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Monitoring the Effects of Transboundary Water Pollution in Imperial Beach, California †

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Abstract: Transboundary water pollution is a major global challenge as its movement and impacts remain unsurveyed. Monitoring pollution along international borders can reveal some of the pathways by which sewage and chemicals enter water bodies, and can hence advance the implementation of measures to prevent leakages and discharges into international waters. In this paper, we surveyed the impacts of sewage pollution and chemicals along the U.S.–Mexico international border, using Imperial Beach (California) as a main case study. Pollution was primarily attributed to the inflow of contaminated waters from the neighboring city of Tijuana (Mexico), where a malfunctioning wastewater treatment plant and a lack of sewage pipes being upgraded have caused direct leakage and toxic discharges into the Tijuana River. Reported effects from water pollution at the Tijuana River estuary in Imperial Beach include frequent beach closure, damages to coastal ecosystems, negative impacts on the fishery industry, and several effects on the health of beach users and surfers. Hence, the situation requires urgent measures oriented at coastal management at the mouth of the Tijuana River as well as the consistent monitoring and reporting of human health effects linked to beach uses.

Keywords: transboundary pollution; monitoring; sewage and chemicals; Imperial Beach; coastal management; human health

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1. Introduction

Over the past few decades, there has been a striking increase in the occurrence and magnitude of harmful emissions entering the world's oceans. It has been estimated that approximately 90% of such emissions originate on land and enter the sea via waterways, wastewater systems, and rivers [1,2], and they can be transported by wind and currents over long distances [3,4]. Hence, scholars emphasized the need to study sources, pathways, and final sinks of pollutants and to assess their related impacts on local marine ecosystems and human health [5].

Transboundary pollution has garnered particular attention due to the challenges associated with tracing material and pollution flows across different countries, the existence of different monitoring and accounting systems and infrastructure, difficulties in keeping material flows accountable, and the insufficient exchange of information across international borders [6], which would require collaborative cross-national efforts [7]. This situation is further complicated when pollutants enter international waters and their monitoring and subsequent management become impossible [8].

As a consequence, marine pollution affects our environment and jeopardizes the health and subsistence of marine life, resulting in physical harm, such as entanglement, and ingestion, or chemical contamination [9]. Furthermore, the occurrence of unanticipated changes in the natural feeding environment could substantiate the incidence of cascade effects across all levels of the food chain, with increased concerns for species survival when such effects fall below the threshold level [10].

Although research in this field is still new and evolving, it has been suggested that pollutants could make their way to the top of the chain, transferring from one trophic level to the next via the food supply, eventually entering the human body [11]. This raises concerns related to food security, food safety, and ultimately human health, as the volume of plastic in the environment continues to grow every day [11]. Hence, curbing and preventing marine litter is a priority for all to ensure a sustainable and safe livelihood towards the achievement of the United Nations (UN) 2030 Agenda and its Sustainable Development Goals (SDGs) [12].

Recognizing the tremendous importance of consistent pollution monitoring, this paper provides a novel methodology for mapping the main hotspots of pollution along the U.S.–Mexico border. In particular, the overarching goals of this study are to (i) expand the use of monitoring techniques to detect pollution along international borders, to (ii) map pollutants sources and pathways, and to (iii) understand the impacts on the environment and human health associated with pollution.

We investigate these issues within the context of the U.S.–Mexico international border, using Imperial Beach (California, U.S.) as a main case study. The scientific hypothesis of this investigation is that transboundary water pollution from Tijuana, Mexico, significantly contributes to environmental degradation and public health risks in Imperial Beach, California. Contaminated waters, primarily due to a malfunctioning wastewater treatment plant and outdated sewage infrastructure in Tijuana, are impacting the Tijuana River and subsequently affecting Imperial Beach. This pollution leads to beach closures, damages coastal ecosystems, negatively affects the fishery industry, and causes health issues for beach users and surfers. The study highlights the need for urgent coastal management at the Tijuana River mouth and the consistent monitoring and reporting of health effects linked to beach use.

The remainder of the paper is structured as follows: Section 2 introduces the study's background. Section 3 presents a replicable methodology for mapping pollution hotspots. Section 4 reports the main findings and implications of the study. Finally, Section 5 draws conclusions and final remarks.

2. Background

2.1. Pollution and Ocean Governance

Marine pollution has long been recognized as a constraint to sustainable ocean governance [13]. Since the problem's recognition, several measures to combat this threat have been put in place. Marine pollution from oil, chemicals, nuclear waste, and urban outflows was first prohibited in the 1950s, during the first United Nations Conference on the Law of the Sea. However, it was not until the 1970s that marine pollution received global attention, fostering international action to reduce marine litter and microplastics [14].

Marine pollution from ships was addressed during the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter in 1972, and subsequent amendments [15], adopted by the International Maritime Organization (IMO) [16]. This was followed by the International Convention for the Prevention of Pollution from Ships 1973/78, also known as MARPOL, that banned marine pollution from ships from operational or accidental causes [17].

The year of 1992 marked a cornerstone in the battle against marine pollution. During the Rio Declaration on Environment and Development, the so-called Earth Summit, serious concerns were raised against pollution and environmental deterioration resulting from anthropogenic activities [18]. Relying on the recommendations of the 1972 Stockholm Conference, the Earth Summit emphasized the central role of the environment's development, framed around the coexistence between humans and the environment [19]. Specifically, concerns were raised on transboundary pollution and its implied impacts on natural systems.

Environmental concerns grew accordingly in the framework of the United Nations' systems, leading to the adoption of the United Nations Environment Assembly (UNEA) in

2014. Furthermore, world leaders recently committed to the 2030 Agenda for Sustainable Development which included a specific goal on the conservation of "*Life Below Water*" (SDG14) [12]. As a result, the United Nations established the Conference to Support the Implementation of Sustainable Development Goal 14, commonly known as the Ocean Conference, which aims to "*conserve and sustainably use the oceans, seas and marine resources for sustainable development*" [12].

Accordingly, an ad hoc expert group on marine litter and microplastics was established in 2018 to discuss relevant issues related to marine pollution, formally structured under the UNEA. Since its foundation, the an ad hoc expert group brought important contributions to the ongoing debate on marine pollution, calling upon governments and institutions to "*address the problem of marine litter and microplastics, prioritizing a whole-life-cycle approach and resource efficiency (...) grounded in science, international cooperation and multi-stakeholder engagement*" [20].

Finally, the UNGC launched the Sustainable Ocean Principles in 2020 on the retention of land-based and sea-based anthropogenic pollution (4: End waste entering the ocean) with the specific goal of "*achieving a clean ocean where sources of pollution are identified and removed (...), reveal the causes and sources of pollution, and help to prioritize and inform the most efficient and effective interventions to eliminate or redirect harmful activities*" [21]. These measures provide a set of guidelines for the industry, from reducing unnecessary leakages along the value chain to establishing circular delivery models and investing in alternative materials.

However, despite 70-year global commitments to ocean governance, a number of challenges in addressing marine pollution remain. In addition, international agreements to prevent and mitigate waste and pollution entering the ocean are not easily agreed upon and are often criticized [13]. Consequently, harmful pollutants continue to enter the ocean [22].

2.2. Pollution Monitoring Along the U.S.–Mexico Border

Efforts to monitor transboundary pollution along the U.S.–Mexico border remain limited in scope and scale. At present, few monitoring programs exist; of these, only one program, the U.S. Section of the International Boundary and Water Commission (USIBWC) on water quality monitoring, targets transboundary pollution flowing in from Mexico in proximity to a collector system designed to capture transboundary flows [23,24]. Other existing programs are primarily focused on monitoring water quality across San Diego County, including California State Water Resources Control Board surface water monitoring, the Department of Environmental Health's conducting bacteriological water sampling, the County of San Diego's Beach & Bay Water Quality Program, City of Imperial Beach water quality monitoring, the Southern California Coastal Water Research Project, and Tijuana River National Estuarine Research Reserve's water sampling [23–27]. However, a specific focus on transboundary pollution is missing and binational monitoring plans are missing.

To the best of our knowledge, this is the third study advancing pollution monitoring along the U.S.–Mexico border. However, the other two studies—the Southern California Coastal Water Research Project and the monitoring program of the Tijuana River National Estuarine Research Reserve [25]—are limited in scope and scale, and thus are not suitable for providing comprehensive monitoring of riverine influx into the Pacific Ocean. Hence, the value of this study is in the systemic assessment and characterization of transboundary pollution flows which allow us to identify the most vulnerable areas that require priority interventions to control and mitigate material losses from socio-technical systems to the environment.

3. Methodology

3.1. Study Area

The city of Imperial Beach is the southernmost beach town in California, located five miles northwest of Tijuana, Mexico, and home to the Tijuana Estuary wetlands with more than 300 species. The persistence of pollution in Imperial Beach is primarily associated with four factors: the (i) lack of pollution removal and leakage containment targets, the

(ii) lack of consistent cleanups and removal efforts, the (iii) inefficiency of the existing waste retainment infrastructure, especially due to waste overflowing during wet periods, and the (iv) lack of consistent monitoring and waste assessment programs [25,27].

According to the San Diego County Department of Environmental Health and monitoring data from the International Boundary and Water Commission, sewage-contaminated runoff from the Tijuana River is the largest contributor to beach advisories and closures in Imperial Beach due to high concentrations of pollution [28]. Researchers have found that during the summer, ocean currents on both sides of the border carry plumes of feces and dangerous pathogens from the plant as far north as Coronado (California), Rosarito (Mexico), and Tijuana (Mexico) [29]. This contamination has led to people suffering from ear infections, airborne sewage bacteria (aerosolization of raw sewage), high levels of bacteria, rashes, skin infections, and other illnesses. Approximately 40 million gallons of sewage flow into the water at South Bay Beaches across the US–Mexico border daily. Although Mexico has approved USD 140 million through 2027 to upgrade sewage pipes and other facilities in Tijuana, Mexico, as part of a cross-border deal with the US, little to no changes have been made [29]. The Mayor of Imperial Beach Paloma Aguirre has put blame on the Mexican government for not providing funding to fix its sewage treatment plant. The mayor noted that "*people in Mexico are also affected, but they only test the water once or twice a year, so you have people constantly swimming in polluted water without ever knowing, and it even affects expats and the US. visitors to Baja*" [30].

For this study, five sampling locations were selected in Imperial Beach, including (S1) Smuggler's Gulch Canyon, (S2) Goat Canyon, (S3) Tijuana River Valley Regional Park, (S4) South Beach, and (S5) Desembocadura del Río Tijuana (Tijuana River Estuary) (Figure 1).

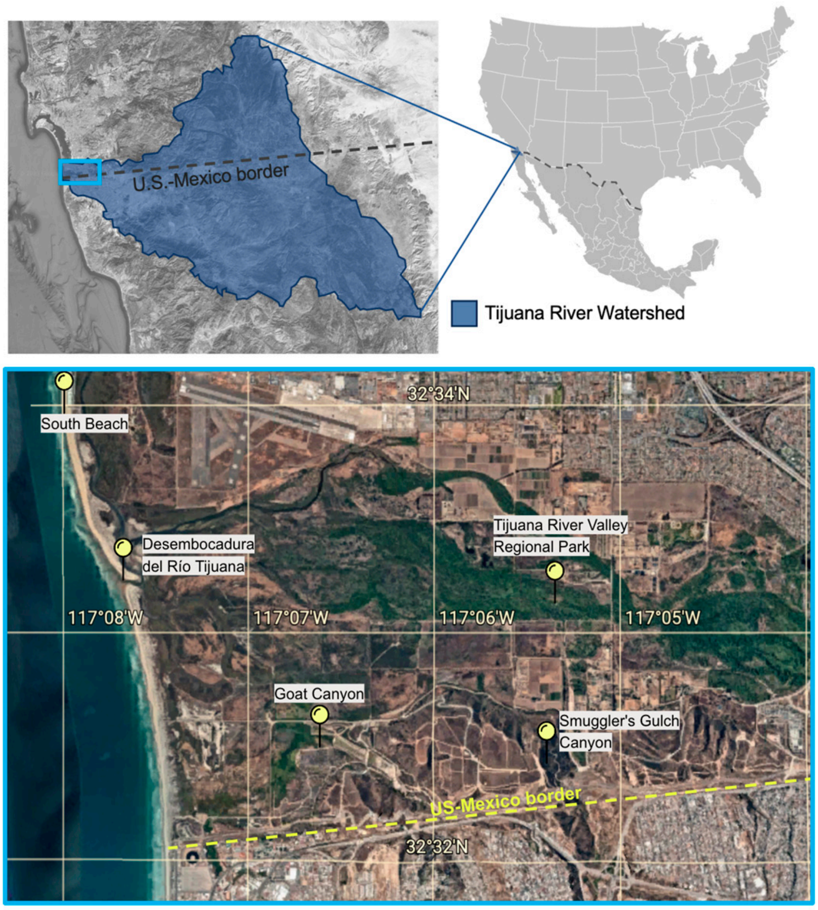

Figure 1. Map of sampling locations, Imperial Beach.

3.2. Experimental Design

Prior to the identification of pollution hotspots, it is imperative to define the scale of analysis, the environmental compartments to be sampled, the existing issues, the methodology to be employed, and the study's objectives, in line with the principle of the experimental design [31]. In general, monitoring pollution hotspots can be conducted at three different levels of analysis, the macro level, meso level, and micro level, with each entailing a specific set of requirements and objectives. Table 1 identifies such requirements and objectives to guide the design of the analysis at the three levels.

Table 1. Characteristics of macro-, meso-, and micro-level monitoring.

	Macro-Level Monitoring	Meso-Level Monitoring	Micro-Level Monitoring
Compartments	- Entire or larger segments of the river basin. - Interregional borders. - Transboundary waters/vegetation.	- Smaller segments of the river basin. - Catchment areas.	- Water. - Sediments. - Biota.
Open issues	- Limited traceability associated with different systems for monitoring and accounting. - Different policies and measures to manage resources and keep ecosystem services accountable. - Lack of information exchanged across administrative borders. - Uneven use and communication of data analytics.	- Need repeated measurements over several consecutive days/weeks/months. - Uncertainty, lack of data, and limited traceability of a given phenomenon.	- Localized ecological, biological, and chemical impacts. - Traceability of translocation mechanisms.
Methodologies	- Space-based observations. - Spectrometric analysis of satellite imagery. - Proximity sensing (e.g., sensors, drones) data acquisition.	- In-site assessment through visual inspection. - Proximity (e.g., sensors, drones) data acquisition.	- Sampling of water/sentiments/biota. - Microscopic/lab analysis. - Image analysis.
Objectives	- Provide real-time/nearly real-time data acquisition, wide area coverage, and high spatial resolution. - Provide a consistent system for environmental assessment.	- Capture spatio-temporal variability over time. - Manageable scale. - Provide a more accessible assessment (including cost-effective tools and citizen science).	- Assess specific impacts associated with human activities/biota interactions. - Capture microscopic transformations (ecological, biological, chemical).

3.3. Monitoring Approach

In line with the objectives of this study, macro- and meso-level monitoring were conducted at the five sampling locations. First, to spatially identify pollution hotspots, we acquired optical images at each site from four different satellites, including Landsat 8–9 (USGS), Sentinel-2 and Sentinel-3 (ESA), and GOES (NOAA CoastWatch). Data were collected over several consecutive dates for the period of February–April, 2022. Individual optical images were consulted to observe main features of the sampling locations, pollution entry points, and areas of possible pollution convergence. To reduce errors and unwanted effects (e.g., clouds and other weather conditions, surface reflectance, viewing geometry), we analyzed a series of images for each site, as prescribed by Maximenko et al. [32] and Pichel et al. [33].

Following this, we conducted in situ observations at all locations during the period of March–April, 2022. Observations were carried out according to two main techniques: observer-based surveying and participatory mapping. Observer-based surveys at the sampling sites S1, S2, and S3 were conducted by a trained team composed of experienced observers and graduate students, due to the difficulty in accessing the area and the high exposure risk. Upon arrival at the sampling site, observers defined the site boundaries using a hand-held GPS device and flag markers. Due to the high exposure to chemical and toxic substances, the team performed distance sampling [34,35]. Each observer separately collected information on the site's main characteristics to provide sufficient context for the analysis. Recorded information included observer notes, estimated pollution coverage, and photographic surveys using a Canon EOS REBEL t3i, a GoPro Hero 9, and mobile phone cameras. Following this, all separately recorded information was analyzed and cross-referenced to avoid biases in data acquisition, as prescribed by Garcia-Garin et al. [36].

For sites S4 and S5, participatory mapping was employed as a main monitoring technique, due to better accessibility to the area. A participatory mapping protocol was developed to offer the preliminary training of participants in both the general and specific goals of data acquisition and bridging existing gaps in citizen science databases via the standardization of sampling procedures in a simple, clear, and understandable manner. A total of 22 participants were involved in data collection, including 8 high school students aged 18 years old, 8 college and graduate students aged 21–36, 2 teachers aged 50 and 65, 2 university staff members aged 34 and 51, and 2 children aged 10 and 11. The citizen scientists were divided into four groups with different backgrounds and age ranges, and equipped with hand-held GPS units, pencils, data recording sheets, gloves, and smartphones. Smartphones were used to register the coordinates of main points of pollution convergence to create pollution hotspot maps.

4. Results and Analysis

Key features and characteristics of the identified hotspots relative to the state of waste and pollution are summarized in Table 2. In general, it can be observed that the main issues concern contamination from sewage, sediment, and trash flowing in the river, especially during peak rainfall events, which is consistent with the findings of previous studies [23,25–27]. Persistence of pollution at all sites can be attributed to uncontrolled urbanization and consequent waste and pollution generation along the Tijuana River, which have compromised the ability of the local pollution retention infrastructure to receive growing quantities of pollutants and adequately divert them to waste treatment facilities [23]. This is also coupled with sporadic and inconsistent cleanup efforts, due to limited and difficult access to the area, especially in proximity to sites S1, S2, and S3, as well as environmental restrictions related to the presence of endangered species at sites S4 and S5 [26,27]. Finally, due to the close proximity to the Tijuana River and its estuary, sewage and chemical pollution find their way to the beach and into the ocean, posing serious threats to the health of marine ecosystems and beach users.

Table 2. Key features and characteristics of identified pollution hotspots.

	Site Information		Observations' Information			Collected Data on Pollution		
Sampling Site	**Site Characteristics**	**Primary Area Usage**	**Description**	**Observation Technique**	**Observers' Notes**	**Entry Points**	**Main Drivers of Pollution**	**Chemical Contamination**
S1	Remote, semi-rural	Agriculture, industrial	Connecting tributary crossing the international border; located near international wastewater treatment plant and subject to sewage and solid waste pollution inflows; subject to illegal immigration movements.	Observer-based survey	Waste is sewage contaminated, strong smell.	- Tributary channel flowing into the Tijuana River.	- Direct littering. - Proximity of illegal housing without formal waste management services. - Proximity of illegal, uncontrolled dumpsites.	- Sewage. - Sediments. - Industrial runoff.
S2	Remote, semi-rural	Agriculture, industrial	Connecting tributary located near the international border; restricted access.	Observer-based survey	Strong smell and sewage contamination. The site has become a habitat for wildlife, posing serious threats of entanglement, contamination, and ingestion.	- Tributary channel flowing into the Tijuana River.	- Direct littering. - Proximity of illegal housing without formal waste management services. - Proximity of illegal, uncontrolled dumpsites.	- Sewage. - Sediments. - Industrial runoff.
S3	Remote, natural	Recreation, camping	Hiking trails along the river banks.	Observer-based survey	Increased stream capacity due to rainstorms, transporting waste and contaminants. Sewage smell.	- Tijuana River banks.	- Direct littering. - Proximity of tourism attractions.	- Sewage. - Sediments. - Urban runoff.
S4	Urban beach	Tourism, recreation, fishing	Sandy beach with scattered rocks; located near commercial and residential area.	Participatory mapping	Greatest variety of pollution and waste.	- Tijuana River. - Beach use. - Coastal waters.	- Proximity of tourism and commercial activities. - Proximity of houses. - Direct littering. - -Beach uses. - Coastal activities.	- Sewage. - Sediments. - Urban runoff.
S5	Beachfront, natural	Ecological restoration, fishing	River estuary; sandy beach with designated wildlife refuges and corridors.	Participatory mapping	Large presence of pollutants in the river's mouth, river's banks, sand and sediments. Presence of dead animals.	- Tijuana River. - Coastal waters.	- Downstream movement of pollution. - Coastal activities.	- Sewage. - Sediments.

5. Conclusions

This study presents a replicable methodology to map pollution hotspots across large regions and border regions. Reported effects from water pollution at the Tijuana River estuary in Imperial Beach include frequent beach closure, damages to coastal ecosystems, negative impacts on the fishery industry, and several effects on public health. In particular, the findings of this study present implications for human and environmental health. Concerning the former, the persistence of pollution and the high exposure risk can cause (i) reduced uses of the beaches and surrounding areas, (ii) risks from repeated exposure to contaminants, (iii) rashes and severe physical conditions from contact with water, (iv) persistent smell/air pollution, and (v) risks from using tap water for cooking/drinking purposes. Concerning the latter, pollution is primarily responsible for (i) contaminated living environments for birds, fish, and turtles, (ii) incidences of fatalities due to chemical contamination, an (iii) inhospitable environment for nursery and early-life stages within wildlife refuges, and the (iv) deterioration of the prey environment. To this end, the situation requires urgent measures oriented toward coastal management at the mouth of the Tijuana River, as well as consistent monitoring and reporting of health effects linked to beach uses.

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