Diagnosis
of Erosion and Pollution by Wastewater in the
Coastal Zone of Tijuana-San Diego

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Introduction

This work is part of the project *Towards Coastal Resilience: Monitoring Water Quality and Erosion through Open and Citizen Science* also known as ***One Community, One Coast***. The project aims to generate and disseminate accessible information on water quality and coastal erosion in the San Diego, Tijuana, and Rosarito regions through an open science and citizen participation approach, to facilitate understanding of climate vulnerability and promote the empowerment of the binational community for greater resilience. This project was selected by the San Diego Foundation during the 2023-2024 period under the *Binational Resilience Initiative*, which aims to support the Cali-Baja region in adapting to climate change impacts. The initiative comprises four main stages: Coastal Vulnerability Diagnosis, Knowledge Management, Generation of Coastal Water Quality and Erosion Data, Data Dissemination, and Education[1]. This document describes the findings of the first stage to identify where the greatest research and strategic attention needs are for developing greater resilience capacities.

The Diagnosis of Erosion and Pollution by Wastewater in the coastal zone of Tijuana-San Diego covers the cities of Coronado and Imperial Beach in the United States and the municipalities of Tijuana and part of the municipality of Playas de Rosarito in Mexico. It includes the collection of historical data from the study area, contextual information maps, general physical and climatic conditions, population, land use, among other data. This exercise allowed identifying the wastewater treatment infrastructure located in the coastal zone to subsequently determine operational improvement requirements and increase community resilience to adverse conditions.

The diagnosis investigates the issue of marine water pollution by wastewater discharge, solid waste, and coastal erosion conditions, by reviewing studies and work done by various institutions and authors on this coastal issue on both sides of the border, previously explored in the "Coastal Resilience in the Baja California-San Diego Region: An Assessment of Science Assets, Gaps, and Priorities."

To start identifying the characteristics of this shared coastal space, the main localities and issues within the coastal zone were mapped out, considering both natural and human factors interacting within the study area.

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[1] In the Knowledge Management stage, a user-friendly digital platform will be established as a tool for disseminating information about the coastal condition, facilitating accessibility and data exchange. The third stage of this project focuses on the generation of coastal water quality and erosion data. Finally, the Dissemination and Education stage proposes the creation and implementation of a social communication strategy, including the development of educational material aimed at students on sustainable coastal management.

For this, the general physical conditions of the territory, population data, land use, installed infrastructure for wastewater treatment, as well as coastal geomorphology aspects recognizing potential erosion areas were considered. The collection of historical data on marine water quality monitoring conducted in the study area, coupled with more recent data with more variables, will provide greater knowledge about contamination conditions, eventually allowing for the determination of preventive and protective measures for coastal communities.

Justification

Given that extreme weather events are becoming more frequent worldwide, achieving greater coastal resilience is especially important in coastal areas. The International Union for Conservation of Nature (IUCN) indicates that in the next 20 years, 94 trillion dollars will be invested in protection infrastructure worldwide due to climate change. While actors from the public and private sectors, including engineering and architecture firms, may understand the potential of nature-based solutions, they often lack the data, design parameters, and construction standards needed to scale hybrid approaches within the context of conventional infrastructure investments. We must systematically measure and learn from the results of hybrid interventions to develop this evidence and data, as well as make them accessible to professionals ("Building Stronger Resilience in Ocean and Coastal Areas," 2021/21d. C.).

In 2023, the United Nations Environment Programme published the 2023 Adaptation Gap Report titled "Insufficient Finance and Preparedness: The Lack of Investments and Planning in Climate Adaptation Leaves the World at Risk." This report indicates that investing in adaptation and mitigation will reduce future climate costs by approximately 14 times. However, the report also concludes that progress in climate adaptation is slowing across all sectors, despite the need for acceleration to address increasingly severe climate change impacts (UNEP, 2023).

Considering climate change scenarios in the region, rainfall could decrease with great variability between very dry and very wet years, leading to temperature increases in the next century[2]. These changes are currently manifesting as intense, brief, and sudden rains that can cause significant damage to city infrastructures[3].

[2] Local climate change scenarios in Baja California have been determined based on a historical analysis of climate reports from 1950 to 2010, considering national climate change studies.
[3] Rafael García Cueto, Head of the Metrology and Climatology Laboratory at the Institute of Engineering and UABC coordinator of the team of researchers for the development of the State Climate Change Action Program (PEACC-BC), 2014.

According to these climate scenarios, a decrease in spring-winter rainfall is projected for 2040. These conditions, coupled with the high water stress in northern Mexico, the state of Baja California, and the state of California in the United States, determine conditions that alter regular climate patterns and threaten water availability in the region, which will have a significant impact on this coastal area.

California, in addition to being the most populous state in the United States and economically predominant globally, has one of the most varied climates in the world, raising concerns about the impact's climate change will generate in the coming decades. Some of the environmental issues already affecting California and Baja California include droughts, wildfires, and extreme weather conditions that will be exacerbated by rising temperatures.

Therefore, it is crucial to design better regional adaptation strategies that have greater reach and impact. Among these, we identify improvements in policies and planning, local land use zoning, review of building codes, among other strategies.

An essential aspect associated with the above is the need to ensure greater public participation by providing more information on the processes and phenomena affecting the coasts. This requires first generating diagnoses on the specific problems afflicting each region and making this information accessible to the general population, particularly those living in high-risk areas. In this same sense, it is necessary to establish monitoring and evaluation processes for the adopted strategies, establishing responsibilities for all actors involved in regional coastal development, which will allow for greater progress in the field.

Therefore, this diagnosis is an effort to begin recognizing the problems threatening the safety and health of those who live and/or use the coast by identifying pollutant discharge sites and recognizing areas with higher susceptibility to coastal erosion.

Description of the study area

The study area covers a total surface of 102.4 km², with 59.3 km² in Mexico and 43 km² in the United States. The study area is located between 32°41'3.38'' north latitude, and 117°13'21.96'' west longitude, from the city of **Coronado** on the

California coast, USA, to 32°19'53.55''N - 117° 3'17.30''W in the **municipality of Playas de Rosarito** in Baja California, Mexico (Map 1).

The coastal zone in the United States includes the cities of Coronado and Imperial Beach, connected by the Silver Strand sandbar extending in a general northwest-southeast direction. It is approximately seven miles long, bounded to the north by the San Diego International Airport and the city of Coronado, to the west by the Pacific Ocean, to the east by San Diego Bay[4], and to the south by the international border with Mexico. The littoral strip of the North American section extends from San Diego Bay to the international border, totaling 13.5 miles in length, 100% of which presents a sandy composition with estuaries, tidal marshes[5], and urbanized areas including the city of Chula Vista and the coast of San Diego Bay

On the other hand, the coastal section located in Mexican territory covers **15 miles** of coastal zone, including urban and natural areas in the municipalities of Tijuana and Playas de Rosarito. The part corresponding to the municipality of Tijuana covers 10.1 miles and is made up of two municipal administrative delegations: Playas de Tijuana and San Antonio de los Buenos. Most of the Mexican coastline presents low sandy shores, whose composition in the municipality of Tijuana is of mixed type, with an area of 0.45 mi^2 of sandy beach and 0.39 mi^2 of rocky cliff (more details are provided in the geomorphology description). In the municipality of Playas de Rosarito, the study area consists solely of sandy beach, with 0.12 mi^2 continuing with a composition of igneous rock.

Population Data for Study Area

From 1990 to 2015, Baja California was among the three coastal states in Mexico with the highest population growth rates[6].

The total population within the study area is 137,770 people: 85,746 inhabitants in Mexico and 52,024 on the U.S. side.

The municipality of Tijuana is the most populated nationwide with 1,922,523 inhabitants. The municipality of Playas de Rosarito has 126,890 inhabitants (INEGI, 2021), with an estimated floating population of 250,000 people[7]. According to data from the Ministry of Tourism, the study area concentrates 66% of international visitors with secondary residences in the Tijuana-Playas de

[4] *San Diego Bay* is a natural deep-water harbor located in San Diego County, California, near the United States-Mexico border. It has a length of 12 miles and a width ranging from 1 to 3 miles. The bay borders the cities of San Diego, National City, Chula Vista, Imperial Beach, and Coronado. The western edge of the bay is protected from the Pacific Ocean by a long, narrow strip of land known as the Silver Strand, whose northern end widens to become the North Island of the United States Naval Air Station.

[5] *San Diego Bay* is recognized for its policy on protection of bays and estuaries in California.

[6] Política Nacional de Mares y Costas de México 2012.

[7] Of the total population in the Mexican study area, 74,586 inhabitants are in Tijuana and 11,447 people are in Playas de Rosarito.

Rosarito-Ensenada Coastal Corridor, classified as either temporary or permanent residents (Map 2).

Considering the total population and the study area, an average population density of 5,902 inhabitants per km² is estimated (Map 3). On the population density map, six areas with a higher population concentration in the binational study area can be recognized. Map 4, shows areas in Mexico that are not registered in INEGI and present a high degree of social lag due to the prevalence of irregular settlements in these zones.

Geographic and Environmental Characteristics

The interaction between the geographic characteristics of the territory (such as topography and geology) and environmental factors (such as climate) plays a determining role in coastal pollution and erosion. This happens both in the removal and transport of materials that form the coastal drift along the coast. An important aspect is to review the susceptibility of these materials to mass movement and removal processes, derived from the interaction of environmental and anthropogenic factors, and not just observe the geotechnical properties of the materials that make up the coast. [8]

For the purposes of this study, we define the coastal zone as:

"A transition zone located between the marine and terrestrial environments, directly under the influence of marine or lagoon hydrodynamic processes, extending from the continental shelf at the ocean boundary to the first significant topographic change (whose height is arbitrarily defined in each country) above the reach of the maximum storm wave." [9].

The coastal zone definition described in the National Policy on Seas and Coasts of Mexico is:

"The geographic space of mutual interaction between the marine environment, the terrestrial environment, and the atmosphere, comprising a) a continental portion defined by 265 coastal municipalities; 150 with beach frontage and 114 adjacent inland municipalities with high and medium coastal influence; b) a marine portion defined from the continental shelf delimited by the 200 m isobath, and c) an insular portion represented by the national islands." [10]

[8] Different data and field observations are integrated to construct an indicator of landslide susceptibility (debris or soil). This indicator is based on the combination of a topographic wetness index (developed from TOPMODEL), a lithological and geological reconstruction, structural features, and slope attributes.

[9] UNAM-SEMARNAT., (2014), Caracterización de la zona costera y planteamiento de elementos técnicos para la elaboración de criterios de regulación y manejo sustentable, p. 12

[10] Comisión Intersecretarial para el Manejo Sustentable de Mares y Costas. 2012. Política Nacional de Mares y Costas de México, Semarnat. México

For the study of coastal zones, three sub-environments are considered, based on their hydromorphology: a) Supra-littoral zone, affected by marine influence only during storms and extending inland when there are surface water bodies; b) Intertidal zone, between the upper and lower reaches of the tide under normal conditions; and c) Infralittoral zone, extending from the base of the intertidal zone to the lower limit of wave action during storms. [11].

The boundaries of the coastal zone are established based on the coastal geomorphological structure and configuration, consisting of low terraces, cliffs, beaches, dunes, and wetlands. The coastal zone's boundary towards the sea is the edge of the continental shelf of the territory, typically located between 100 and 200 meters, and inland it extends along the seashore called the "littoral axis" and perpendicularly to the shore called the "land or high sea axis," which tends to vary from place to place, modifying the coastal zone dimension. [12]

Climate

The Tijuana Risk Atlas determines a predominant arid, temperate, and dry climate (also called Mediterranean). According to data from the Tijuana meteorological station for 2023, the annual average temperature in Tijuana is 61.5°F. The warmest average is 75°F in July and August, and the coldest average is 45°F in January. The hottest temperature recorded is 102°F, and the coldest observed is 28°F[13]. Rainfall is very scarce in most of the region, with an annual average precipitation of 10.3 inches. Of the total precipitation volume, 21 percent occurs in January, the month with the highest precipitation, and only 0.1 percent during July, the month with the lowest precipitation. Eighty-seven percent of the precipitation occurs from November to April, with an average of 24 days per year with precipitation exceeding 0.1 inches (CONAGUA, 2023).

The municipality of Playas de Rosarito has an arid temperate or temperate dry climate[14]. The annual average temperature ranges between 54°F and 64°F. The coldest month's temperature ranges between 26°F and 64°F, and the warmest month's temperature is less than 72°F. The annual precipitation is 8.1 inches of rain[15]. Due to its proximity to the sea, the humidity is 78.5 percent. Precipitation significantly impacts soil saturation, making it a triggering factor for landslides and slope failures.

In Coronado and Imperial Beach, very favorable climatic conditions are identified due to their proximity to the ocean, which maintains a temperate temperature

[11] Maldonado, 1983

[12] The importance of these definitions lies in the diversity of habitats and ecosystems found in these spaces, which can be reviewed and compared through a standardized coastal classification system. These spaces are considered valuable resources because they provide multiple benefits and environmental services, supporting the economy through activities such as tourism, trade, recreation, real estate development, among others. By definition, they are one of the favorite recreational spaces for the population's leisure activities (James, 2000; de la Lanza et al., 2006; Cervantes & Espejel, 2008; Popoca & Espejel, 2009; Noguera et al., 2012; Botero et al., 2015 as cited by Antonio Romualdo Márquez González, Sara Rubí Tovar Hernández, and Verónica Alejandra Mondragón Jaimes).

[13] Although other sources indicate record high temperatures of 118.8°F and a low of 15°F, snowfalls are reported in the years 1967, 2007, 2008, 2014, and 2021.

[14] According to Köppen's classification (CONAGUA 2012).

[15] PDUCPR 2021-2040, pp.50.

(Purer, 1936), with a desert foggy climate[16]. The average seasonal precipitation is 247.1 mm/9.7 inches[17]. During the rainy season, soil moisture is abundant. In summer, water availability is very scarce, and plants suffer from water deficit.[18]

Geomorphology[19].

In the municipality of Tijuana, the coastal geology predominantly features poorly consolidated sedimentary materials, whose layers can align with the slope, imparting greater structural weakness. These materials sometimes underlie deposits of harder volcanic origin, which, when exposed to moisture and the erosive action of waves, can lead to coastal retreat areas. The sedimentary lithological units, such as marine and fluvial sandstones and siltstones, cover a total area of approximately 1,692 acres, while the igneous basaltic lithological units cover 7,376 acres.[20] Due to this, the coast is predominantly rocky, with igneous and sedimentary cliffs. Map 5 shows the geological composition of the coastal analysis section.

In the case of the municipality of Playas de Rosarito, the dominant lithological units consist of a succession of intrusive and extrusive igneous rocks and an intercalation of sedimentary pyroclastic rocks and Cretaceous sandstones.[21] The sandstones are located a few meters above sea level and are found in hills, fluvial-origin alluviums, and all ravines and valleys, making these areas difficult to urbanize, even when the slope is favorable. The urban area is settled on primarily basaltic, firm, and stable rock, while areas with alluvial deposits are especially vulnerable during torrential rains.

Within the study area, a sandy beach strip with an approximate area of 128 acres is recognized; however, it is generally recognized with a mixed geomorphology, integrated by areas of rocky cliffs. This condition can be clearly observed at the southern section's boundary of the Playas de Rosarito coastal area, where sandy beaches transition into rocky high cliffs. During the field reconnaissance, the use of materials foreign to the natural depositional geology was observed at various points along the coastal littoral, where fill soils exist in both the Tijuana and Playas de Rosarito areas. These fills are not well documented and consist of alluvial materials and rubble, used to protect areas from erosion or "reclaim land from the sea."

[16] R J. Russell, Climates of California, University of California Publications In Geography, vol. 2, No. 4, pap 73-84, 1926

[17] National Weather Service, San Diego

[18] Edith A. Purer, en estudios de ciertas plantas de dunas de arena costeras del sur de California, Monografías ecológicas, Vol. 6, No. 1, 1936. https://www.naturespeace.org/purer1936silverstrandpark.htm

[19] Understanding coastal geomorphology is essential for quantifying vulnerability (Thieler and Hammer, 1999; Islam et al., 2015), accurately determining its evolution in response to sea level rise, and proposing protection alternatives (ECLAC, 2012; Torresan et al., 2012).

[20] Atlas of Physical Risks of the Municipality of Tijuana and the INEGI cartography.

[21] This unit has been designated, according to geological maps, as the Rosarito Beach Formation, which consists of gentle hills, broad plains, plateaus, hills, and dunes formed by the accumulation of recent unconsolidated sediments, occupying most of the coastal study area.

In Coronado and Imperial Beach, the coastal geomorphology is composed of sands deposited along the coast from Imperial Beach to the north, forming a long tongue extending to Coronado[22]. The sand composition analysis shows sections of loose, incoherent, and coarse sand containing around 90% quartz and some feldspar, with basaltic material being particularly prominent.[23] Rocky cliffs represent approximately 1 percent of the 39.5 mi^2 study area.

Topography

Factors such as topography and slope enhance erosion. Tijuana and Playas de Rosarito have areas of higher altitude and topographic differentiation compared to the U.S. study area. The Mexican study area presents a greater diversity of geomorphological landscapes, including plateau units and coastal plains, low flood plains, and coastal dune zones.

Map 6 of contour lines shows the presence of coastal plains and low marine terraces, both in the northern part of Tijuana and in the population center of Playas de Rosarito[24]. The average altitude of the urban area in Rosarito ranges from 13 to 951 feet above sea level (ft asl), while the rural areas are situated on low hills and windward mountains to the east, relative to the Pacific Ocean (PMDUOT 2015-2035).

In the Tijuana study area, the altitude differential ranges from 16 ft asl to 591 ft asl towards the eastern limits of the study area. The altitudinal ranges show drastic changes in the slope, which greatly influences the erosive dynamics of the coastal zone.

For the study area in Coronado and Imperial Beach, United States, the coastal zone has a less drastic elevation, ranging from 3 ft asl to the elevations of the Otay and San Miguel mountains.[25] Most of the coastal area is occupied by wetlands known as Watershed Management Area (WMA), which border the Mexican border.

Surface Hydrology

The coastal region of the Mexican study area belongs to Hydrological Region 1 "Northwest Baja California," located in the central-northwest portion of the state. This region comprises international streams, including the Tecate and Tijuana rivers, which join and flow into the Pacific Ocean. Hydrological Region 1 includes

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[22] A smaller sand spit connects with North Island. Therefore, neither Coronado nor North Island are true islands, as they are connected to the mainland by these sand spits. Gradually, these sand spits are migrating inland due to the action of both waves and wind, with their advance slowed by the retentive action of vegetation and the construction and maintenance of the causeway that shares the same name. This coastal zone comprises five regions: to the west, a broad sandy beach where storm waves roll and leave debris; further inland, small dunes out of reach of the waves, which can be reached by storms; in the central part, a road and a railroad extend from end to end, built on heavier soils introduced for this purpose. To the east of this zone, there are dunes formed by wind action; on the eastern edge, along the bay, there are clay materials, and in other sections, a deposited sand cover forms a narrow beach.

[23] Purer, 1936. Analysis conducted by the Office of Chemistry and Soils, United States Department of Agriculture

[24] These areas are surrounded by significant relief and topographical changes, such as the elevations of Mesa Redonda in Playas de Rosarito at 650 meters above sea level (masl) and El Coronel, which reaches 735 masl. These important reliefs establish an intermediate system of subplateaus to the north and south of Rosarito, where there is a high rate of occupation and land use change.

[25] For the section located in the United States, beach slopes that affect wave run-up also vary widely depending on the time of year, ocean energy conditions, and sediment grain size. The analysis of historical beach profiles shows a variety of beach slopes (1:25 and 1:10). It should be noted that the Beach Nourishment Project II, completed in 2012, introduced sediment that was substantially coarser at 0.021 inches (larger grain sizes) than the native sediment (~0.008 inches), which has likely steepened the beach profile and slope, increasing the wave run-up incidence (Ludka 2016).

the sub-basins of the Arroyo El Descanso, Río Las Palmas, and Río Tijuana, Arroyo de Maneadero, Ensenada, Río Guadalupe.[26].

In the Mexican section, the study area is located within the Arroyo El Descanso sub-basin, in the northwestern portion of Baja California, extending from the United States border in Playas de Tijuana to Playa de la Misión south of the municipality of Playas de Rosarito. The Mexican study area presents a set of coastal sub-basins, dominated by low mountains, stream beds, and deeply dissected canyons, with smaller areas of hills and plains in Playas de Rosarito. Here, streams and runoff are intermittent, active only during the rainy season.[27].

The fluvial systems on the coasts of the binational study area present a composition of channels and beds with a marked east-to-west dissection pattern, influencing the deposition and balance of continental materials toward the coastal zone. Continental flows from streams and rivers (Map 7) generate erosive processes that impact the steep and rocky terrains along the coastal littoral .[28]

In the Mexican study area, a system of eight coastal micro-basins is recognized. Within these, 29 discharge points of streams and natural surface runoff were identified, with the most significant being the Arroyo San Antonio in Tijuana and the Arroyos Rosarito and Huacatay in Playas de Rosarito (Map 8) [29]. The image of the surface runoff network (watersheds) and topographic curves identifies areas with the highest potential for coastal erosion, featuring the least resistant geological materials and the highest concentration of human settlements (Population Density and Erosion Potential Map). Other types of watersheds are those located in granitic rocks, which have a wide distribution in the middle section between Tijuana and Rosarito. The significant aspect of these watersheds is the medium, high, and very high slopes with sparse coastal scrub or riparian vegetation. This type of watershed has a well-developed drainage system in the San Antonio de los Buenos delegation in Tijuana.

The San Diego Bay watershed supplies approximately one-third of San Diego County's population and is considered the largest watershed within the county's limits. This watershed comprises three hydrological sub-basins: Pueblo San Diego, *Sweetwater River, and Otay River*[30]. The rainfall contributions in this basin mainly derive from four main water reservoirs: Sweetwater, Loveland, Upper and Lower

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[26] This region is divided into three basins: Basin (1A). Arroyo Escopeta-Cañón de San Fernando: It has an area of 3,453.9 square miles and its southern limit is marked by the Cañón de San Fernando. It has intermediate sub-basins including Cañón de San Fernando (1Aa), Cañón de San Vicente (1Ab), Arroyo El Rosario (1Ac), Arroyo del Socorro (1Ad), Arroyo San Simón (1Ae), and Arroyo de la Escopeta (1Af). Basin (1B). Arroyo de las Animas-Arroyo Santo Domingo: It drains an area of 3,818.4 square miles and has sub-basins including Arroyo Santo Domingo (1Ba), Río San Telmo (1Bb), Río San Rafael (1Bc), Arroyo Salado (1Bd), Río San Vicente (1Be), Río Santo Tomás (1Bf), and Arroyo Las Animas (1Bg). Basin (1C). Río Tijuana-Arroyo de Maneadero.

[27]The morphogenetic configuration of these runoff systems operated in the region during the Miocene period, creating a drainage network with a high level of incision and dissection in the stream beds with linear erosion on the slopes. Although this configuration is a form inherited from the Miocene period, these systems maintain significant influence on the geodynamics of the coastal region's modeling. It is known that extreme precipitation events activate geomorphological processes in the sub-basins, generating hyperconcentrated debris flows, flash floods, and fluvial floods (Castro, 2009; Maerker, 2012; Soto, 2010, 2012, 2015, 2017).

[28] The input of these terrigenous materials can also correlate with the presence of heavy metals along the coastline. Although this work does not analyze these components, it is important to highlight the affinity between grain size and the ability to adhere and disperse contaminants (organic matter and silicoaluminates), which can affect biological productivity and other processes within the coastal zone (Galindo and collaborators, 1994).

[29] This system of natural runoff that constitutes the basins and sub-basins also undergoes significant changes, which are more evident during the rainy season, when they exhibit torrential flows, increasing the potential for fragmentation, erosion, and dispersion of sedimentary materials, which are a factor to consider in the occurrence of landslides. In the coastal zone, this phenomenon of erosion and sediment transport to the coast is further favored by slope changes; these sediment inputs occur systematically every rainy season, mobilizing large amounts of sediments and contaminants to coastal waters. The Lower Cottonwood sub-basin, whose upper part is located in U.S. territory, is the most important tributary contributing to the urban area of Tijuana, via the Arroyo Alamar and Tijuana River in Mexico.

[30] San Diego Bay Watershed Management Area Analysis, October, 2014, and San Diego Bay WMA Water Quality Improvement Plan Monitoring and Assessment Program.

Otay, along with other significant water bodies such as Sweet Water River, Chollas Creek, and Otay River. The Sweetwater Hydrological Unit is the largest of the three mentioned units, covering more than 227 square miles (145,000 acres) and containing three main drainage areas: Lower, Middle, and Upper Sweetwater (The lower hydrological area of Sweetwater is the most densely populated and includes the port of San Diego and the cities of San Diego, *National City, Chula Vista, La Mesa, and Lemon Grove*).

The U.S. study area is influenced by the presence of San Diego Bay, which captures most of the rainwater from the continental basins, so there are no direct rainfall or sediment contributions from the land basins to the sandbar. The Otay Hydrological Unit, located south of San Diego County at the border with Mexico, is identified as the second largest and covers almost 154 square miles. This unit is divided into three hydrological areas: Coronado, Otay Valley, and Dulzura, which are distributed in San Diego County and the cities of Imperial Beach, Coronado, National City, Chula Vista, and San Diego. This hydrological unit drains runoff and sediments through the Tijuana River estuarine system, which supplies sediments and continental flows, including those from the Tijuana River, crossing the border and discharging its waters and sediments into the Tijuana River National Estuarine Research Reserve.[31]

Vegetation

The presence of vegetative cover in the coastal zone is a factor that helps protect the soil, preventing it from being exposed to erosion and wear processes. [32] Urban development and certain agricultural practices can accelerate soil erosion and increase the input of terrestrial sediments to marine ecosystems, extending the impact of pollutants to the sea. The ecosystems present in the U.S. study area primarily consist of sand dune vegetation[33], vernal pools, and coastal marshes. These ecosystems are found in threatened and impacted environments in California[34]. The function of dunes and coastal ridges becomes more critical in the face of climate change effects[35], with rising sea levels and more frequent and intense storms. [36]

In this study, a general review of vegetation cover in the Mexican section was conducted based on INEGI[37] cartography, allowing for the analysis of vegetation as

[31] Through the Watershed Urban Runoff Management Program (WURMP), focused on identifying and establishing management priorities for the WMA, and implementing activities that include reducing pollutants, emphasis has been placed on interagency coordination to help achieve water quality improvement goals in accordance with the Clean Water Act.

[32] Coastal Rosette Shrubland: Low spiny shrub vegetation with rosette-shaped leaves and cacti.

[33] From this functional point of view, dunes represent the sand reserves of the beaches, that is, the areas where, during extreme episodes such as major storms, tsunamis, or exceptional tides, the sea takes the sand and materials it needs for the cross-sectional profile of the beach to accommodate the harsher conditions of the incident wave energy.

[34] Purer, et al,1936

[35] Dune ridges and sand spits are the elements that regulate the hydrodynamics of estuaries, marshes, and coastal lagoons, and they are what these ecosystems owe their existence to, their environmental interest, and their biodiversity, which is among the most productive of existing ecosystems.

[36] Pérez F, 2007, Carlos Ley Vega de Seoane, Juan B. Gallego Fernández, César Vidal Pascual, 2007 Manual de Restauración de Dunas Costeras. Ministerio de Medio Ambiente. Dirección General de Costas

[37] Serie V del 2013 que tiene año base de análisis al 2011, con satélite Lansat

a contributing factor to continental soil erosion. This condition is crucial in coastal environments, as vegetation cover is closely related to lithology, topography, climatology, land-use changes, and vegetation removal. Within the study area, the types of vegetation on rustic land are mostly areas with induced vegetation, crops, grasslands, and other opportunistic species that grow explosively during the rainy season. This results in a large amount of combustible material that fuels fires, increases habitat fragmentation, and makes the soil more susceptible to erosion.

Along the coastal zone, areas are recognized where land-use change has increased, associated with a higher potential for erosion and soil more vulnerable to the transport of materials such as silts, clays, and sands from the high parts of the continental basins to the coastal marine environment. This trend has been recognized in the COCOTREN[38] Program, mentioning a 6% loss of natural surface due to increased urban, industrial, and tourism activities.[39]

Map 9 shows how vegetation cover is reduced as urban land use and human settlements consolidate. Both in Playas de Tijuana and in the urban center of Playas de Rosarito and the upper parts of the coastal sub-basins, vegetation cover has changed significantly. The areas with the most vegetation cover are located in the canyons and streams in the south of Playas de Tijuana and the San Antonio de los Buenos delegation in Tijuana, as well as in the main streams of Playas de Rosarito.

In the coastal section of the cities of Coronado and Imperial Beach, California, the most significant reduction in vegetation is seen in the urban area and the southern end of Imperial Beach and the north of Coronado. Along the southwest border of San Diego and Tijuana lies the Tijuana River Valley, home to one of the last functional coastal wetlands in southern California (TRNERR, 2015). Unlike other coastal ecosystems in the region that have fragmented or disappeared entirely, the valley has a contiguous beach of dunes, riparian marshes, and upland ecosystems[40].

Land Use

In the Mexican study area, within the delegations of Playas de Tijuana and San Antonio de los Buenos, an increase in urban land can be observed, especially in the Monumento and Santa Fe sectors.

[38] Tijuana, Rosarito, Ensenada Coastal Corridor.

[39] It is worth noting that, of the species recorded in Mexico for dune environments, only 95 species are defined as preferential to beaches and coastal dunes. This low proportion of species (4.5%) reflects that few species are specialized for the extreme conditions of the changing environments of beaches and mobile dunes (large movements of sand, soil and air salinity, and high temperatures) (Espejel, I., O. Jiménez-Orocio, G. Castillo-Campos, P. P. Garcillán, L. Álvarez, S. Castillo-Argüero, R. Durán, M. Ferrer, D. Infante-Mata, S. Iriarte, J. L. León de la Luz, H. López-Rosas, A. Medel Narváez, R. Monroy, P. Moreno-Casasola, J. P. Rebman, N. Rodríguez-Revelo, J. Sánchez-Escalante, and S. Vanderplank. 2017. Flora in beaches and coastal dunes of Mexico. Acta Botánica Mexicana 121: 39-81. DOI: http://dx.doi.org/10.21829/abm121.2017.1290

[40] Some of the coastal plant species that are distributed in the San Diego and Silver Strand areas include: Atriplex leucophylla, Camissoniopsis cheiranthifolia, Calystegia soldanela, Verbesina encelioides, Genus Cakile, Spergularia marina, Cotula australis, Subphylum Angiospermae, Erodium botrys, Malva arborea, Lobularia maritima, Carpobrotus edulis, Echium candicans, Eriogonum parvifolium, Ambrosia chamissonis, Chamizo Atriplex leucophylla, Sisymbrium irio, Abronia maritima, among the most frequent and recognized. These habitats are largely public property as part of the Tijuana River National Estuarine Research Reserve (TRNERR) and are managed by the National Oceanic and Atmospheric Administration (NOAA), the U.S. Fish and Wildlife Service, and the California State Parks System.

The land-use classification recognized in the partial development programs of Playas de Tijuana and the Population Center of Tijuana identifies the following: For the Tijuana coast, the predominant land uses in the Monumento and Santa Fe areas are vacant land, commerce and services, residential, industrial, mixed, and special use. Industrial land use is in urban areas, with Playas de Rosarito concentrating most of the infrastructure and services in the energy sector, represented by the PEMEX distribution center and the CFE Thermoelectric plant. Tourism use is one of the main activities in the municipality of Playas de Rosarito, as the main source of income is in commerce and tourism services.

According to COCOTREN, the urban area in Playas de Rosarito consists of 5,772 acres, of which 38.8 percent is allocated for roads, 35.7 percent for vacant lots, 17.5 percent for residential use, 5 percent for commercial use, 1.3 percent for industrial use, and 1.8 percent for equipment. Even though there is identified surface area for conservation, there are no appropriate mechanisms for the control and monitoring of these spaces at the municipal level, resulting in the loss of many of these spaces, which in itself is already an indicator of the poor compliance with environmental protection policies. Population, urban, and tourism growth in the municipalities of the study area have generated negative environmental impacts, with seawater quality being one of the most affected aspects due to insufficient infrastructure for wastewater treatment, followed by inefficient municipal solid waste collection.[41]

Over the past seven years, the upper parts of the coastal basins of Tijuana and Playas de Rosarito have experienced accelerated growth with urbanization processes and earth movements that produce significant volumes of sediments. These sediments are exposed to the erosive action of the wind, emitting particles that can be transported through rainwater runoff. Earth movements and the opening of new roads lead to activities of sand extraction and other stone materials that decrease the supply of essential materials to the coastal zone. Additionally, urban solid waste impacts the landscape and affects human and animal health, as it is ingested by animals such as fish and birds, causing entanglements and deaths.[42]

The emergence of illegal dumps and landfills that predominate in new growth areas affects the slopes and canyons with vegetation, natural drainage channels, and generates significant alterations to the carbon flow. Similarly, the construction of housing, works, and infrastructure in the coastal zone, such as retaining walls, breakwaters, bridges, roads, and similar structures, generate alterations in sediment transport to the littoral zone, causing changes in the behavior of physicochemical variables.

These aspects also represent a financial burden. It is estimated that cities on the West Coast of the United States spend an average of 500 million dollars annually to

[41] Márquez, 2013.
[42] Boergner, 2010; Ryan, 1989; Azzarello, 1987

remove trash from streets and neighborhoods in an effort to prevent it from reaching the oceans[43 44].

This process of land occupation and activity development causes soil denudation, resulting in soil compaction, degradation, erosion, and loss of fertility. Among the most important factors that intervene with such soil degradation and erosion, which even surpasses the influence of precipitation and slope factors, is the loss and replacement of vegetation cover by other land uses. Indirectly, these processes also affect the increase in risk areas, both due to floods, landslides, and decreased biological diversity. An example of this is that 45 percent of the urban surface increase in Tijuana does not occur as stipulated in the 2010 Urban Development Program, highlighting that 18 percent of urban growth developed on land initially determined for conservation.

This process of land occupation and activity development causes soil denudation, resulting in soil compaction[45], degradation, erosion, and loss of fertility. Among the most important factors that intervene with such soil degradation and erosion, which even surpasses the influence of precipitation and slope factors, is the loss and replacement of vegetation cover by other land uses[46]. Indirectly, these processes also affect the increase in risk areas, both due to floods, landslides, and decreased biological diversity[47]. An example of this is that 45 percent of the urban surface increase in Tijuana does not occur as stipulated in the 2010 Urban Development Program, highlighting that 18 percent of urban growth developed on land initially determined for conservation[48].

In the case of the coastal section located in the United States, the land use characterization of the Otay watershed, which delimits our study area to the north, recognizes a component of open, undeveloped spaces, representing approximately 68 percent of the entire watershed. In the Coronado area, military uses occupy 52 percent of this zone, while open spaces and undeveloped lands represent 3 percent of the area. In the Otay Valley and Dulzura areas, open spaces and undeveloped lands dominate, with 47 percent and 83 percent respectively. In each of these areas, residential land use occupies 16 and 18 percent, followed by transportation, industrial, and institutional uses. In the San Diego Bay Watershed Management Area, the impacts of MS4 discharges on receiving water conditions are considered (Map 10).

Private developments occupying much of the coastal study area impose structural loads on these slopes with buildings erected on artificial fill. Added to this is the poor management and disposal of large amounts of rubble and other urban waste,

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43 Stickel, 2012

44 The Southern California Bight Regional Monitoring Program (Bight Program is a large-scale monitoring program consisting of more than 60 organizations focused on assessing emerging or priority environmental concerns throughout the coastal zone of Southern California. The Bight Program surveys, conducted once every five years between Point Conception and the U.S.-Mexico border, focus on evaluating issues of common interest among stakeholders.

45 Denuded soil is that which has been stripped or deprived of vegetation cover, making it especially vulnerable to nutrient loss and erosion, which is harmful both to the environment and the economy.

46 Thornes, 1990, Kosmas et al., 1997, Wainwright y Thornes, 2004

47 J. R. Díaz-Rivera; D. Pérez-Costa; y Rodríguez-Álvarez; J. M. Febles-González.

48 IMPLAN, 2022 documento de propuesta de actualización del Programa de Desarrollo Urbano del Centro de Población de Tijuana.

which are observed scattered along the coastal zone. Coupled with winter wave erosion, slope stability can be compromised. In the United States, Scripps researchers study coastal erosion in San Diego County to understand how changes in sea level, wave activity, and precipitation will affect the coast. The collapse of coastal cliffs is expected to increase due to rising sea levels and wave impacts at the base of these cliffs, which support homes, businesses, railways, and road infrastructure.

Institutional Coastal Management Instruments in the Study Area

Mexico has made great efforts to advance the integrated management of the coastal zone. In 2000, the National Institute of Ecology, now the National Institute of Ecology and Climate Change (INECC), published the *Environmental Strategy for the Integrated Management of the Coastal Zone*, which represented a significant advance in identifying the ecological, social, and economic problems affecting this area. However, it did not include a morphological, hydrodynamic, ecological, and risk characterization of the Mexican coastal zone.[49]

On June 13, 2008, the Mexican government published an agreement in the Official Gazette of the Federation creating the Intersecretarial Commission for the Sustainable Management of Seas and Coasts. The objective of this commission is to coordinate the actions of the Federal Public Administration agencies related to the formulation and implementation of national policies for the planning and sustainable development of the seas and coasts of the national territory. In 2015, this Commission published the National Policy of Seas and Coasts of Mexico, with the goal of establishing a management instrument for the planning of four marine regions adopting the following regionalization[50]: Region I North Pacific, Region II Gulf of California, Region III South Pacific, Region IV Gulf of Mexico and Caribbean Sea. In the same year, the National Coastal Resilience Laboratory (LANRESC) was established in association with research institutions from different regions of Mexico, through CONACYT, now the National Council of Humanities, Sciences, and Technologies (CONAHCYT), which led to the creation of coastal resilience observatories, of which there are currently seven at the national level, with a purely academic and non-profit nature. These observatories aim to expand the scientific and technological capacities of different research groups on coastal resilience issues in the country, and Baja California does not yet have one, even though the Marine Sciences Faculty, Sciences Faculty, and Institute of

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49 This omission was also identified in the document where the National Environmental Policy for the Sustainable Development of Oceans and Coasts of Mexico is published (SEMARNAT, 2006).

50 The then National Institute of Ecology and Climate Change, in the years 2004 and 2006, developed workshops with scientists to determine the regionalization scheme mentioned here.

Oceanological Research in Ensenada, have the Specialty Program in Environmental Management in Integrated Coastal Zone Management.

In the United States, the integrated management of coastal zones has been promoted for more than 40 years, being one of the countries with the greatest advances in this field. Since 1972, the U.S. government enacted the Coastal Zone Management Act (CZMA), which has facilitated the management of coastal zones in each state of the country. This program is voluntary and is based on general and flexible guidelines, facilitating management through the provision of funds for planning and implementation at the state level. It also includes technical support, as well as federal review and approval of state programs, resulting in 35 coastal states participating in the program, and 29 of them developing federally approved plans since early 1993.

In 1990, two new programs were established: the Coastal Zone Enhancement Program and the National Estuary Program. The Coastal Zone Enhancement Program encourages states to develop new methods in eight fields that correspond to national priorities, such as: wetland protection, mitigation of coastal hazard risks, public access to the coast, control of cumulative and secondary impacts of development, reduction of marine debris, management of ocean resources, management of special areas, and measures to facilitate coastal energy use and public facility construction.

Additionally, the San Diego Association of Governments (SANDAG) created a regional coastal monitoring program to measure changes in beach width over time, document the benefits of sand replenishment projects, and improve the design and effectiveness of beach fills. This comprehensive approach to coastal monitoring has provided valuable data for the design of the Regional Beach Monitoring Program from 2001 to 2012. This regional coastal monitoring program includes programs and actions such as habitat inventory near the coast, a sand compatibility and opportunistic use program, a regional coastal sediment management plan, and a guide for sea level rise assessment and adaptation, among other subprograms and actions. Additionally, in 2008, the Shoreline Photo Monitoring project was initiated, creating a visual record of the San Diego coast through monthly[51] photographs, identifying critical erosion points[52].

One of the institutional instruments created in 2003, within the framework of the Alliance for a Healthy Mexico, was the signing of the Coordination Agreement with the Federal Executive and the participation of the Ministry of Environment and Natural Resources (SEMARNAT); the Ministry of Health (SS), assisted by the Federal Commission for Protection against Sanitary Risks (COFEPRIS); the Navy (SEMAR) and Tourism (SECTUR) Secretariats; the National Water Commission (CONAGUA) and the Federal Attorney for Environmental Protection (PROFEPA), to establish coordination and collaboration to comprehensively address the problem

[51] Although beaches change according to the season, generally being wider in summer and narrower in winter, when collected year after year, these photographs can provide important information that helps generate guidance for future specific research needs.

[52] https://www.sandag.org/projects-and-programs/environment/shoreline-management/monitoring-program

of pollution impacting tourism activity in the country's beach destinations, giving rise to the Clean Beaches Program and the Clean Beaches Committees. In 2006, SEMARNAT established the Mexican Standard for Clean Beach Certification and Beach Quality Certification NMX-AA-120-SCFI-2006 to ensure better management and planning of tourism products and services with an environmental focus that would allow for sustainable use[53]. The Clean Beaches Program included various actions aimed at the sanitation of Mexican beaches under a scheme of coordinated actions between SEMARNAT, SS, SEMAR, SECTUR, COFEPRIS, PROFEPA, and CONAGUA (Figure 3). However, this Program has not yet achieved a cross-sectoral and transdisciplinary approach.

In Tijuana, the Clean Beaches Committee was established in May 2004. Since then, 64 meetings have been held, with minutes documenting the follow-up agreements and actions taken. In 2011, at the initiative of the National Water Commission, Management Programs were developed at the national level for all coastal municipalities in the country, including Tijuana, where such a program was developed in May of that year. However, there has never been an approved budget or evaluation mechanisms. The mentioned Management Program completed its 10-year validity period and is awaiting CONAGUA to begin its update. This program outlines the development of various studies, including erosion monitoring, but these studies have not been conducted due to a lack of budget allocation[54].

The irregularity of the meetings and the constant change of heads of the member agencies of the Tijuana Clean Beaches Committee have hindered the follow-up of commitments, obstructing the effectiveness of coastal zone management instruments, including the watersheds related to the identified problems[55]. Although a proposal was presented in 2019 to design a protocol for addressing environmental contingencies for the beaches in Tijuana, it is still pending approval. Regarding the monitoring of seawater quality, the Navy and COFEPRIS, as part of their activities, carry out water quality sampling in coastal zones and recreational beaches in the region.

In the United States, there is a Shoreline Preservation Strategy for the San Diego Region, dating back to 1993, integrated by SANDAG, which recognized the coastal zone between Mexico and the United States as a critical area. As part of this strategy, the SANDAG Shoreline Erosion Committee was established, primarily composed of officials from the coastal jurisdictions of the region. Around this strategy, other avenues of action are identified, such as the Coastal Preservation Working Group, which advises on coastal preservation, beach replenishment, and coastal zone monitoring[56].

53 Dodds & Joppe, 2005; Hansen, 2007; Esparon, 2013; Rosas et al., 2013

54 Among the studies on marine water and beach fecal contamination at the global level, the works of Epstein & Rapport (1996), Boesch & Paul (2001), Prieto (2001), WHO (2001; 2003), Turbow (2003), Aranda (2004), Fleming (2006), Fleming & Laws (2006); UNEP (2006), Martínez (2007), Kite-Powell (2008), UNEP-GEMS (2008) stand out. Mexican authors have contributed to this topic, such as Delgadillo & Orozco (1987), Ortiz & Sáenz (1997), Aranda (2001), Enríquez (2003), Barrera & Wong (2005), Muñoz (2005), Ortiz (2005), Wong & Barrera (2005), de la Lanza (2006), Orozco (2006), Silva (2007a, 2007b), Figueroa (2007), Arreguín & Mejía (2010), Flores (2011), González (2011), among others..

55 Figure 4 shows a problem tree developed by this committee.

56 This Working Group reports to the Regional Planning Committee, which in turn reports to the SANDAG Board of Directors..

Furthermore, the document "Coastal Resilience in the Baja California-San Diego Region, An Assessment of Science Assets, Gaps, and Priorities" identified approximately 254 representatives from different affiliations linked to coastal issues, of which 57% work in San Diego County and 43% in Baja California. This highlights the significant institutional capital that exists on both sides of the border, which can enhance collaborative efforts and processes to make coastal issue knowledge more effective.

Regional Coastal Pollution Issues

For decades, water quality problems have caused various environmental and public health impacts with economic and political implications on both sides of the border. Wastewater discharges into the Pacific Ocean primarily come from the Tijuana River and the Punta Bandera wastewater treatment plant (PTAR), as well as from the discharge points described in Map 11. The lack of infrastructure to recover and treat wastewater causes pollutants to enter the Tijuana River Estuary through canyons and the Tijuana River.

In February 2017, a massive wastewater spill occurred into the Tijuana River, crossing the border into the United States. This spill was caused by the collapse of one of the main collectors of the sanitary sewer system in the city of Tijuana. This led the International Boundary and Water Commission (IBWC) to publish a report on the incident under Minute 320, with recommendations and measures to mitigate the discharge of untreated wastewater into the Tijuana River (IBWC, 2020).

Between December 2018 and February 2019, both sections of the IBWC developed a Binational Monitoring Program to collect samples and analyze the water quality of the Tijuana River and adjacent transboundary drains for one year[57]. This program analyzed parameters such as metals, organics, and pathogens in water and sediments. Sampling is conducted quarterly in the canyons draining into the Tijuana River and monthly in the Tijuana River and Alamar Creek, both in Mexico and the United States. Water and sediment samples established a baseline under normal conditions during dry weather, before and after precipitation events, as well as during discharge or spill events into the Tijuana River or its canyons and tributary drains (IBWC, 2017).

[57] From the results obtained during the rainy months from December 2018 to February 2019, high levels of bacteria and typical parameters present in domestic wastewater were detected. Most of the remaining parameters were not detected.

In the latest 2019 IBWC report, the beaches in San Diego County received a total of 118,936 gallons of wastewater, numbers lower than those reported on beaches in other California counties with large urban areas, such as Los Angeles (1,300,000 gallons), Contra Costa-Alameda (2,500,000 gallons), Marin (247,861 gallons), Sonoma (2,800,000 gallons), and San Mateo (155,107 gallons) [58]. While in the U.S. study area, treated wastewater discharges are regularly conducted through underwater emitters [59] (Bascom, 1982), in Tijuana and Rosarito, discharges are made directly onto the shoreline. Map 11 shows the location of some of the wastewater discharge points located along the study area, both on the Mexican side and in the United States.

Infrastructure, Equipment, and Public Services

Wastewater collection in Mexico has been a highly relevant topic regarding binational coastal pollution. The urban growth of Tijuana has surged in recent years due to migration, industrial growth, and rising rents in California. This has increased the demand for potable water and higher volumes of wastewater. An estimate of per capita potable water consumption in the Mexican study area was made with data from INEGI, 2020[60], obtaining a figure of 59.4 gallons per capita per day (225 liters per capita per day), to which a wastewater generation factor of 0.80 is applied. This results in a daily per capita wastewater generation of 47.7 gallons (180 liters) for the Mexican section of the study area.

On the other hand, within the study area, there are informal settlements in various canyons and coastal terraces, where there is partial sanitary infrastructure coverage, which has significant repercussions in the coastal zone. Official population growth projections serve as a reference to foresee future infrastructure needs for wastewater management and treatment. Table 1 refers to the population growth projections for Tijuana.

Table 1. Population Growth Projection for Urban Sectors of Tijuana, IMPLAN 2022.

Municipal Borough	**Urban Sector**	**2020**	**2025**	**2030**	**2040**
	Playas de Tijuana	144,467	179,803	200,489	247,759

[58] Bulletin on Transboundary Issues of the Tijuana River Basin, IBWC, Volume 11, July 2019. https://healthebay.org/

[59] These discharges include those from the Point Loma wastewater treatment plant, located near the border area. Background studies on coastal water pollution in Southern California indicate that suspended particles from wastewater accumulate in sediments (Katz and Kaplan, 1981; Schmidt and Reimers, 1991; Huh et al., 1992), Martín et al. (1988).

[60] According to studies on the elasticity of water demand in Tijuana with other determinants of consumption, they indicate that, with an increase in real income, water demand will rise. Establishing that water behaves as a normal good, which indicates that when per capita income increases, so does water demand, both in residential and industrial sectors (Mayorga, Salazar, and Flores, 2021).

Municipal Borough	Urban Sector	2020	2025	2030	2040
Playas de Tijuana/ San Antonio de los Buenos	El Monumento	19,810	20,010	20,668	20,828
	San Antonio del Mar	20,372	20,433	20, 626	21,419
	San Antonio de los Buenos	141,033	143,867	145,022	148,282

Source: IMPLAN, 2022

The estimated projections of wastewater generation based on population and water consumption data for 2020 allow for a linear estimation of wastewater generation, as indicated in Table 2[61]. Infrastructure needs have been increasing in the municipalities of Tijuana and Playas de Rosarito. In response, the Government of the State of Baja California, through CESPT, developed the Comprehensive Plan for Wastewater Treatment and Reuse in Tijuana and Playas de Rosarito in 2017, which establishes guidelines and funding sources for the short, medium, and long term to strengthen sanitary sewer systems, treatment, and sustainable reuse of treated wastewater.

Table 2: Estimated Wastewater Generation Projections in the Study Area, Based on 2020 Population Data.

Coastal Section	Population 2020	Average Water Consumption (m^3/day)	Average Wastewater Volume (m^3/day)
Tijuana	74,586	16,781.85	13,471.3
Playas de Rosarito	11,160	2,511	2,008.8
USA	52,024	16,127.44	12,586.38
Total	**137,770**	**10,103.475**	**8,082.78**

Source: Own elaboration based on population data and INEGI consumption data, 2020.

[61] According to the United States Environmental Protection Agency (EPA), each American uses an average of 82 gallons per day (310.40 liters per capita per day) (EPA, 2022). For comparative purposes, this study will use the same wastewater generation factor for the United States, although this could be higher or lower due to differences in technologies, regulations, and enforceable compliance levels in terms of discharges, or water consumption reduction policies, among others, which were not considered in this study.

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Although the results of these projections appear similar for Tijuana and the United States, there are significant differences in terms of per capita water supply, considering that both the socioeconomic level and access to basic services are higher in the United States, as well as the average daily per capita expenditure[62]. The population differential on both sides of the study area seems to harmonize these figures, so a more precise estimate would need to consider these differences.

On both sides, despite the promotion of private wastewater treatment systems to serve subdivisions and/or private companies, which help alleviate pressure on installed infrastructure, the lack of data availability on both the capacity of private systems and their actual operational condition prevents a clearer determination of infrastructure sufficiency. In the binational study area, wastewater control and treatment systems use natural surface water drains to convey treated discharges. The California State Water Resources Control Board has identified specific data gaps and limited information about the operation of small water treatment systems in the U.S.

In Mexico's case, although there are a significant number of wastewater treatment plants (PTAR), this does not translate into an indicator of greater discharge control capacity. This is because the PTARs lack the maintenance necessary to ensure proper operation, resulting in deficient infrastructure that does not operate based on the criteria of the operating agency CESPT. The agency itself has indicated the need for these systems to operate based on its criteria, but there is a lack of support mechanisms to incentivize and improve these infrastructures.

The lack of maintenance of sanitary and storm drainage systems that discharge on the beach causes the deterioration of slopes. These slopes are also being impacted by the occupation of the federal maritime-terrestrial zone or beachfront of Tijuana, resulting from the lack of territorial planning with adequate surveillance.

Sanitation Infrastructure Needs

In the Mexican study area, the potable water and sanitation services are managed by CESPT, which operates the wastewater conveyance systems, PTARs (wastewater treatment plants), regulation tanks, and pumping stations in Tijuana and Playas de Rosarito, among others. A problem recorded since 2015 is the operational deficiency of the PTAR Punta Bandera (PTAR PB) located in Tijuana. PTAR PB covers an area of 314 acres (127 hectares). It began operations in 1987 and was designed to treat 198,000 gallons per second (750 liters per second) with an aerated lagoon treatment system with coarse bubble diffusers. In 2003, its capacity was increased to 290,600 gallons per second (1,100 liters per second), changing its system to one of surface aerators. A functional and physical analysis conducted by CESPT in 2010 showed that the operation was not adequate, concluding that the removal efficiency was far below the required level, causing severe environmental problems on both sides of the border.

[62] For this calculation, the highest figure provided by the EPA was used, which refers to 82 gallons per capita per day, equivalent to a consumption of 310.404 liters per capita per day.

In addition to PTAR PB, there is additional infrastructure that supports the conveyance, treatment, and discharge of wastewater in the coastal zone. This infrastructure consists of 17 pumping stations in the coastal zone, 8 collectors and 4 sub-collectors, interceptors, a 11.5-mile (18.5 km) coastal outfall, and 13 pumping lines corresponding to the coastal zone of Tijuana. The International Wastewater Treatment Plant (PITAR) operates for both Mexico and the United States, with a capacity of 290,600 gallons per second (1,100 liters per second).

In the Mexican study area, a total of 22 PTARs were identified out of the 38 in the region, with 20 in Tijuana, including the International Wastewater Treatment Plant, and 2 more in Rosarito (Tables 3 and 4) [63] [64]. Of these, 13 PTAR[65]s of smaller treatment capacity, mostly operated by private urban developments along the coastal zone, cater to the sanitation needs of each development. However, these 13 smaller PTARs are not part of an integrated CESPT drainage system plan[66]; rather, they have been "isolated" solutions with little operational control and almost no monitoring of effluent quality. The location of these 13 private plants in the coastal section of the study area is shown in Map 12. In the case of Playas de Rosarito, two PTARs are in operation: PTAR Rosarito and PTAR Rosarito Norte, both with a capacity of 55,500 gallons per second (210 liters per second). The first receives contributions from the central and eastern zones of the municipality, and the second from the northern and northeastern colonies. The treated effluent at PTAR Rosarito is discharged through a submarine outfall into the Pacific Ocean, while PTAR Rosarito Norte discharges through the arroyo of the same name.

Currently, the first stage of the Coastal Collector *(Colector Costero)* is under construction, an infrastructure project that will capture and convey wastewater from settlements along the Tijuana-Playas de Rosarito scenic highway to PTAR Rosarito Norte.

Table 3: Treatment Plants Located in the Study Area, Dec-2021

	Municipality	Locality	Plant Name	Process	Installed Capacity (l/s))	Treated Flow (l/s)	Receiving Body or Reuse	Operation Responsible
1	Playas de Rosarito	Playas de Rosarito	Rosarito 1	Aerated lagoons	120.0	73.2	Submarine discharge	State Commission of Public Services of Tijuana (CESPT)
2	Playas de Rosarito	Playas de Rosarito	Rosarito Norte	Conventional activated sludge	210.0	74.8	Unnamed stream	State Commission of Public Services of Tijuana (CESPT)
3	Tijuana	Tijuana	PITAR	Conventional activated sludge	1100.0	1086.2	Pacific Ocean	Comisión Internacional de Límites y Agua Secc. EUA.

[63] National Inventory of Treatment Plants 2021 by CONAGUA
[64] Urban Development Program for the Population Center of Playas de Rosarito 2021-2040 (PDUCP-PR 2021-2040)
[65] Other PTARs operated by CESPT that do not appear in the 2021 National Inventory are: PTAR Refugio Quintas Campestre, PTAR Vista del Valle, PTAR Centro de Rendimiento de UABC, PTAR la Cúspide, PTAR Parque Industrial Pacífico, PTAR Samsung, PTAR Hacienda las Fuentes I and II, and PTAR Valle Sur I and II, which are located outside the study area.
[66] For wastewater treatment plants to function properly, detailed planning is necessary, ensuring no relevant aspects are omitted in the design phases and that the base information used is reviewed and validated. This ensures that the designed, constructed, and finally operational treatment plant can withstand variations in the quantity and quality of the wastewater entering the plant and produce an effluent with the quality established in the design, in accordance with the type of reuse and/or utilization considered in the planning (CESPT, 2017).

4	Tijuana	Tijuana	PTAR Punta Bandera, San Antonio de los Buenos	Surface aerated lagoons	1100.0	1230.8	San Antonio de los Buenos stream and Pacific Ocean	State Commission of Public Services of Tijuana (CESPT)
5	Tijuana	Tijuana	San Antonio del Mar	Conventional activated sludge	2.5	4.0	Pacific Ocean	State Commission of Public Services of Tijuana (CESPT)
6	Tijuana	Tijuana	Santa Fe	Conventional activated sludge	19.0	18.0	Unnamed stream	State Commission of Public Services of Tijuana (CESPT)
7	Tijuana	Tijuana	Pórticos de San Antonio	Conventional activated sludge)	15.0	3.0	Unnamed stream	State Commission of Public Services of Tijuana (CESPT)
8	Tijuana	Tijuana	Las Maravillas	Lodos activados (convencional)	40.0	24.3	Unnamed stream	State Commission of Public Services of Tijuana (CESPT)
9	Tijuana	Tijuana	Natura 90	Oxidation ditches	90.0	15.0	Rosarito Stream	State Commission of Public Services of Tijuana (CESPT)

Source: National Inventory of Municipal Potabilization and Wastewater Treatment Plants in Operation. December 2021

Table 4. Treatment Plants Operated by Private Entities in the Coastal Section of Tijuana

	Municipality	Locality	Plant Name	Process	Installed Capacity (l/s))	Treated Flow (l/s)	Receiving Body or Reuse	Operation Responsible
1	Tijuana	Real del Mar	PITAR Real del Mar	N/A	24.0	N/A	Golf course reuse	Developer
2	Tijuana	Lomas del Mar	PTAR Lomas del Mar	N/A	1.4	N/A	Unnamed stream	Developer
3	Tijuana	La Joya	PTAR Parque Industrial la Joya	N/A	0.5	N/A	Small reception lagoon	Industrial Park "la Joya"
4	Tijuana	COLEF	PTAR COLEF	N/A	0.4	N/A	Green area reuse	COLEF
5	Tijuana	Santa Fe	PTAR Real de la Gloria	N/A	0.1	N/A	Unnamed stream, Pacific Ocean	N/A
6	Tijuana	San Antonio de los Buenos	PTAR Jibarito	N/A	1.2	N/A	San Antonio de los Buenos Stream, Pacific Ocean	N/A
7	Tijuana	Bella Vista	PTAR Bella Vista	N/A	N/A	N/A	Green area reuse	Developer

8	Tijuana	Hacienda del Mar	PTAR Hacienda del Mar	N/A	N/A	N/A	N/A	Developer
9	Tijuana	Los Delfines	PTAR Los Delfines	N/A	N/A	N/A	N/A	Developer
10	Tijuana	Brisas del Mar	PTAR Brisas del Mar	N/A	N/A	N/A	N/A	Developer
11	Tijuana	Playa Blanca	PTAR Playa Blanca	N/A	N/A	N/A	Pacific Ocean	Developer
12	Tijuana	Baja Marabú	PTAR Baja Marabú	N/A	N/A	N/A	N/A	Developer
13	Tijuana	Rancho del Mar	PTAR Rancho del Mar	N/A	N/A	N/A	N/A	Developer

Source: Own elaboration based on CESPT* and IMPLAN 2018. *https://implantijuana.gob.mx/mapa#close

It is worth highlighting that although these wastewater treatment plants currently present efficiency problems, they constitute an important decentralized support to cover the treatment deficit in areas of lower population density. Additionally, there is a coverage deficit in some sectors of the city and particularly in the coastal zone. There is also a problem related to the age of the network, which affects its functionality and capacity, hindering the planning of new installations and the monitoring of treatment systems. This monitoring of PTAR operation depends entirely on CESPT, which, lacking sufficient budgetary resources, is unable to fulfill this task. It is necessary to consider schemes oriented towards greater operational decentralization, not only focusing on installed infrastructure issues but also on administrative and responsive capacity.

In the study area of Playas de Rosarito, the infrastructure for wastewater disposal and sanitation is composed of the Rosarito Norte treatment system. This is an activated sludge treatment plant consisting of a series of independent and integrated modular treatment plants, with a total treatment capacity of 210 lps, operating at a capacity of 120 lps. The construction of this system allowed for the expansion of the Rosarito I treatment plant's capacity in Playas de Rosarito, as well as the modernization of the plant to generate effluent that meets the official Mexican standard for non-potable reuse water. This plant will cover, in the future, the volume of water from the additional flow of the Tijuana coastal collector, which is yet to be constructed.

Despite the existence of the improved treatment system, some industries, businesses, and services conduct clandestine discharges, and private treatment systems are continually out of operation, resulting in the presence of raw water discharges into the sea. This has caused significant point-source pollution on the beaches of Playas de Rosarito, evidenced by the strong smell of wastewater. To mitigate the current problem of discharges, water chlorination is currently being carried out. However, it is desirable to establish more appropriate methods that do not impact marine biota[67].

[67] See the section on the analysis of water quality monitoring results and residual chlorine concentration in this same study.

Water Quality Monitoring in the Study Area

Since the creation of the Clean Beaches Program, Mexico has utilized a guiding manual instituted by COFEPRIS, SEMARNAT, and the SS to determine the water quality of recreational beaches.[68] The manual applies the direct sampling method on the coast, using the bacteriological indicator *Enterococcus faecalis.*[69] This indicator was adopted by the Ministry of Health in Mexico since 2010 and is recognized as the most efficient worldwide for determining sea water quality. It is applied because Enterococcus bacteria are more resistant to high salt concentrations than fecal coliforms and can also grow at pH levels greater than 9.6 and 10, and temperatures between 10 and 45°C. The indicator shows a sustainable level when it is less than or equal to 100 (most probable number in a 100-milliliter sample - MPN/100), an inadequate level when it is in the range of 101-199 MPN/100, and it is considered a *health risk* when it is above 200 MPN/100.

According to the Manual of Organization and Operation of the Clean Beaches Committee in Mexico, the state health departments are the authority responsible for monitoring sea water quality. In Baja California, the Ministry of Health designates the State Commission for the Prevention of Health Risks (COEPRIS) to monitor 11 points monthly in Tijuana and Playas de Rosarito. Additionally, CESPT has been conducting weekly sea water quality monitoring for 30 years at 6 points in Tijuana and Playas de Rosarito. However, the information has only been made public since 2008, using three indicators (Enterococcus faecalis, total coliforms, and fecal coliforms), which are published a week later. The results of these monitoring efforts can be reviewed in Chapter 2 on the analysis of coastal water quality monitoring, which is part of this project.

In 2014, Proyecto Fronterizo de Educación Ambiental (PFEA), under the Tijuana Waterkeeper program, initiated a citizen coastal water quality monitoring program in the Delegation of Playas de Tijuana to contrast official coastal water quality data. It reviewed the results from 2015 to 2024 of water analysis obtained at five sites in Playas de Tijuana: El Faro, Parque México, Cañada Azteca, El Vigía, and Playa Blanca, by PFEA and COEPRIS. These results were generated by PFEA in parallel

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68 https://www.gob.mx/cms/uploads/attachment/file/845894/

69 E. faecalis is a bacterium that is part of the gastrointestinal microbiota in humans and animals and is used as an indicator of fecal contamination in water quality analyses, which allows predicting health risks from exposure to contaminated waters (Sinclair et al., 2012). Diseases such as gastroenteritis and respiratory infections, conjunctivitis, and dermatitis, among others, associated with swimmers, are directly related to the levels of fecal contamination (SS-COFEPRIS, 2013)

with official samples on the same day and time, using the Enterolert test to detect Enterococcus. The graphs show seasonal variations, with increases in summer and winter periods. In the case of winter results, these are usually associated with the occurrence of rains and/or storms that increase the runoff of terrestrial material (clay sediments). [70]. One hypothesis is that these variations could be caused by dilutions of wastewater or chlorination processes. These aspects are often overlooked when annual averages are calculated.

On the other hand, the data shows a significant increasing trend in some of the biological parameters monitored, which differs from the pattern presented in previous years. However, in all cases, they are outside the acceptable range, especially in the case of Playa Blanca, which in 2018 led to a health risk declaration, a condition that remains at high levels of contamination.

The results of the 9 years of monitoring show consistent results in terms of establishing that the water is contaminated, implying risks and restrictions that do not allow safe use of the beaches. However, other parameters that are also recorded during monitoring, such as dissolved oxygen, total suspended solids, and temperature, among others, have not been correlated with variations in the data that may influence the seasonal increase of biological parameters. It could be significant that these parameters show higher values in the spring and late fall, presenting differences along the coast, which may be influenced by thermal anomalies mainly associated with El Niño events and other climatological phenomena.

Ensuring that sea water meets quality parameters for recreational use is essential to guarantee the protection of the health of both human and non-human communities that inhabit and visit the beaches. [71] This aspect is of particular interest to the tourism sector, as it is a requirement that beaches meet the minimum standards established in the applicable regulations.

In Coronado and Imperial Beach, California, water quality monitoring in a body of water is governed by the Water Quality Control Policy and the Water Quality Improvement Plan (WQIP) of San Diego Bay (SDB). To determine a deteriorated zone, Section 303(d) of the California Clean Water Act is applied, and State and Regional Water Boards evaluate California water quality data every two years to determine if they contain pollutants and ensure that protection levels and standards are not exceeded. This biennial evaluation is required under Section 303(d) of the Federal Clean Water Act. The Ocean Standards Unit is responsible for

[70] There is a close relationship between the concentration of suspended solids and water quality due to their ability to adsorb contaminants such as pesticides, heavy metals, and nutrients, the control they exert over water turbidity, and their heat absorption, which increases water temperature (Dagne et al., 2005; INVERMAR, 2011).

[71] Water quality is a term that cannot be classified as good or bad without reference to the intended use of the water. It describes both the composition of the water and the extent to which it is affected by the concentration of substances produced by natural processes and anthropogenic activities. Accordingly, water quality criteria, standards, and objectives vary depending on the activity to which they are applied (Montoya, 2008; Severiche, 2013, cited in Campo and Salcedo, 2016)

developing and updating state plans and policies involving marine waters, providing scientific support and interagency coordination on marine pollution and resource management by establishing water quality objectives and implementation provisions in water quality control plans and policies at the state level. Ocean standards plans and policies include: the Water Quality Control Plan for Ocean Waters of California (Ocean Plan); the Water Quality Control Plan for the Control of Temperature in Coastal and Interstate Waters and Enclosed Bays and Estuaries of California (Thermal Plan); and the Water Quality Control Policy on the Use of Coastal and Estuarine Waters for Power Plant Cooling

As part of the requirements of the National Pollutant Discharge Elimination System (NPDES), the city's Ocean Monitoring Program (OMP) must report all monitoring, quality control, and outfall inspection results to the San Diego Regional Water Quality Control Board and the U.S. EPA. These results are made available to the public through monthly and annual reports, quality control reports, outfall inspection reports, and other documents, which are available on various websites where the data is published.[72]

The results of historical monitoring conducted on the beaches of San Diego County show daily, seasonal, and annual fluctuations that can be understood as the product of various factors, including the movement of transboundary flows common in summer months, moving contaminants northward across the international border, contributing to increased levels of bacteria found in the water, and causing beach closures in the southern county. Because the populations of these indicator bacteria (total coliforms, fecal coliforms, E. coli, Enterococcus) do not persist in the environment for an extended period, the effects are relatively short-lived. Therefore, having a lot of historical data on indicator bacteria is not necessarily an indicator of current health risks, especially when more recent data is available to adequately assess the water quality standard. On the other hand, the results of these historical monitoring show a clear trend toward a higher frequency of elevated data, compared to older data, as well as the prevalence of data repeatedly outside the norm in certain specific areas of the coastal zone, which maintain data monitoring (see Annex of monitoring results data in San Diego).

One notable aspect is that during 2023, the San Diego Department of Environmental Health Quality began implementing a newly approved water quality test in May. The test uses ddPCR, a type of genetic analysis that helps identify fecal indicator bacteria (FIB). In addition to providing data more quickly, these tests are showing higher concentrations of FIB. The new methodology offers 150 parameters, which will not be comparable to the previously used method, which has received some criticism.

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[72] https://www.waterboards.ca.gov/water_issues/programs/water_quality_assessment/#impaired; https://mywaterquality.ca.gov/safe_to_swim/interactive_map/#

Erosion Control in the Study Area

In the Mexican study area, there is little research on coastal erosion. National-level[73] research describes soils and their erosion rates, but the complexity and balance between pedogenic and morphogenic processes at regional and local levels do not allow for identifying the level of transformation resulting from urbanization processes. At the local level, no studies have been identified that analyze the effects of urbanization on sub-basins and micro-basins[74], which are directly linked to the increase in sediment contributions. Additionally, the control infrastructure (sediment basins) installed along the hydrological basins can significantly influence sediment contributions and the stability of the coastal cell systems.[75]

In contrast, erosion along Imperial Beach has been documented since 1937[76]. Estimates by the United States Army Corps of Engineers (USACE) have placed the annual erosion rate between 4.7 and 6.5 feet per year[77]. With the increase in human settlements in the US study area, commercial, industrial, fishing, and tourism activities have increased, interfering with the free movement and transport of sediments along the coast. Breakwaters have also been constructed to combat erosion after acute storm events. Figure 20 shows how these protective infrastructures have been placed to address the coastal erosion problem in the United States. [78]

On the other hand, property owners residing in the coastal area of Coronado and Imperial Beach have built protective structures individually in an attempt to protect their property, leading to parcel-by-parcel interventions. At least 83 structures have been identified with a wide variety of shielding forms, including engineering cladding, random breakwaters, and the placement of vertical or recurved dikes. Currently, there are very few places along the seafront without coastal shielding.[79]

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73 The information on soil erosion in Mexico has important antecedents, but there are not many updated works like the one conducted in 2011 by Montes-León and collaborators for the update of the National Map of Potential Erosion, which uses the Universal Soil Loss Equation, determining an extreme erosion condition for Baja California > 250 tons/ha/year. On the other hand, there is the erosion map edited for the National continuum, scale 1:50,000, prepared by SAGARPA-INEGI-CONAFOR-COLPOS in July 2016, which refers to an extreme erosion condition in areas of human settlements because most of the topsoil has been removed by construction works or buried under a layer of concrete (Bolaños G, 2016).

74 The evaluation of the spatial distribution of water erosion rates and their relationship with soil units and geomorphological and structural features are topics that have not been analyzed, so it is not known how the distribution of soil types and geomorphological features contributes to the distribution of these erosion rates within each of the drainage basins.

75 The sands supplied to the coast are controlled by 3 dams: Morena Dam, Barrett Dam, and Rodríguez Dam. These dams have captured approximately 70% of the entire area of the basin draining through the Tijuana River (Patsch and Griggs 2007), and it is estimated that they have reduced the sand supply by 49% (Willis and Griggs 2003). As sediment sources have been blocked due to the construction of dams, debris, and reservoirs along the Tijuana River, erosion rates in Imperial Beach have increased, which in recent years has necessitated artificial sediment supply to the beaches (City of Imperial Beach Sea Level Rise Assessment 2016).

76 Inman 1976.

77 These rates are complicated by the periodicity of feeding cycles and large erosion events that have characterized this coastline. A particular storm in 1988 with a height of 7.5 feet, tides, and 20-foot waves resulted in 50 to 150 feet of erosion along the entire Silver Strand coastline (Figure X) (USACE 2002).

78 In the mid-1950s, the USACE built two of five proposed groins designed to stop erosion and create a wide beach area; the first structure was partially built just north of the city, at the boundary with the city of Coronado in 1959. Others are in front of the end of Palm Ave, the Surf YMCA camp, on Silver Strand Blvd in Imperial Beach, the Hotel Coronado, and Moffett Rd, where it can be seen how these elements work to maintain the width of the beach.

79 Everest 2001.

Determining erodibility indices is not within the scope of this work; however, by correlating the determination of slope, land use, and vegetation cover, the aim is to establish an initial zoning of potential erosion risk levels. [80]

To characterize areas with greater susceptibility to erosion, a reclassification of contour lines of the topography was performed, resulting in a map of slope ranges. Map 13 shows the flattest and most extensive areas in green tones, corresponding to narrow coastal plains present in the study area, both in the coastal part of Coronado and Imperial Beach in the United States and in Playas de Tijuana, as well as in the southern part of the study area in the municipality of Playas de Rosarito. In these areas, climate change conditions could result in significant impacts. In Mexico, these impacts could even be greater than in Imperial Beach due to the lack of mitigation strategies and support infrastructure for climate change scenarios in Tijuana and Playas de Rosarito.

Erosion Susceptibility Zoning

Zone 1: The susceptibility to erosion in this zone at the continental level is low. For the specific case of Playas de Tijuana, the map identifies the paved urban part with low susceptibility, as the physical variables considered are controlled or modulated by urban infrastructure. However, in Playas de Tijuana, geomorphological components with higher erosion sensitivity are identified, consisting of a system of low hills bordering the central plain of Playas. These low hills constitute a geomorphological unit with a higher slope and soft sediments, rapidly transformed by urban growth, making the iteration of variables classify it as a zone of very high erosion susceptibility, followed by a set of low hills located in the Cañón de las Cabras, on the northern boundary of the Sub-basin of the Laureles. Except for these two areas, the rest of Zone 1 presents a low level of erosion. However, considering some past events related to erosion by piping in Playas de Tijuana, it is important not to neglect construction requirements, both for stormwater drainage and to promote the maintenance of native vegetation in natural streams and runoff, which acts as a buffer for erosion.

In this Zone 1, besides the two mentioned hill areas, the highest erosion susceptibility is concentrated in the coastal area. There, elements impacting the stability of coastal slopes are found, with two main aspects influencing their deterioration: one is the wave incidence, mainly in winter when erosion energy is highest; the second is the construction processes along the beach-facing coastline. Here, conditions of wear, weakening, and erosion are present along almost the entire beach area, although more markedly from the Condominios del Parque and

[80] Using the multi-criteria evaluation method, with reference to the methodology proposed by CORINE, 1992. Based on the spatial distribution of the values assigned to each variable, maps were constructed using Geographic Information Systems (GIS) and the ARCGIS-PRO program, which allowed for overlaying layers and reclassifying variable values to compare the mentioned layers and obtain a map of erosion susceptibility in the bare soil category.

Cañada Azteca to El Vigía. In these locations, the materials of the slopes and cliffs consist of fine sandstones and coarser, poorly consolidated sands intercalated with conglomerates present in the El Vigía area.

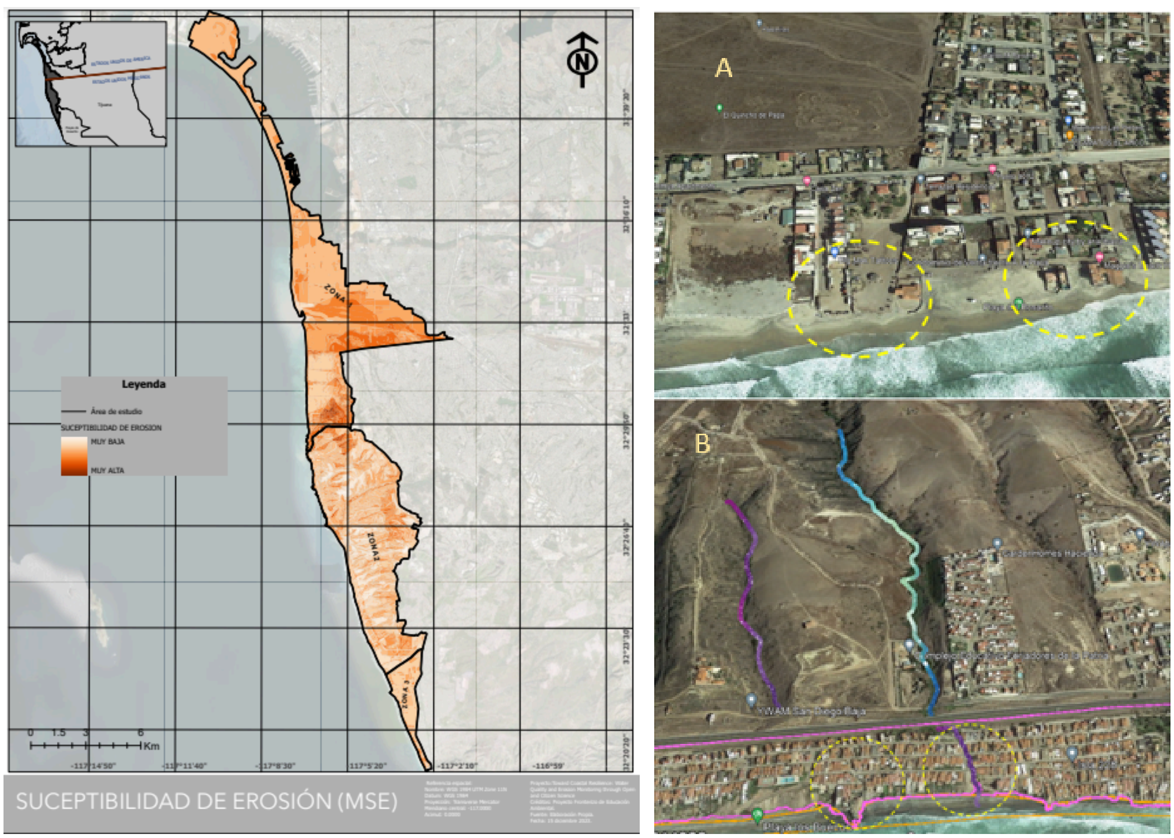
Along this stretch, both the surf and wave breaking zones are geomorphologically closer to the base of the slopes and buildings. To the north, this distance increases due to two possible conditions: the first is the artificial sand nourishment performed on the beaches of Silver Strand and Imperial Beach, which travels south through sediment transport dynamics; the second is associated with the presence of the Tijuana River Estuary, which, according to the susceptibility map, has a low level due to its depositional dynamics, and this condition allows for coastal protection against erosion. The presence of this estuary, just north of Playas de Tijuana, is a natural element providing environmental protection services and sediment supply to the beach area. In Coronado, erosion processes are well identified, mostly associated with its low topographic level along the entire length of the Silver Strand sandbar, making it susceptible to the effect of oceanic-atmospheric variables that impact more strongly during the winter season. North of Zone 1, the presence of San Diego Bay delimits the influence and role of runoff within the study area.

Zone 2: The three aspects that markedly characterize the geomorphology of this zone are lithology, topography, and runoff density. Within the proposed zoning, Zone 2 predominates in surface area. The rest of the zones, in terms of erosion susceptibility, are at a medium to high level, with some areas at a very high level, similar to those described with that level in Zone 1, where slopes are above 30%. These are concentrated to the north of the zone, grading to gentler levels to the south of the unit, mainly due to changes in lithological composition; to the south, it is predominantly sedimentary, which will be reflected in a gentler slope. Runoff and surface drainage have a lower density than in the northern part of the zone. This zone contains both rocky cliff areas, mainly concentrated in the northern part of the zone, and sedimentary slopes with sandy beaches to the south.

The state of soil denudation (Map 9) increases widely in the zone but maintains greater coverage towards the northern end, concentrating in the sub-basins of La Joya, San Antonio, and Real del Mar. To the south of the zone, there is less vegetation cover, coupled with land sales and urbanization processes, which increases erosion susceptibility.

Zone 3: The watersheds it comprises are located in Playas de Rosarito. Its runoff density is low, as geomorphologically, the zone, like Playas de Tijuana, is located on a floodplain, and although the Playas de Rosarito coast is also mixed like that of Tijuana, the coastal study area only includes sedimentary materials. The erosive potential of the runoff is low, as the longer part of the drainage basin is outside the study area limits. This implies that the highest erosion susceptibility in this Zone 3 is mainly influenced by oceanic-atmospheric factors, and like Silver Strand to the north of the study area, strong wave incidence and atypical winter storms often cause flooding and coastal erosion problems.

Figure 27. Coastal Sensitivity to Erosion in the Continental Part

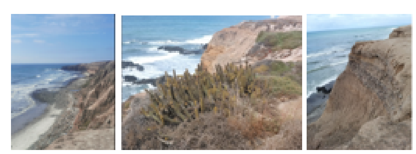


Source: Own elaboration based on the correlation of coastal geomorphology variables

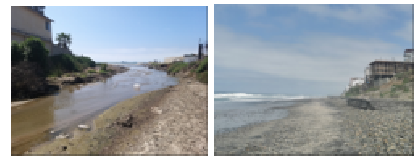
Regarding the second scope of review to establish areas of higher susceptibility to coastal erosion, a specific field review was conducted along the coastal shoreline. Georeferenced locations of stormwater and sewage discharge points, mostly from buildings, were taken in these areas. At these points, water and beach sediment samples were also collected, although no coastal profiles were made.

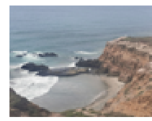
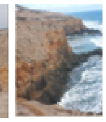
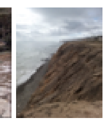
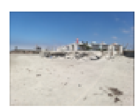
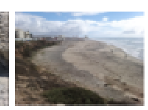
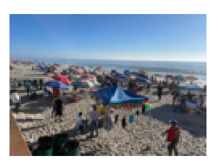
Field visits allowed for the identification of a total of 39 stormwater and sewage discharge points to the beach, either through natural streams or hydraulic infrastructure, some of which are also included in the water and sediment quality monitoring analysis.

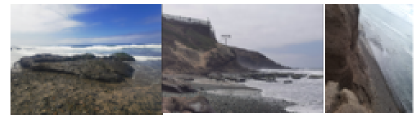
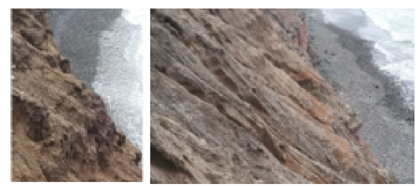
Regarding areas with higher coastal erosion conditions, it was possible to identify areas that, due to their geomorphological and lithological characteristics, indicate conditions of greater exposure and sensitivity to erosion, as well as zones where the presence of human settlements has favored conditions of higher risk for the population. Map 11 shows the location of stormwater and sewage discharge points found along the coastal shoreline.

Potential Erosion Conditions in the Mexican Section of the Study Area.			
Erosion Potential	Location	Conditions	Photo
	Cañada Azteca	Medium to low cliffs, composed of sandstones and shales, with marked and progressive deterioration at the front and head of the slope, high moisture presence with the formation of gullies perpendicular to the coastline; the walls adjacent to the sandy beach show undercutting at the base of the slope, marked presence of buildings and structures with overload.	
	El vigía, Playas de Tijuana	El Vigía, Playas de Tijuana | Open sandy beach area, with marked seasonal fluctuations, high presence of dark minerals forming high berms, tendency to erosion at the base of the slopes, presence of falling blocks, slopes without vegetation and in a state of high deterioration, mostly intervened by human activity, presence of protections, staircases, balconies, and other built elements, marked tendency to degradation of the slope by the erosive action of both physical and human factors.	
	Punta Bandera, Tijuana	High cliffs (>10 m) with intercalated sedimentary and igneous materials, with reddish clays, without pocket beaches or absent at the foot of cliffs. Presence of some human settlements, presence of discharges and water flows from the upper parts of the draining sub-basins.	
	San Antonio del Mar, Tijuana	Medium cliffs with beaches at the foot of the slope, high presence of predominantly single-family and commercial human settlements, steep slopes with falling blocks, predominantly sedimentary materials, generally without natural vegetation, intervened by human activity, installation of protections, staircases, balconies, and other built elements, buildings damaged by erosion, and occasionally built at high tide level, discharge of wastewater and rainwater.	

Potential Erosion Conditions in the Mexican Section of the Study Area.

Erosion Potential	Location	Conditions	Photo
High	Playa Santa Mónica, Playas de Rosarito	Low, extended, and open coasts, with high fluvial erosion potential, with the presence of stream mouths with high rainwater discharge from the Cuesta Blanca Sub-basin, with untreated water input, increasing risks during extreme events. High volume of garbage and contamination at discharge plume, retreat of the coastline in some areas, presence of protective elements in front of the beach, predominantly single-family residential settlements, and equipment..	
	Playa del Rosarito, Playas de Rosarito	Low coast, with sandy beach area, marked seasonal fluctuations, but with a tendency to coastal erosion during high wave conditions, sedimentary materials, and fill materials are used to elevate the topographic level and as a protective element against erosive wave action and extreme events, retreat of the coastline, predominantly single-family residential settlements, buildings constructed at high tide level.	
	Playa Laurel, Playas de Rosarito.	Open and flat coastline, low coast with potential for flooding and erosion during high wave conditions, and by the mouths of streams, with untreated rainwater discharge from the upper Guaguatay basin, increasing the vulnerability of human settlements during extreme events and impacts from storm high waves (neighborhoods: Obrera, Villa del Mar, Basso, Costa Azul, and Coronado). Pollution input at discharge point, construction of protections in front of the beach for predominantly single-family residential and commercial settlements.	
	Coastal Walk and Parque México	Presence of low coast with linear and extended sandy beach, with low sandstone and shale cliffs sensitive to erosion, with high moisture presence and erosion at the base over the Coastal Walk, construction of protections in the high tide zone damaged due to erosion, high density of human settlements, single-family houses, vertical buildings, and businesses, high presence of rainwater discharge pipes and frequent wastewater spills..	
	CESPT Recreational Center and Océano 21	Presence of medium to high slopes formed by deteriorated sandstones and shales, with detachments and falling materials mainly on the faces of the slope and crown, without protective vegetation, presence of linear and extended sandy beach, with human settlements, single-family homes, vertical residential complexes, installation of staircases, balconies, and other access elements to the beach, rainwater and wastewater	

Potential Erosion Conditions in the Mexican Section of the Study Area.			
Erosion Potential	Location	Conditions	Photo
Medium		discharge pipes that contribute high moisture to the slopes, high concentration of buildings, some damaged and eroded.	
	Real Mediterráneo	Presence of irregular coastal geomorphology, with high cliffs, of igneous and sedimentary materials, with red clays, with erosion at the base of the cliff and the formation of small coves, with coastline retreat. Formation of pocket beaches, presence of few human settlements, mainly single-family homes, and the Colegio de la Frontera Norte, presence of natural rainwater discharges from upper basins with sediment input due to land-use changes (development zone).	  
	Bella vista, Tijuana	Presence of high cliffs (>10 m) with continental and clayey sedimentary materials, formation of pocket beaches, presence of low-density human settlements, presence of slopes with marked gullies and erosion cavities, sedimentary and clayey materials, high volume of rainwater and wastewater discharges and debris from the upper parts of sub-basins.	  
	Playa Mar y Sol, Playas de Rosarito	Area of low cliffs, with extended and open sandy beaches, low density of human settlements, presence of lower height sedimentary slopes (<10 m) with signs of erosion and marked gully formation, smaller rainwater contributions, open and linear coastline.	
	Public Beach, Playas de Rosarito and Rosarito Beach	Open and linear coastline, with extended sandy beach, without significant slopes, construction of front protections for low-density residential area, some of which are located in the high tide zone, exceeding the coastline, impacts from high storm waves in neighborhoods: Obrera, Villa del Mar, Basso, Costa Azul, and Coronado, located on low coast, on reclaimed land, presence of streams with significant rainwater discharges from Rosarito canyon.	  
	Northern Malecon, Tijuan	Sandy, linear, and open beach area, occurrence of coastline retreat processes due to historical storm events, concentrated erosion on fronts and bases of slopes, where various erosion protection elements are present, mainly of gabion type. Currently, the beach shows a slight tendency towards accretion, giving a greater beach width, possibly due to proximity to the Tijuana River estuary, and the littoral transport process along the Silver Strand bar in the USA.	 

<table>
<tr><th colspan="4">Potential Erosion Conditions in the Mexican Section of the Study Area.</th></tr>
<tr><th>Erosion Potential</th><th>Location</th><th>Conditions</th><th>Photo</th></tr>
<tr><td rowspan="3">Low</td><td>South of El Vigía, Tijuana</td><td>Rocky coasts, with high cliffs, with irregular coastal edges and formation of small bays, there are sections of greater stability and areas with higher exposure to erosion in the sedimentary cliff zones with formation of deep gullies and erosion cavities, low presence of human settlements, reduction of the coastal plain and reduction of slope width, presence of rainwater and wastewater discharge points from the upper parts of the coastal sub-basins..</td><td></td></tr>
<tr><td>Baja California Center, Playas de Rosarito</td><td>Low cliffs (=> 5 m) with presence of gullies and erosion cavities, open and extended sandy beaches, undeveloped free surface, low-density human settlements, single-family and vertical residential (hotels), presence of minor rainwater flows, construction of beach front protections for residences, seasonal variations in beach width.</td><td></td></tr>
<tr><td>Playa el Bebe</td><td>Low cliffs (=> 5 m) with presence of gullies and erosion cavities, open and extended sandy beaches, presence of vacant land, concentration of second home human settlements, single-family residential, presence of several rainwater flows, with sediment input that leads to beach accretion points, construction of beach front facilities, limited public access due to PEMEX installations.</td><td></td></tr>
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Source: Own elaboration based on fieldwork and aerial photograph analysis.

Conclusions

The diagnostic results identified general aspects of the current state of coastal zone occupation and its relationship to the issues of pollution, land-use changes, and erosion in the catchment areas and coastal littoral zone. Urbanization and land-use change are identified as the primary causes of the deterioration and loss of the coastal natural system's protective capacity. A significant portion of the growth in human settlements in the continental catchment areas in Mexico has been rapid, precarious, and poorly planned.

Inadequate use of coastal space has led to the emergence and increase of real and potential hazards, as well as problems with wastewater discharges into the coast. This not only contributes to water pollution but also accelerates the deterioration of beach slopes, threatening the resident population and their properties with the destructive effects of storm events.

The occupation and urbanization processes observed in the Mexican coastal strip of the study area appear poorly monitored and lack adequate urban control. This has led to problems of wastewater pollution, inadequate solid waste management, and the construction of housing in areas exposed to destructive extreme climatic events, such as some settlements in Playas de Tijuana, San Antonio del Mar, and Playas de Rosarito. In these areas, climate change conditions could result in severe impacts, potentially greater than in Coronado and Imperial Beach, because Tijuana and Playas de Rosarito lack mitigation strategies and have not developed the necessary support infrastructure to respond to climate change scenarios.

One of the most significant identified changes is vegetation cover or the analysis of denuded areas, which clearly correlates the pressure exerted by coastal land occupation processes with the growth of urban areas. Many areas where erosion is exacerbating have been identified, continuously reducing vegetated surfaces. This points to an increase in erosion conditions in the upper parts of the coastal sub-basins that will affect the littoral zone in the coming years, highlighting the lack of public policies for the protection of important coastal (terrestrial and marine) spaces and ecosystems. The minimal attention given to this issue suggests a further increase in coastal erosion potential in the future, compounded by the projected population growth mentioned in the diagnosis, which will reflect in increased social vulnerability.

In the Mexican coastal section, there are significant information gaps regarding the environmental conditions of coastal basins and sub-basins. This has prevented an objective evaluation of the current and trending erosion risk conditions in the coastal zone, representing a risk factor and a significant limitation in coastal ecological and territorial planning. There is a clear disparity in the amount of information generated and the priority given to this issue between the two countries, with the United States placing greater emphasis on generating and making relevant information accessible. This difference is not only in terms of the resources and budgets allocated to research and dissemination, which has been ongoing in Imperial Beach since 1937, but also in the data treatment approaches applied in each country.

In Mexico, research emphasis is on human health impacts, tourism, and service economy protection; whereas, in the northern part of the study area, research focuses on environmental effects and the application of technical measures and regulatory controls for restoration and environmental recovery. This translates into another notable contrast in the amount of space dedicated to conserving natural and open spaces in the northern portion of the study area compared to the Mexican portion.

Despite having a National Marine and Coastal Policy, coastal management in the Mexican section of the study area is virtually non-existent, with no developed indicators of pressure, state, and response. Coastal real estate and tourism development promotion policies continue to be pushed forward without strategies promoting conservation, improvement, and resilience of the coastal region.

Regarding wastewater treatment systems operated by private developments in the Mexican coastal zone, there are notable problems due to operational failures and inadequate maintenance, causing raw water discharges into the sea through creek channels connected to the sea. Although the number of treatment plants operating on the coast could be seen as a good indicator of installed treatment capacity and good performance of the real estate sector, this is not the case due to compliance issues with some of these plants. However, this can be considered an important indicator in terms of the future possibility of expanding treatment capacities under decentralized operation schemes. The reality is that beyond the wastewater from treatment plants in the coastal zone, poorly treated and untreated water is discharged from multiple inland sources in both portions of the Tijuana River basin, predominantly from the river's flow itself.

On the other hand, in California beaches, coastal area water discharges indicate that urban stormwater runoff is the main source of pollution. In Imperial Beach, wastewater discharges from the Tijuana River and canyons crossing the border are reported, affecting both tourists and local residents. Monthly monitoring reports to determine the bacteriological quality of seawater in Tijuana's coastal zone conducted by COEPRIS over eight years within the National Clean Beaches Program have shown compliance data, except for seven months that exceeded the standard during that period. These were generally concentrated in San Antonio del Mar Beach, where the highest contamination values were recorded. Additionally, there is uncertainty regarding the data generated from government agency monitoring in the Mexican coastal section, as both COEPRIS and CESPT present data with variations in recorded contaminant levels due to non-simultaneous and non-identical location monitoring. Therefore, the data generated by both agencies show inconsistencies or differences when comparing reported figures for enterococci at the same dates and sites. Comparatively, monitoring results by PFEA since 2014 show that, in general, the beach condition in Tijuana has high contamination levels, far exceeding established norms. This trend has progressively increased from 2015 to 2023, moving from 30 days exceeding the standard in 2016, mainly concentrated in Playa Blanca, to 113 exceeded samples in

2023 at all sampling points, showing seasonal variations in pollutant behavior and concentration.

In summary, despite having a legal framework on coastal matters and being signatories to international agreements, the situation of the coastal zone in Mexico has not been consolidated as a top priority issue, clearly lacking coastal zone planning and integrated management programs.

Recommendations

It is important to conduct work that helps identify management priorities in coastal areas to prevent conflicts in the upper basins and improve degraded areas with significant land use conflicts. For example, identifying restoration spaces with strategic ecosystems for nature conservation is fundamental for promoting resilience and restoring the carrying capacity of the coastal system. Having a strategic management plan for risk and coastal erosion management would contribute to reducing erosion risk levels in the sector. This plan should consider the various social and economic actors involved, with the direct participation of different government levels responsible for decision-making within the coastal zone, as each has different perceptions, interests, and responsibilities.

In terms of urbanization processes occurring in the coastal zone, it is necessary to examine the territorial variations in the intensity and speed of coastal urbanization. The urbanization process has been markedly unequal and irregular along the coast. This requires a territorial analysis of urban growth and occupation processes both in the upper parts of the basins and in the federal maritime-terrestrial zone, for which there is no updated occupancy inventory. The process of housing abandonment leading to deterioration increases the risk in coastal areas, where the risk atlases of Tijuana and Rosarito are insufficient. Therefore, it is necessary to promote territorial planning instruments and coastal monitoring guidelines focused on preventing and mitigating erosion and other coastal risks, strengthening the intervention competencies of municipal and state environmental authorities.

Establishing a baseline for understanding coastal erosion risk will promote the periodic profiling of coastal areas, as well as the evaluation of threats and vulnerability of exposed elements in the coastal zone. This is essential for determining risk scenarios and preventing and mitigating impacts, especially in the Mexican coastal section, where the identification of erosion problems in beach-front slopes makes the adoption of protection measures urgent, considering oceanic, atmospheric, and continental water and sediment contributions. It is pertinent to evaluate the geotechnical condition of coastal slopes to recognize their current state and how these coastal areas are affected. It is important to recognize that coastal zones are not only spaces for the economy and tourism but also changing environments supporting a wide diversity of ecosystems.

For constructing indicators incorporating a sustainability perspective, various actors must be involved, considering the different land uses and dimensions of action. Therefore, promoting a more coherent and uniform conceptualization of the binational coastal zone is necessary, recognizing and integrating the region's needs so that Tijuana does not adopt a different approach from Playas de Rosarito or Imperial Beach. Working to establish indicators that help integrate actions and review the government discourse, which a priori considers a high number of treatment plants as necessarily indicative of good wastewater management, or that the mere existence of a climate action plan (such as PACMUN) will be sufficient for public policy compliance. Within this context, the definitions of integral coastal territorial planning observing regional approaches constitute a valuable aspect that should be strengthened in the next ten years, in the interest of adopting climate change prevention and mitigation strategies.

In line with this, the border nature of this region offers the possibility of integrating various working groups on both sides of the border. Establishing joint regional strategies for coastal zone management is necessary, identifying aspects requiring greater regulation and coordination. This should consider, beyond legal instruments, activities that should be promoted by different sectors in the coastal zone, offering updated information on climate change effects.

Besides the information that can be constructed from forming working groups, reviewing schemes oriented towards operational decentralization is very necessary, given the increasing and more urgent need to operate actions at different scales of action, considering not only installed infrastructure but also administrative and response capacity that can be built from various collaborative models.

Along with this, regulatory guidelines should be established to control the development of bad practices and monitor good ones, identifying relevant actors who, along with other academic institutions (such as Scripps, the Institute of Oceanographic Research of Ensenada, CICESE, El COLEF, SDSU, the Faculty of Marine Sciences of UABC Campus Ensenada, the IMPLANES of Tijuana and Rosarito, among others), contribute to better interventions and manage financial resources not only applied to project execution. An example is water quality guidelines, which can provide useful information for reviewing investment needs and improving wastewater treatment infrastructure, including small-scale ones promoted by private entities.

At the same time, the presence of diverse runoff, particularly in Zone 2, opens possibilities to establish projects to restore these important spaces, keep them free of obstructions, and improve water infiltration into the coastal system, which has multiple associated implications that can help reduce vulnerability to climate change. The ecological relevance of coastal areas should not be questioned but rather promoted, following the National Marine and Coastal Policy in Mexico, the most important coastal management instrument at the national level. One aspect lacking government interest in Mexico is the value of treated water for restoring and conserving coastal ecological and natural systems offering protective environmental services. It is important to design mitigation options to improve the resilience of coastal areas. Some options could include establishing a plan to preserve coastal natural spaces contributing to maintaining protective environmental services through ecological restoration actions of riparian and coastal scrub ecosystems. Restoration and protection actions for beaches with significant erosion problems should also be considered, involving different actors and coastal zone users who recognize risk factors and incorporate adaptation measures. These actions may require mitigation works and mechanisms to maintain vegetation cover, which significantly prevents risks. An important milestone within this aspect is the Tijuana River Estuary, offering services for coastal erosion protection but affected by negative externalities that, if not reduced, could affect coastal dynamics in the study area's coastal section.

Regarding issues in wastewater treatment systems operated by private developments in the coastal zone, it is necessary to conduct an inventory and specific evaluation of this infrastructure and its operation so that these systems can function adequately and be considered decentralized infrastructure elements for wastewater treatment, considering their treatment capacity and adaptation and improvement processes. This will require opening dialogue spaces to review the specific conditions of each case and project a line of compliance goals, crossed with financing possibilities as a first line of work focused on expanding administrative and response capacity.

Recognizing the different capacities (institutional, educational, legal, and financial) available in the region will allow generating collaboration schemes to establish interdisciplinary solutions that enable a better characterization of the coastal littoral ecosystem and apply effective policies to mitigate climate change.

The need for a Water Quality Index (WQI) that allows more comprehensive assessments and a clearer idea of pollution status concerning other physicochemical parameters in different areas on both sides of the border would offer possibilities to establish abundance relationships.

Another important aspect to consider is the characterization of different coastal zone user types to promote differentiated social participation in coastal management and planning policies. Involving more actors to enhance the individual actions of different coastal users, focusing not only on protecting private property value and parcel-based intervention approaches but evolving to an approach to improve environmental health to maintain biodiversity in different environments and coastal basins. This would contribute to improving the ecological integrity index with which we can better face urban growth challenges in the coastal zone.

One of the major weaknesses relates to the lack of coordination between governmental institutions and actors impacting the marine and coastal space, linked to a wide range of activities in these spaces. The work allowed understanding and comparing responses made in the northern section of the study coast, confirming that many ways exist to deepen coastal knowledge and that more effective and efficient formulas are needed to use coastal resources and generate collaborative knowledge. We hope this exercise opens possibilities to expand our coastal knowledge, resulting in more actions and more information contributing to public knowledge and a greater search for solutions.

Glossary of Acronyms

CESPT: Comisión Estatal de Servicios Públicos de Tijuana (State Commission of Public Services of Tijuana)

CICESE: Centro de Investigación Científica y de Educación Superior de Ensenada (Center for Scientific Research and Higher Education of Ensenada)

COCOTREN: Programa Corredor Costero Tijuana, Rosarito, Ensenada (Coastal Corridor Program Tijuana, Rosarito, Ensenada)

COFEPRIS: Comisión Federal para la Protección contra Riesgos Sanitarios (Federal Commission for Protection against Health Risks)

CONAGUA: Comisión Nacional del Agua (National Water Commission)

COLEF: Colegio de la Frontera Norte (College of the Northern Border)

CZMA: Coastal Zone Management Act / Acta de Manejo Costero

IMPLAN: Instituto Municipal/Metropolitano de Planeación (Municipal/Metropolitan Planning Institute)

IUCN: Unión Internacional para la Conservación de la Naturaleza (International Union for Conservation of Nature)

PACMUN: Plan de Acción Climática Municipal de Tijuana, B.C. (Municipal Climate Action Plan of Tijuana, B.C.)

PDUCPT: Programa de Desarrollo Urbano del Centro de Población de Tijuana (Urban Development Program of the Tijuana Population Center)

PDUCPR: Programa de Desarrollo Urbano del Centro de Población de Rosarito (Urban Development Program of the Rosarito Population Center)

PFEA: Proyecto Fronterizo de Educación Ambiental A.C. (Border Environmental Education Project)

PEMEX: Petróleos Mexicanos (Mexican Petroleum)

PROFEPA: Procuraduría Federal de Protección al Ambiente (Federal Attorney for Environmental Protection)

SS: Secretaría de Salubridad (Health Department)

SANDAG: The San Diego Association of Governments / Asociación de Gobiernos de San Diego

SECTUR: Secretaría de Turismo (Ministry of Tourism)

SEMAR: Secretaría de Marina (Navy Department)

SEMARNAT: Secretaría de Medio Ambiente y Recursos Naturales (Ministry of Environment and Natural Resources)

SDSU: San Diego State University / Universidad Estatal de San Diego

TRNERR: Tijuana River National Estuarine Research Reserve

WMA: Water Management Area / Área de Gestión del Agua

USACE: United States of America Army Corps of Engineers / Cuerpo de Ingenieros del Ejército de EE. UU.

Bibliography

Appendix: Geographic Location Table of Discharges

Appendix: Maps

Appendix: Methodological approach