Heavily Polluted Tijuana River Drives Regional Air Quality Crisis

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Abstract

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

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

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

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

Identifying the Tijuana River H_2S and Malodor Hotspot

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

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

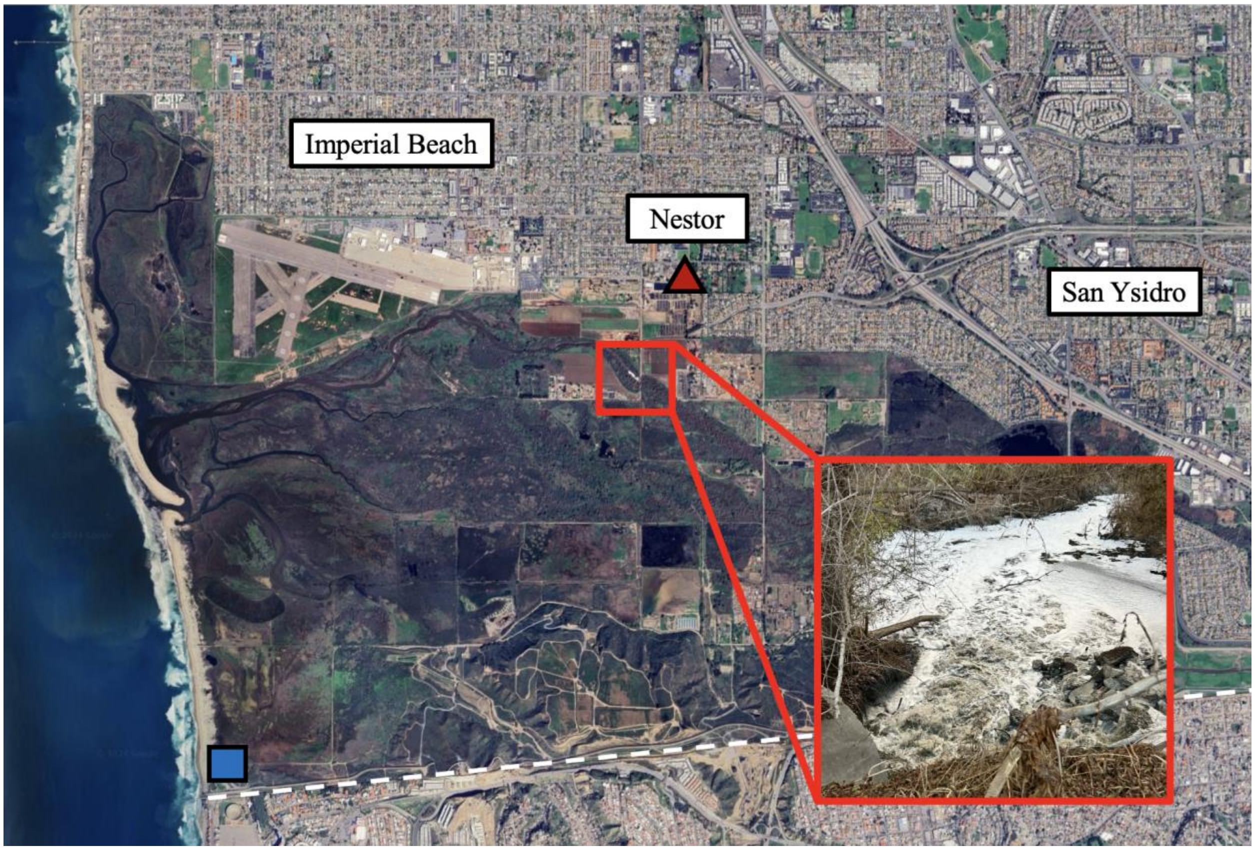

Fig. 1. Map of Coastal and Inland Air Sampling Sites. The blue square represents the coastal sampling site at Border Field State Park; the red triangle marks the inland sampling site in Nestor; and the red box shows the river crossing at Saturn Boulevard, identified with community

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

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

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

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

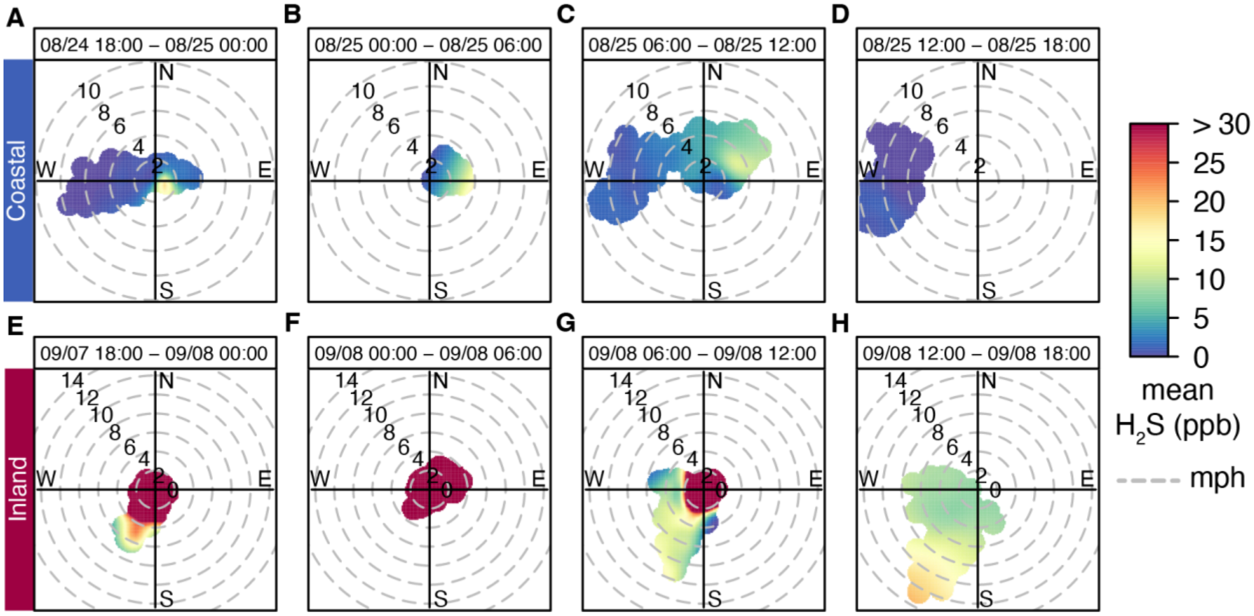

Fig. 2. Polar heat maps of H_2S levels at coastal and inland sampling sites segmented into four six-hour periods. (A, B, C, D) H_2S polar heat maps at the Border Field State Park coastal site, spanning August 24-25, 2024. **(E, F, G, H)** H_2S polar heat maps at the inland site of Nestor, spanning September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

Unprecedented Dry Summer Season Flows in 2024

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

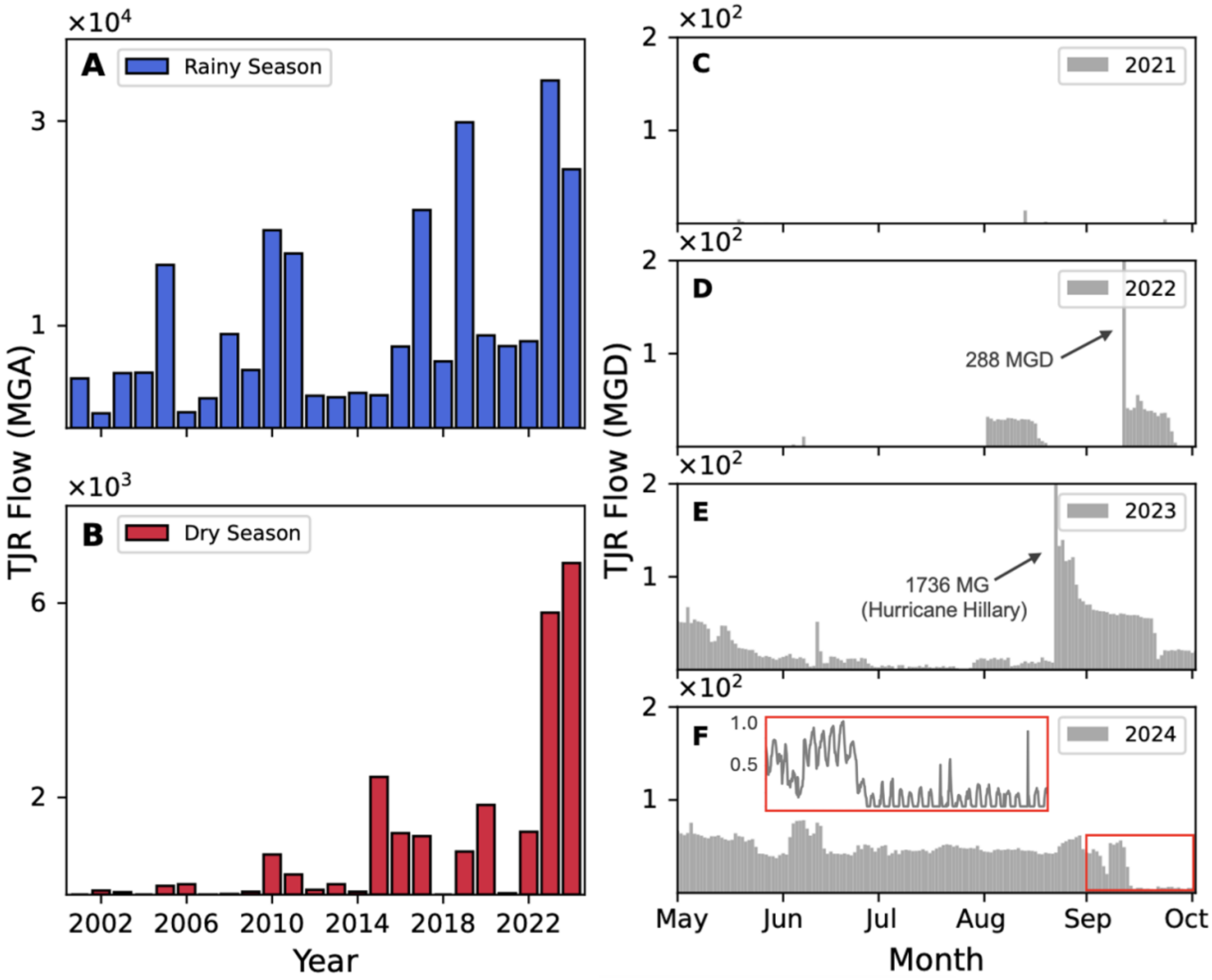

Fig. 3. Historical annual transboundary river flow. (A) Tijuana River flow during the San Diego rainy season (November-March) between January 2001- October 2024 in millions of gallons annually (MGA). **(B)** Tijuana River flows during the San Diego dry season (May-September) between January 2001- October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

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

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

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

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

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

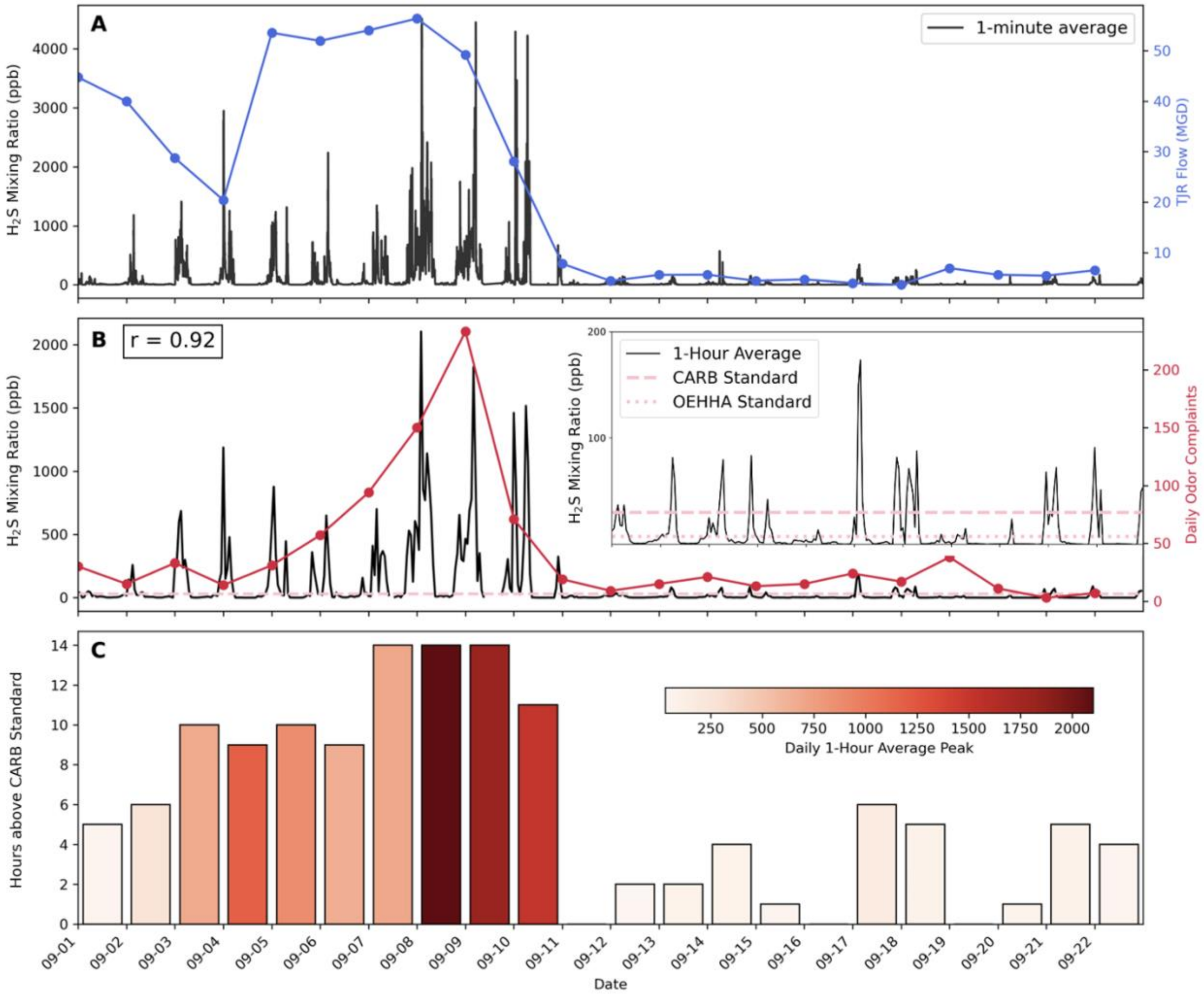

Fig. 4. Time Series plots, H_2S and malodor reports correlation, and comparison to CARB Ambient Air Quality Standard. (A) H_2S levels (1-min average) and daily river flow in millions of gallons per day (MGD). **(B)** H_2S levels (1-hr average) and daily malodor reports received by the SDAPCD. Correlation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

Air Dispersion of Pollutants Broadens Tijuana River Impact to Regional Scale

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

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

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

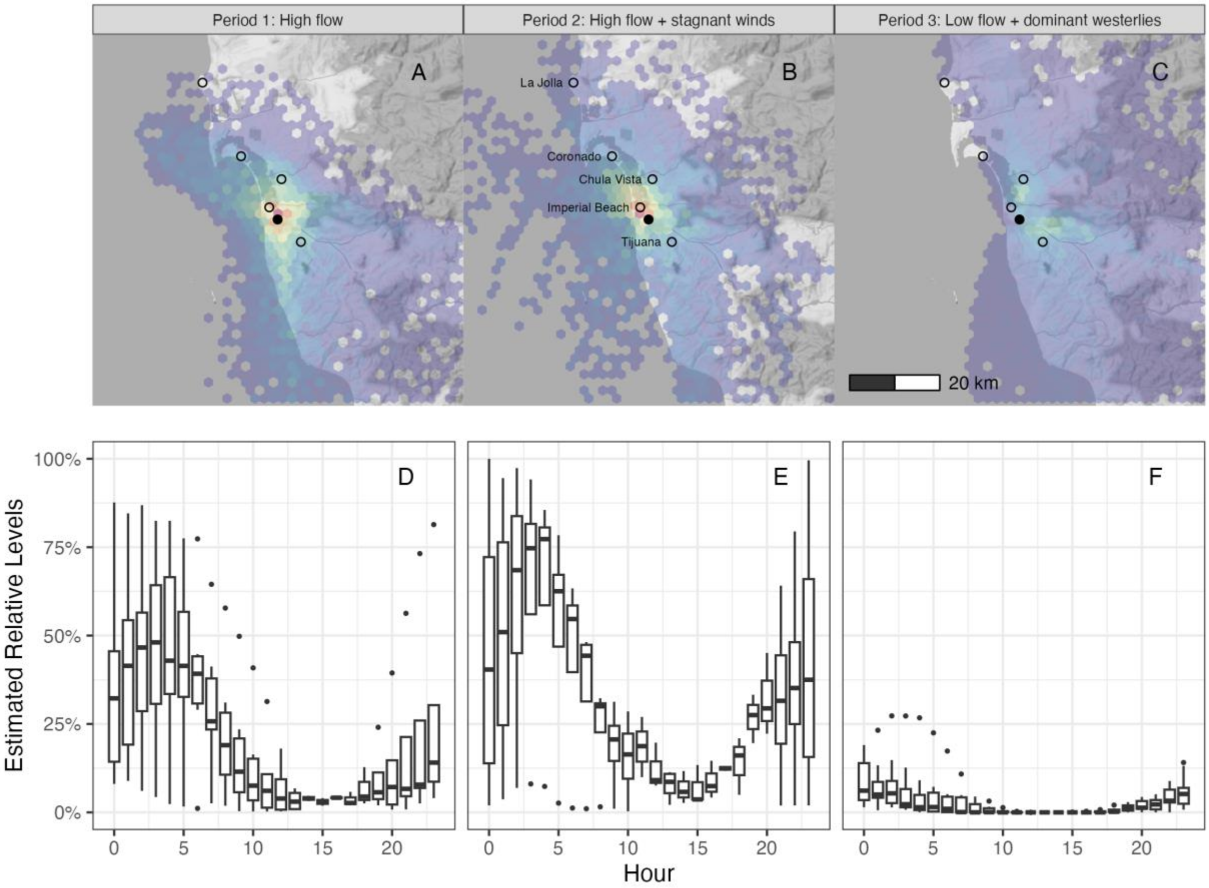

Fig. 5. Dispersion modeling showing spatial and diurnal patterns for trajectories starting at the Saturn Boulevard river crossing H_2S hotspot. Relative dispersion and spatial intensities across Tijuana River Valley and surrounding area are shown for **(A)** Period 1 (September 1-5), **(B)** Period 2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

Polluted Water Bodies as Emission Sources for Air Quality Modeling

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

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

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

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

Addressing Environmental Justice and Protecting Public Health

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

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

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

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

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