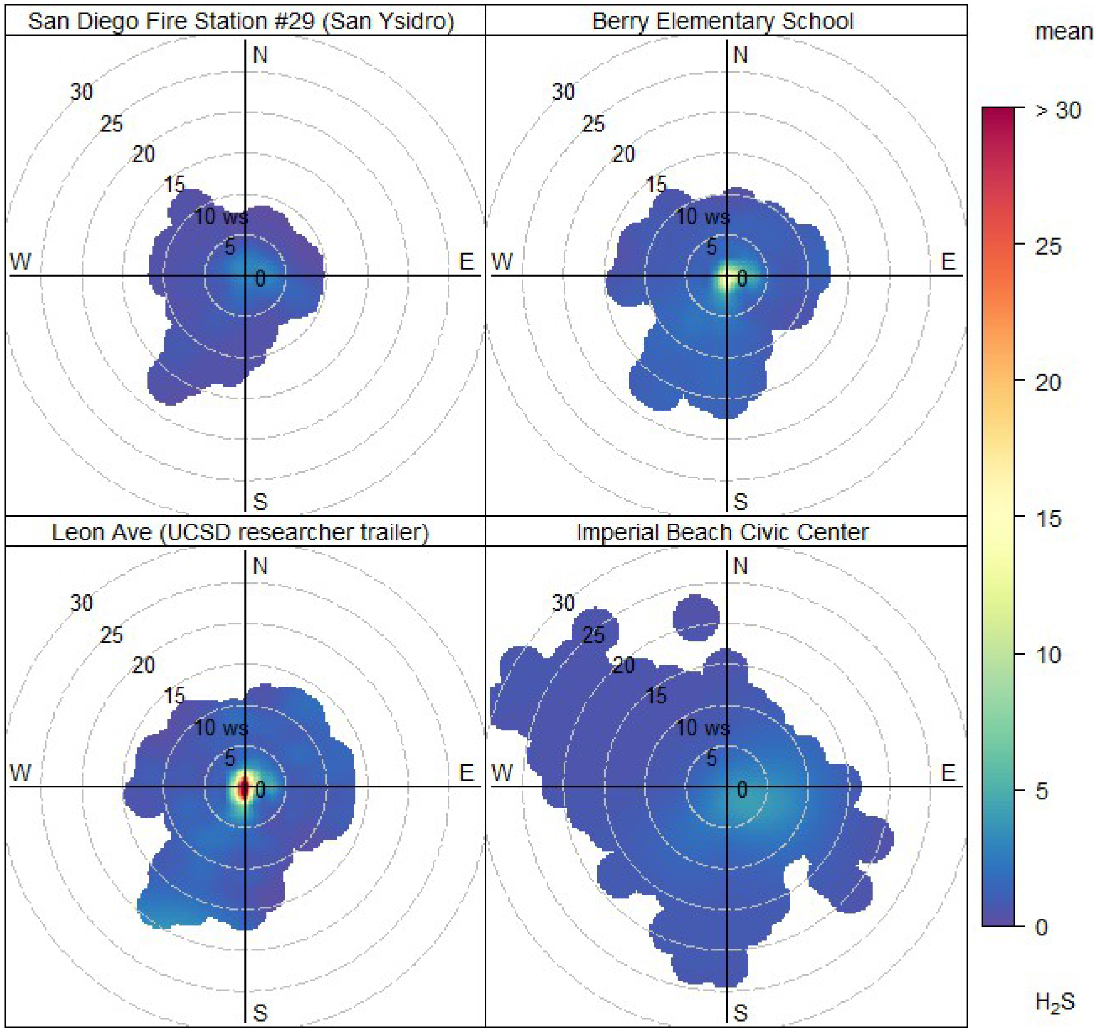

Figure 5: Polar Plots of TeledyneT101 Monitoring Locations

Abbreviations: W = west; N = north; S = south, E= east; ws = wind speed (miles per hour); H_2S = hydrogen sulfide (ppb)

Figure 6 shows the 24-hour average daily concentrations of hydrogen sulfide for each of the four monitoring locations. The horizontal lines in the figure show the hydrogen sulfide odor threshold and screening levels ATSDR used to evaluate acute (70 ppb), intermediate (20 ppb), and chronic (1.4 ppb) exposures. At all four locations, most daily average hydrogen sulfide concentrations exceeded the hydrogen sulfide odor threshold and EPA's RfC (e.g., the chronic screening level). On occasion, daily average concentrations exceeded the intermediate screening value (e.g., the intermediate MRL). On rare occasions, the hydrogen sulfide concentration exceeded ATSDR's acute screening value (e.g., the acute MRL). These findings do not necessarily indicate a health concern, but they do demonstrate where the daily concentrations of hydrogen fell from September 2024 to May 2025 relative to the values ATSDR considers to be warranting further attention. More appropriate EPCs were used to compare exposures to the health guideline values, but daily averages are a simpler way to view the comparison

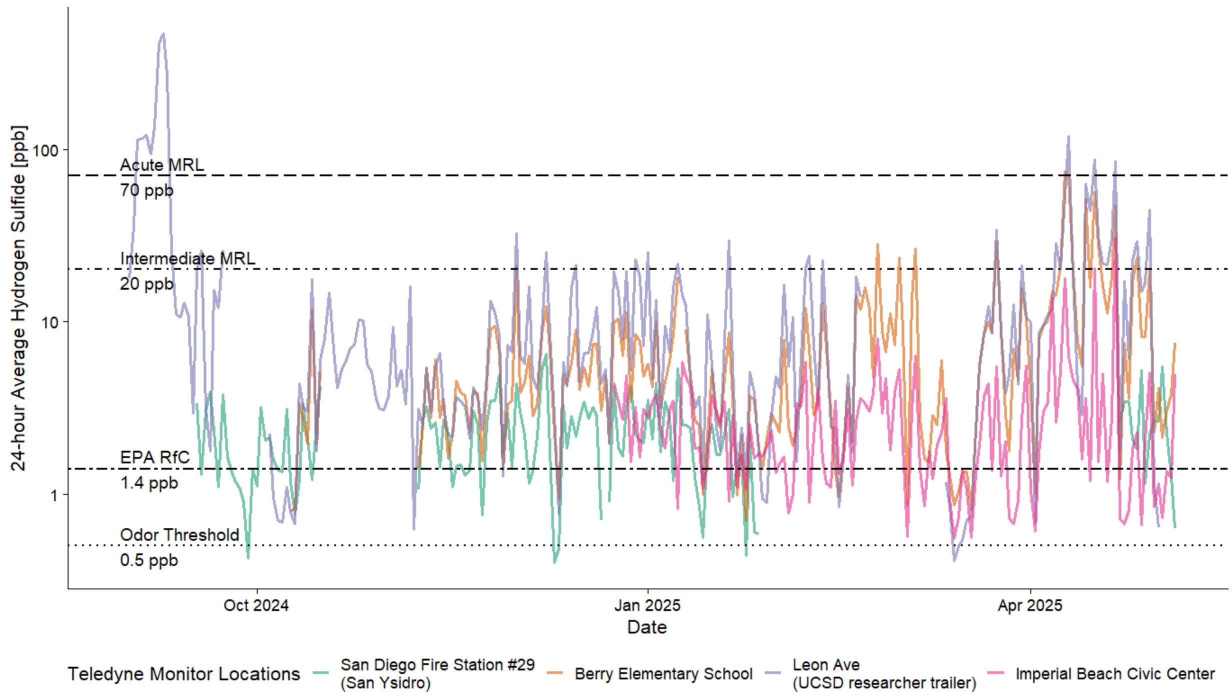

Figure 6: Daily Average Hydrogen Sulfide Concentrations Compared to Health Guideline Values

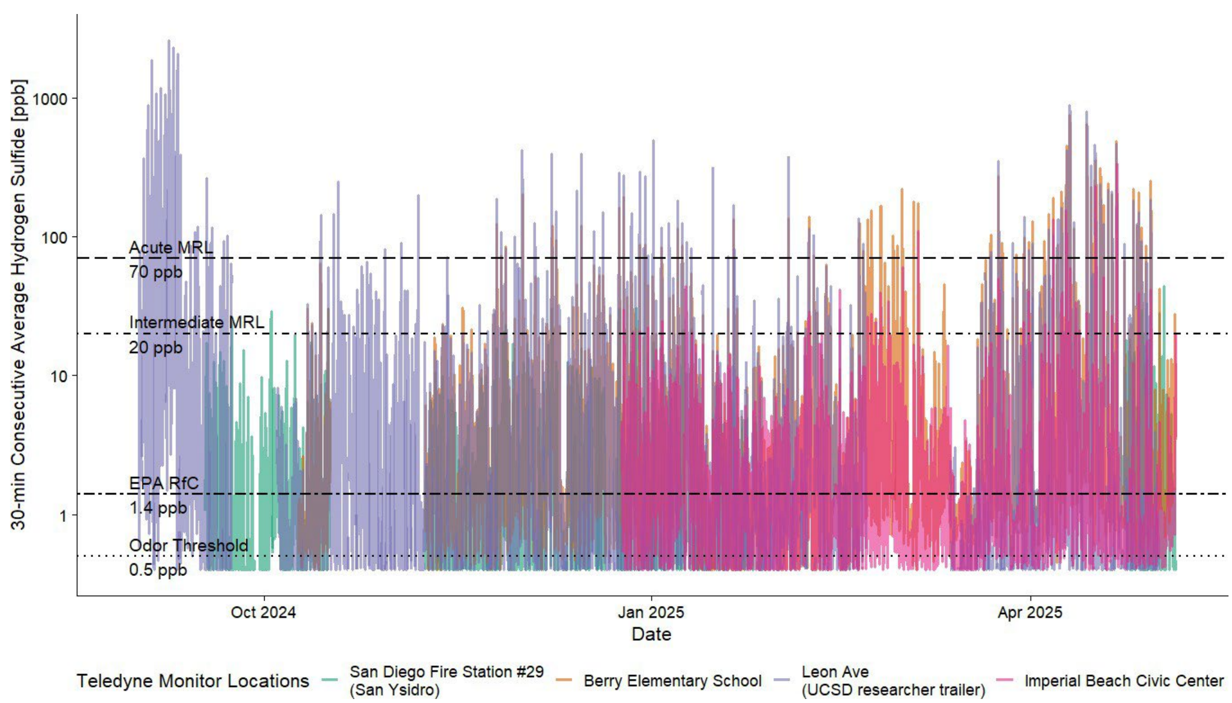

Figure 7: 30-Min Consecutive Averages Compared to Hydrogen Sulfide Health Guideline Values

SDAPCD collects odor complaints from residents in the South Bay area [SDAPCD 2025c] through an app, phone calls, and email. To analyze the odor complaints, ATSDR calculated two-day rolling averages of hydrogen sulfide concentrations for each monitoring location. ATSDR selected two days to account for the fact that some people may not report a strong odor at night until the following morning. ATSDR compared the two-day rolling averages with the quantity of odor complaints, converted to two-day rolling averages, and found that odor complaints appear to trend with hydrogen sulfide concentrations. Results are shown for each of the four monitoring locations in Figure 8 (Berry Elementary School), Figure 9 (Leon Avenue), Figure 10 (Imperial Beach Civic Center), and Figure 11 (San Diego Fire Station #29, San Ysidro).

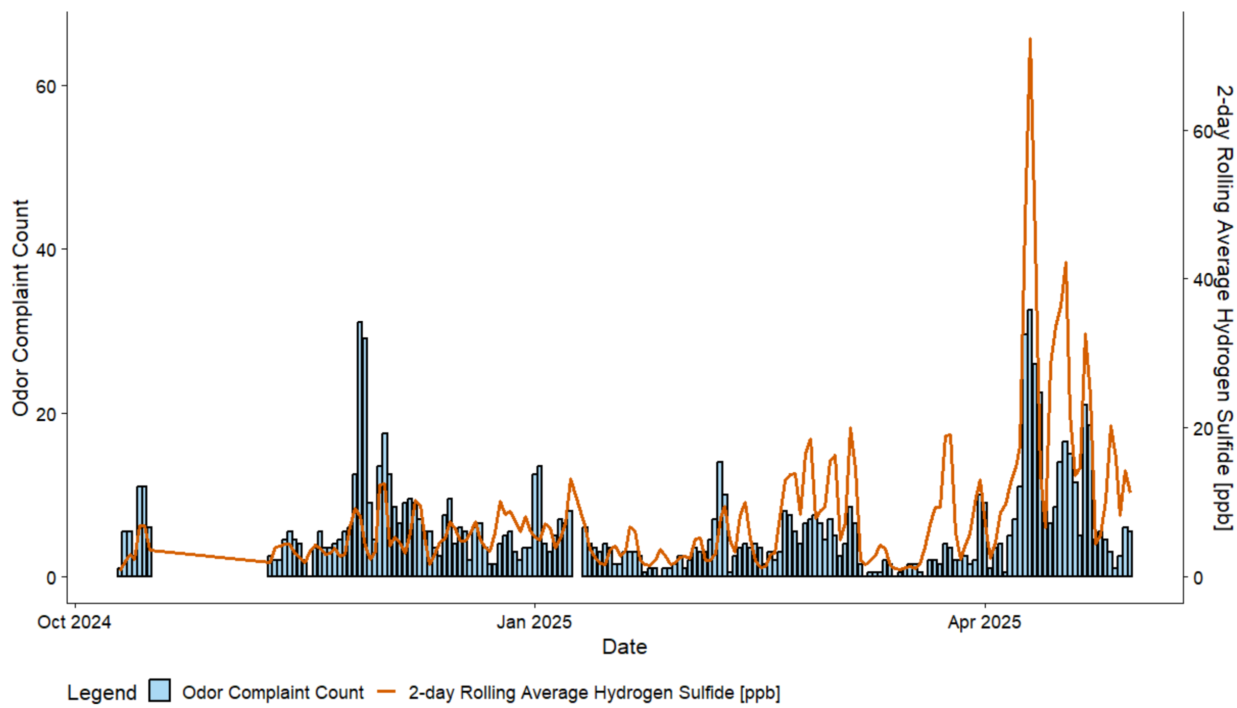

Figure 8: Averaged Two-Day Hydrogen Sulfide Concentrations compared to Odor Complaints at Berry Elementary School

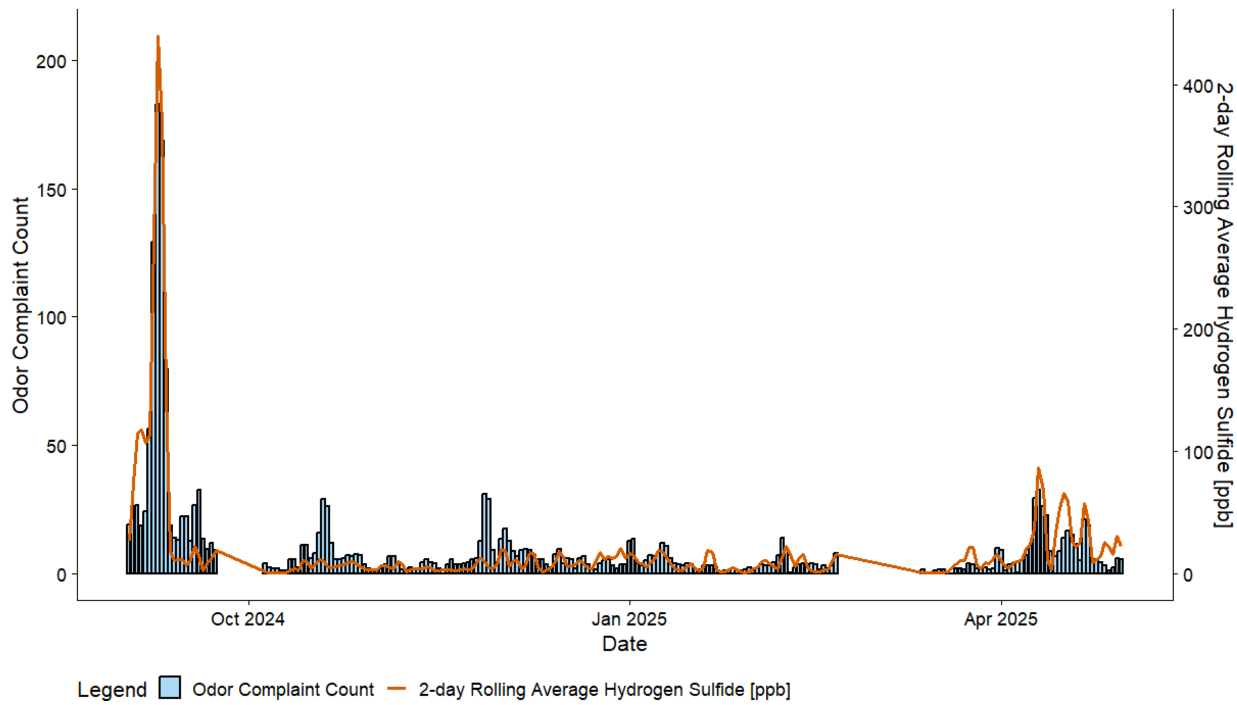

Figure 9: Averaged Two-Day Hydrogen Sulfide Concentrations compared to Odor Complaints at Leon Avenue

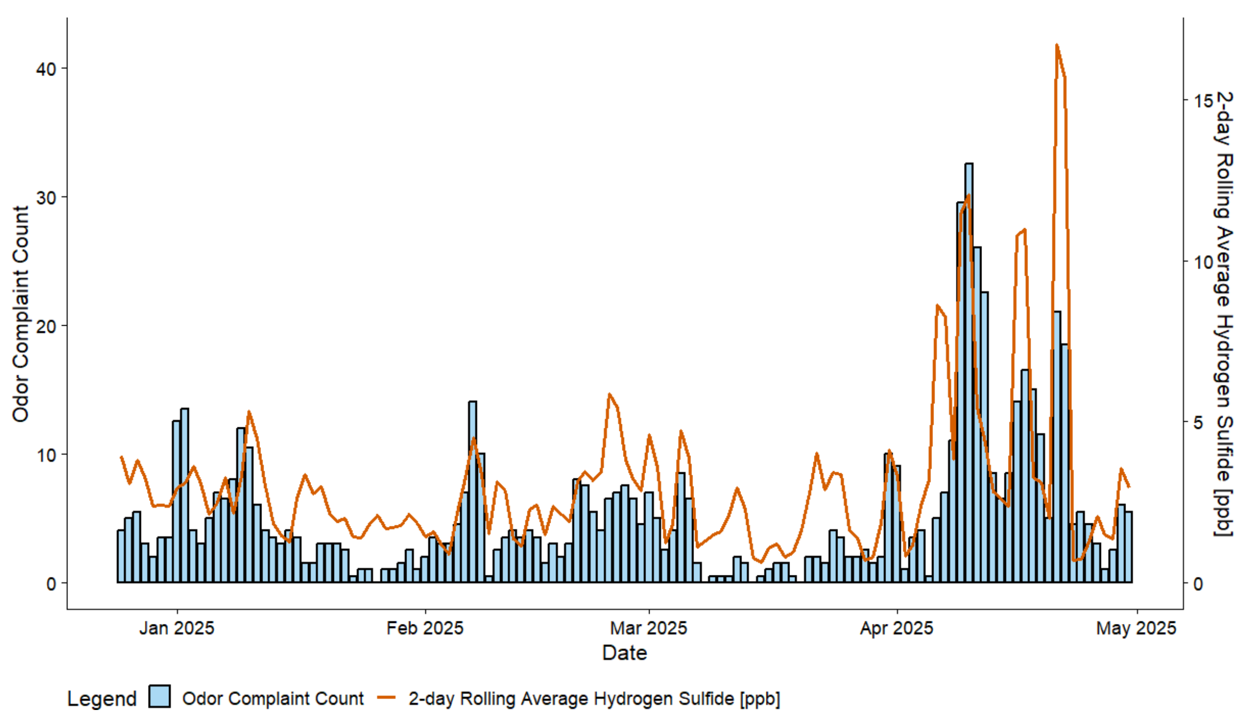

Figure 10: Averaged Two-Day Hydrogen Sulfide Concentrations compared to Odor Complaints at Imperial Beach Civic Center

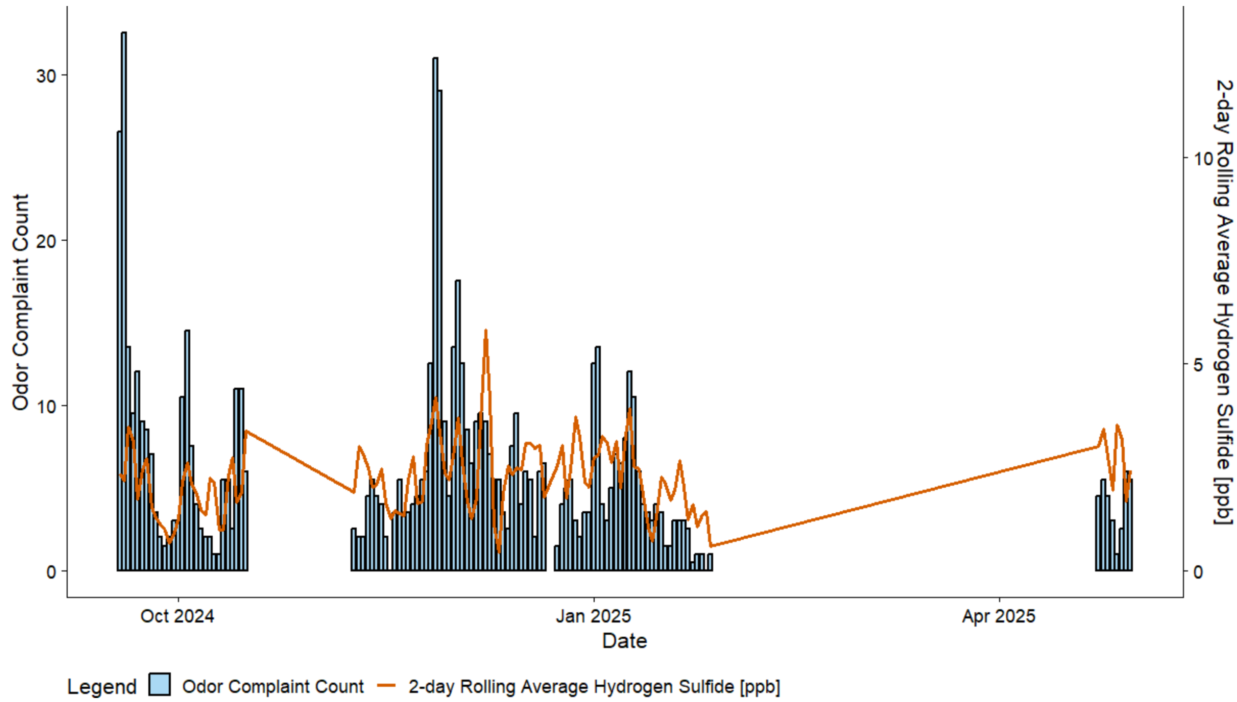

Figure 11: Averaged Two-Day Hydrogen Sulfide Concentrations Compared to Odor Complaints at San Diego Fire Station #29 (San Ysidro)

ATSDR analyzed the one-hour river flow data with one-hour averaged hydrogen sulfide data from Leon Ave. Figure 12 shows the comparison between river flow and H_2S concentrations during the initial UCSD hydrogen sulfide monitoring at the Leon Ave site, from Sept 1, 2024, to Sept 22, 2024. Visually, hydrogen sulfide spikes matched closely with spikes of river flow. San Ysidro Fire Station had significant correlation between riverflow and hydrogen sulfide concentrations, but the correlation coefficient is small (Kendall's Tau Rank Correlation coefficient = 0.053; p <0.001). Other TeledyneT101 monitoring locations had no significant correlations.

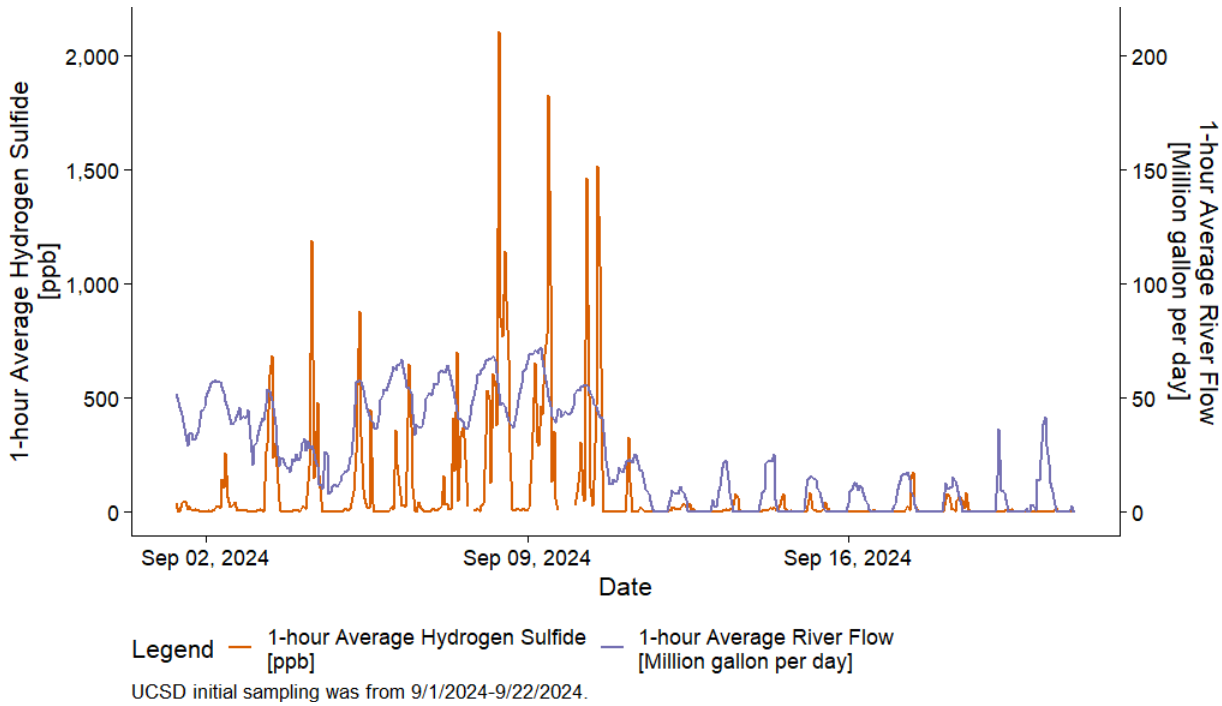

Figure 12: One-hour Tijuana River flow rates compared to hydrogen sulfide concentrations at the Leon Avenue monitoring location from September 1-September 22, 202

Figure 13 shows acute EPCs (30-minute rolling average) during the day and during the night. Hydrogen sulfide concentrations remained below the acute MRL most of the time, but concentrations did exceed the acute MRL at Berry Elementary School, Leon Avenue, and Imperial Beach Civic Center. At Imperial Beach Civic Center, the exceedance occurred only at night. More exceedances also occurred at Berry Elementary School and Leon Avenue during the night.

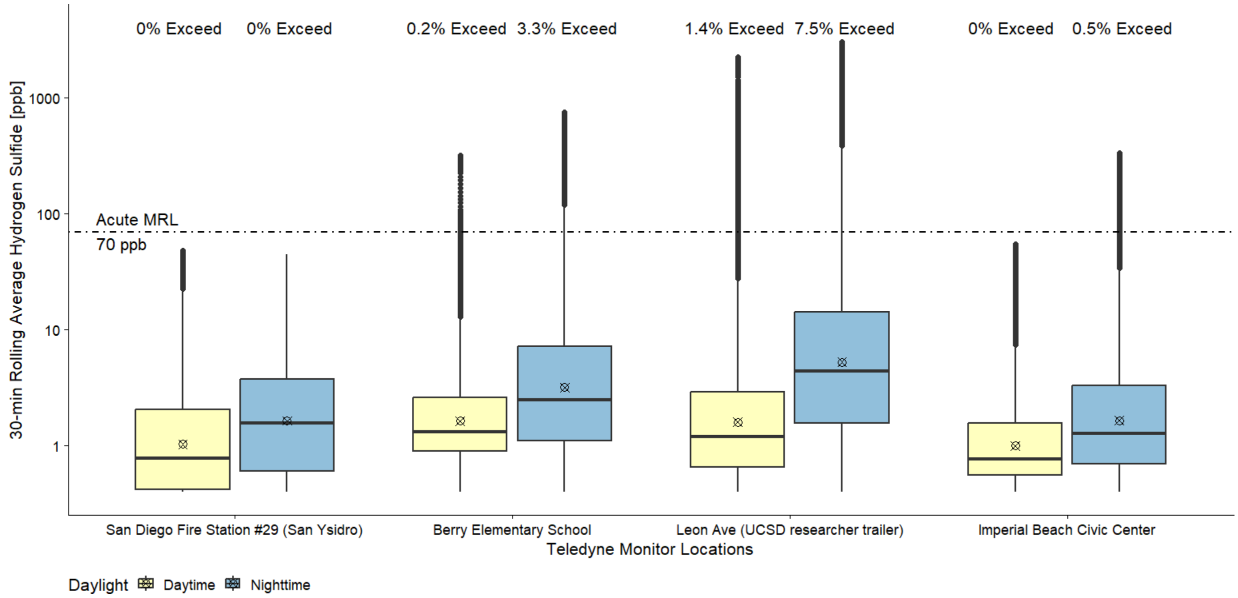

Figure 13: Acute EPCs during the day and night by location compared to the acute hydrogen sulfide MRL

Figure 14 shows intermediate EPCs (14-day rolling average) by location. Hydrogen sulfide concentrations remained below the intermediate MRL most of the time, but concentrations did exceed the intermediate MRL at Berry Elementary School and Leon Avenue. ATSDR did not analyze the data by daytime/nighttime because the 14-day rolling average included both times of day.

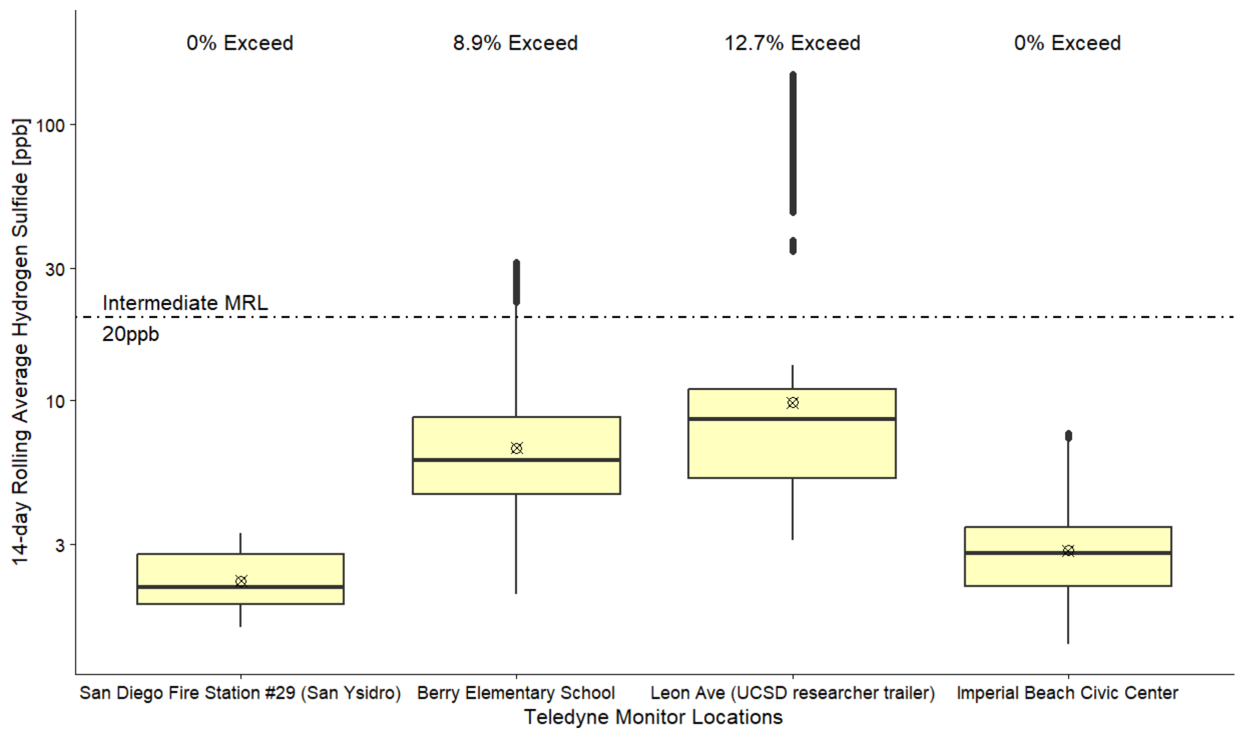

Figure 14: Intermediate EPCs by location compared to the intermediate hydrogen sulfide MRL

Appendix C: Correlation between Leon Avenue and Berry Elementary School Monitoring Sites

ATSDR assessed how closely related the Berry Elementary School and Leon Avenue hydrogen sulfide concentrations were when data were available from both sites at the same time. Kendall's Tau Rank Correlation was tested on the raw one-minute data between each Teledyne monitoring location to see which locations were most correlated with each other (Figure 15). Results showed that Leon Ave and Berry Elementary School monitoring sites had the highest correlation and required further analysis.

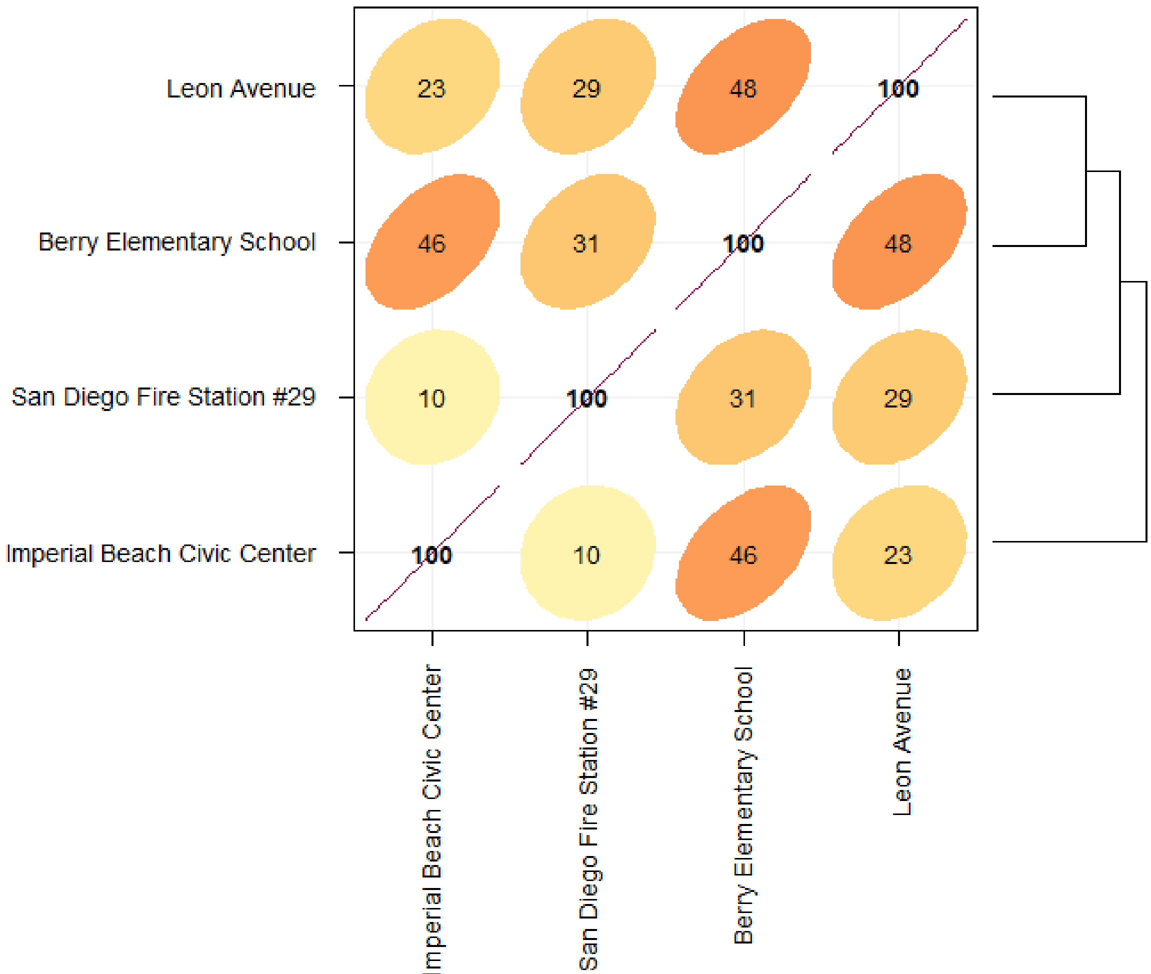

Figure 15: Kendall's Tau Rank Correlation plot for all monitoring sites

ATSDR also looked at the cross-correlation between each site. First, ATSDR used the Augmented Dickey-Fuller (ADF) test to see if the time-series data at each site were stationary (not trending higher or lower). Table 16 shows the results of the ADF test. The higher magnitude negative ADF values more strongly favor stationarity. If the p-value is less than 0.05, we reject the null hypothesis that the time series has a root unit for the alternative hypothesis that the time series is stationary, which means that the time series has constant mean and variance over time.

Table 16: Augmented Dickey-Fuller (ADF) Test Results

Site	ADF	p-value
San Diego Fire Station #29 (San Ysidro)	-24.2	<0.01
Berry Elementary School	-34.7	<0.01
Leon Avenue	-30.6	<0.01
Imperial Beach Civic Center	-26.8	<0.01

Abbreviation: ADF = Augmented Dickey-Fuller

Because all sites have time-series that are stationary, cross-correlation was calculated between each site. Table 17 shows the maximum cross-correlation and its respective lag found at each site. Air monitoring at Leon Avenue and Berry Elementary School had the highest correlation, at 0.69.

Table 17: Cross-correlation between monitoring sites

Site	San Diego Fire Station #29 (San Ysidro)	Berry Elementary School	Leon Avenue	Imperial Beach Civic Center
San Diego Fire Station #29 (San Ysidro)	--	0.17 (lag -7)	0.18 (lag 42)	0.06 (lag -1)
Berry Elementary School	--	--	0.69 (lag -7)	0.35 (lag -62)
Leon Avenue	--	--	--	0.28 (lag -78)
Imperial Beach Civic Center	--	--	--	--

The Berry Elementary and Leon Avenue Teledyne T101 monitors were located close each other, so correlation between the two monitors was further analyzed. Maximum lag of 120, or two hours, is visualized in a cross-correlation plot between the measurements located at Berry Elementary School and Leon Avenue, matched by date and time of the measurements, found in Figure 16. For all lag values, cross-correlation between Berry Elementary and Leon Avenue Teledyne monitors are greater than zero. The cross-correlation between the monitors are most strongly correlated, with lag of about five minutes.

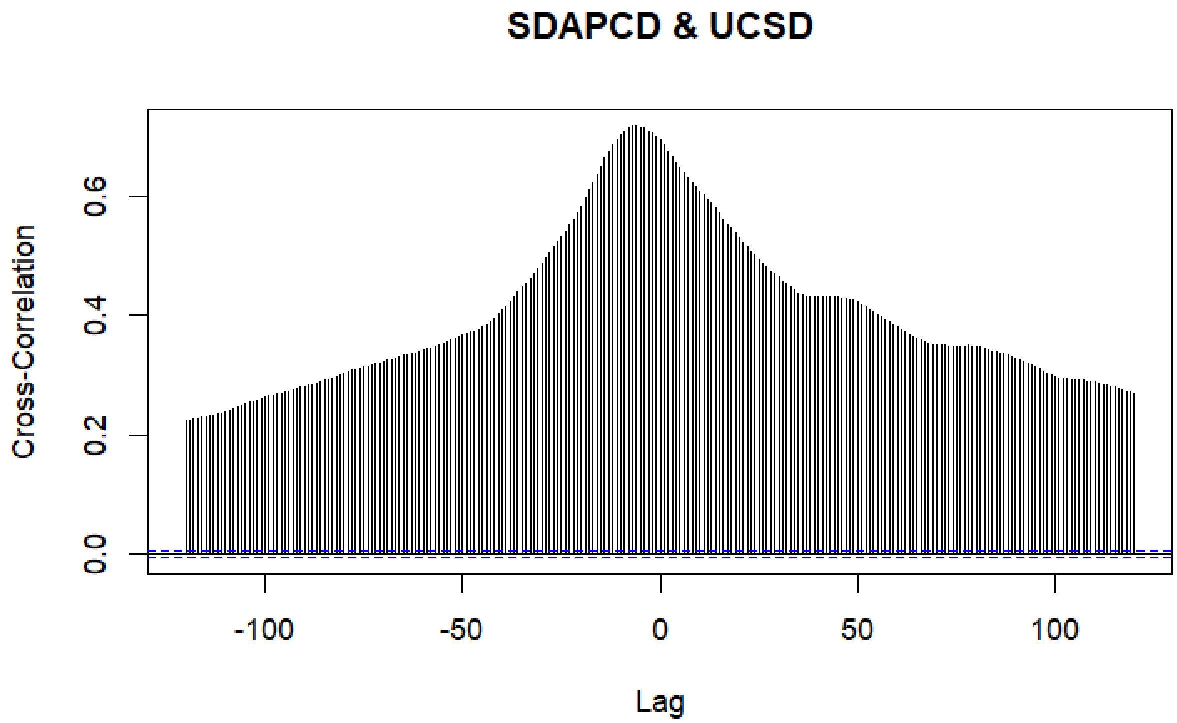

Figure 16: Cross-Correlation Plot between Berry Elementary School and Leon Avenue

ATSDR also tested the correlations and median differences between the two sites. Using Kendall's Tau Rank Correlation, ATSDR found correlation between the two monitors to be significant with r = 0.49. In a Paired Wilcoxon Signed-Rank Test, ATSDR found that differences to be significant ($p < 0.001$) with a difference of 0.69 ppb, but this difference was small (effect size of 0.27).

Looking at the matched pairs of only the Berry Elementary and Leon Avenue TeledyneT101 monitoring data, ATSDR found that there are three distinct time periods created by the missingness of the data. These represent times when data was available for both TeledyneT101 monitors. ATSDR tested the correlations and differences between the Teledyne monitors by these time periods (Figure 17).

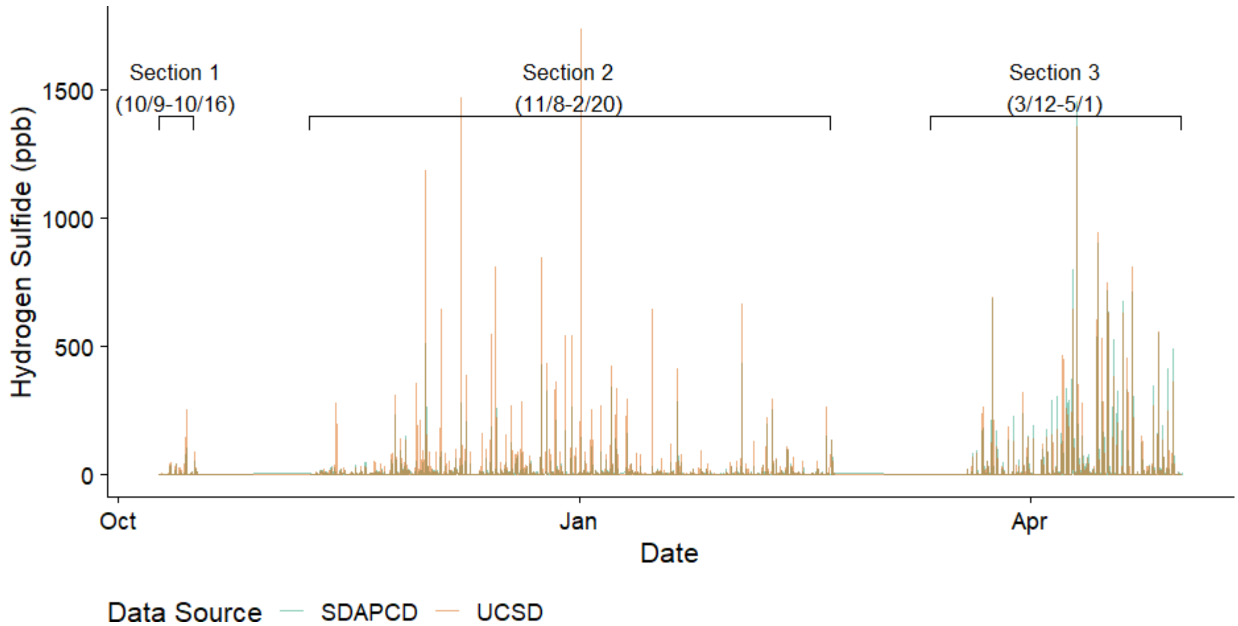

Figure 17: Matched Hydrogen Sulfide Concentrations for Leon Avenue and Berry Elementary School

Table 18 shows the Kendall's Tau Rank Correlation and Paired Wilcoxon Signed-Rank Test with effect size for each time period and all time periods together. Significant correlation was found and significant differences between the two Berry Elementary and Leon Avenue Teledyne monitors were found, with effect size ranging from small to moderate.

Table 18: Kendall's Tau Rank Correlation and Paired Wilcoxon Signed-Rank Test and effect size for each time period (Leon Avenue and Berry Elementary)

Period	Kendall Tau Correlation (Test Significance)	Paired Wilcoxon Signed-Rank Test Median Difference (Test Significance)	Paired Wilcoxon Signed-Rank Test (Effect Size)
Period 1	0.40 (***)	0.12 ppb (***)	0.19 (small)
Period 2	0.41 (***)	0.50 ppb (***)	0.20 (small)
Period 3	0.64 (***)	1.65 ppb (***)	0.43 (moderate)
Full time period	0.49 (***)	0.69 ppb (***)	0.27 (small)

***p-value of statistical test is less than 0.001