



Integrating Satellite Remote Sensing and Local Knowledge to Decipher Two Decades of Coastal Change in the Ensenada de La Paz, Mexico

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Abstract. This study presents a comprehensive, two-decade (2005–2025) assessment of coastal morphodynamics in the Ensenada de La Paz, Mexico, by synergistically integrating satellite remote sensing with local knowledge. We employed a multi-sensor approach (Landsat 7 ETM+, Sentinel-2 MSI, and very-high-resolution imagery) to quantify spatiotemporal changes in bathymetry, shoreline position, and turbidity patterns. The analysis reveals a persistent trend of bay-wide shallowing (with an average depth reduction of 0.10 m per five-year period), significant net coastal erosion (21.34 ha), and increased nearshore turbidity, particularly adjacent to urban areas. Hurricanes Newton (2016) and Lorena (2019) triggered distinct, spatially heterogeneous geomorphic responses, driven by differences in rainfall distribution and fluvial sediment inputs. Crucially, structured engagement with local fishers, aquaculturists, and coastal residents provided essential ground-truthing and causal explanations for the remotely sensed patterns, identifying anthropogenic pressures such as illegal fishing, vessel traffic, waste discharge, and proposed infrastructure as key drivers. This integrated framework not only validates local observations with quantitative evidence but also bridges the gap between large-scale change detection and process-based understanding. The findings underscore the system's vulnerability and provide a robust, evidence-based foundation for participatory coastal management and climate adaptation strategies in data-scarce regions.

1 Introduction

Local stakeholders, fishers, aquaculture workers, and coastal residents—have consistently reported pronounced physical changes within the Ensenada de La Paz, a vital tropical coastal lagoon in the Gulf of California (Cervantes-Duarte et al. (2021)). Their direct observations describe a dynamic system: shifting navigation channels, the infilling of known fishing grounds, accelerated erosion of particular shorelines, and alterations in water clarity following storms or development projects. These anecdotal, place-based accounts point to significant morphological and environmental transformation but lack the quantitative, spatially explicit evidence needed to inform formal management.



Satellite remote sensing emerged as the critical tool to systematically investigate these local reports. The availability of long-term, publicly accessible archives from programs like Landsat 7 (U.S. Geological Survey (2023)) and Sentinel 2 (Copernicus Programme (2024)) provided the means to translate qualitative observations into quantitative data. By applying advanced algorithms to this imagery, we could reconstruct decadal trends thereby testing and scaling the insights offered by local knowledge.

25 This approach allows for a synoptic, evidence-based assessment of change across the entire lagoon system over a 20-year period (2005–2025).

The integration of these two knowledge strands—grounded local observation and geospatial analysis—addresses a key methodological gap in coastal science. While remote sensing excels at documenting the what and where of change over large scales, it often struggles to explain the why, particularly in disentangling anthropogenic drivers from natural variability (Khorram et al. (2012)). Conversely, local knowledge offers nuanced, process-based explanations and historical context but is inherently localized and qualitative. A synergistic framework is therefore essential for a holistic diagnosis.

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This study implements such an integrated framework for the Ensenada de La Paz. We first employ a multi-sensor satellite analysis to quantify the system’s physical evolution. We then systematically engage local stakeholder knowledge through structured interviews to contextualize the geospatial data, identify specific drivers, and validate observed patterns. Our work

35 has three primary objectives: (1) to quantify multi-decadal trends in bathymetry, turbidity and shoreline dynamics; (2) to assess the distinct geomorphic impacts of major hurricanes (Newton, 2016 and Lorena, 2019); and (3) to synthesize remote sensing findings with local ecological knowledge to identify the principal natural and anthropogenic drivers of transformation. The result is a comprehensive, evidence-based baseline crucial for the participatory and sustainable management of this UNESCO World Heritage site (UNESCO (2023)). This methodological framework is presented in Figure 1.

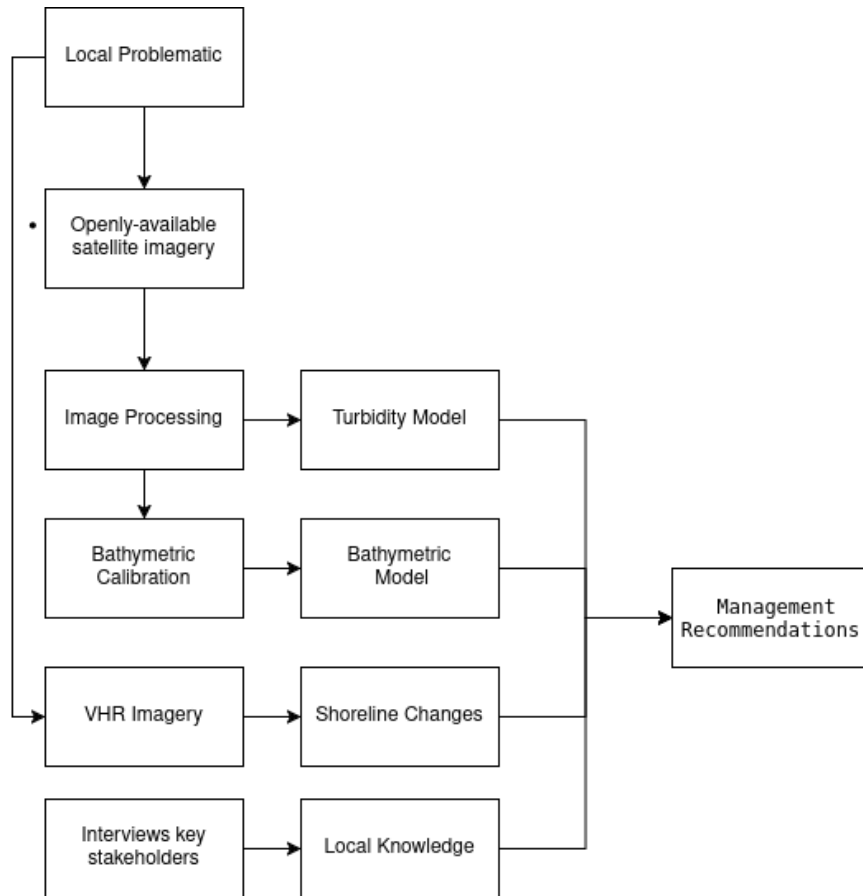


Figure 1. Metodological framework applied in the study; merging the remote sensing and the local ecological knowledge to produce management recommendations.



40 2 Materials and Methods

2.1 Study Area

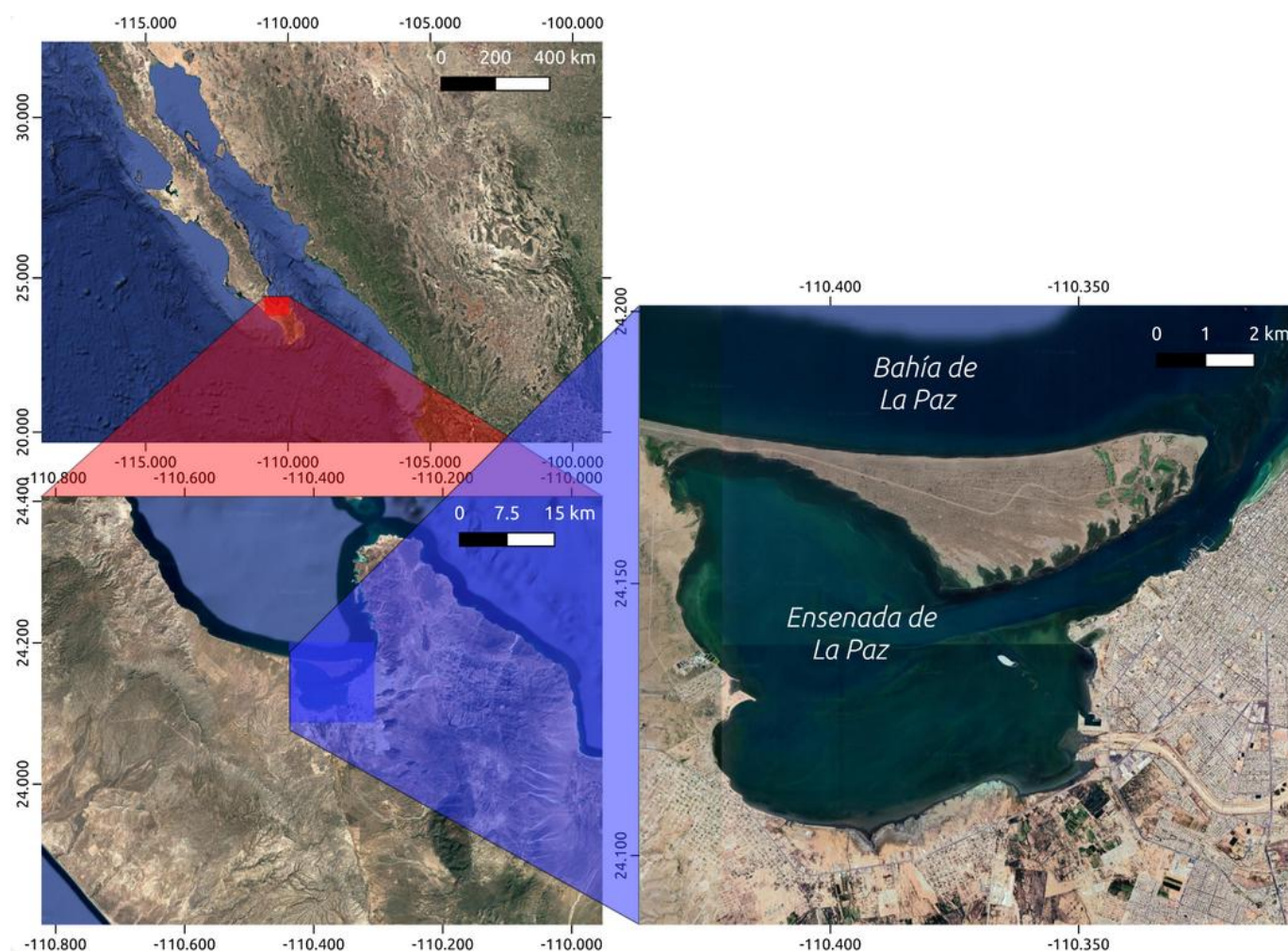


Figure 2. Geographic location of the study area. Ensenada de La Paz.

The Ensenada de la Paz is a bay located on the southwestern coast of the Gulf of California in Baja California Sur, Mexico (Figure 1). Geomorphologically, it is classified as a non-estuarine coastal lagoon (Lankford (1977)), confined by a long, sandy barrier known as "El Mogote" which separates it from the open waters of the Gulf. The lagoon exhibits a partially mixed, moderately stratified salinity structure, primarily influenced by tidal circulation and high evaporation rates, with minimal perennial freshwater input (Pritchard (1955)). Its bathymetry is generally shallow (mostly <10 m), with a deeper tidal channel running along its central axis. The surrounding watershed includes several ephemeral streams (e.g., El Cajoncito, La Palma) that become active during rainy seasons or extreme events, serving as key sediment and nutrient sources. The area is of high



ecological and economic importance, featuring mangroves, seagrass beds, shellfish aquaculture sites, and being adjacent to the
50 city of La Paz, which exerts significant anthropogenic pressure on the system (Morales-García et al. (2024)). A map showing
the main sources of sediment can be seen in Figure 2.



Figure 3. Geographic location of main sources of sediment in the study area. Ensenada de La Paz.

2.2 Satellite Data

To reconstruct the multi-decadal dynamics of La Paz Bay, we utilized a combination of multispectral and very high-resolution (VHR) satellite imagery covering the period 2004–2025.

55 For the analysis of bathymetry and turbidity, we employed the publicly available archives of Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Sentinel-2 MultiSpectral Instrument (MSI). The technical specifications of these sensors are summarized in Table 1. Sentinel-2 imagery (available from 2015 onward) was preferred for its higher spatial and radiometric resolution. To ensure a continuous time series starting in 2004, Landsat 7 data were used for the earlier period.

A total of 16 multispectral images were selected for the bathymetric and turbidity time-series analysis. Images were chosen
60 at approximately five-year intervals (2004, 2005, 2009, 2010, 2014, 2015, 2020, 2024, 2025), with two scenes per interval representing the distinct dry (spring-summer) and wet (autumn-winter) seasons of the region (Table 2). To assess the impact of extreme events, six additional images were acquired—one before and two after the landfall of Hurricane Newton (2016) and Hurricane Lorena (2019). All images were subjected to strict selection criteria to ensure optimal conditions for aquatic remote sensing: cloud cover < 3%, tidal deviation within ± 0.35 m of the mean sea level (verified using the TPXO tidal model and
65 local tide tables (Egbert and Erofeeva (2002)), and an absence of significant sun glint.



Table 1. Technical specifications of the satellite sensors used for bathymetry analysis.

Characteristic	Landsat 7 ETM+	Sentinel-2 MSI
Visible Resolution	30 m	10 m
Panchromatic Band	Yes (15 m)	No
Radiometric Resolution	8 bits	12 bits
Revisit Frequency	16 days	5 days (S2A/B combined)
Spectral Coverage	7 useful bands	13 bands (10 useful)
Data Availability	1999–present	2015–present

Table 2. Multispectral image dataset used for bathymetric time-series analysis.

Year	Season/Event	Satellite	Acquisition Date	Primary Use
2004	Autumn-Winter	Landsat 7	19 Nov 2004	Bathymetry, Turbidity
2005	Spring-Summer	Landsat 7	17 Jul 2005	Bathymetry, Turbidity
2009	Autumn-Winter	Landsat 7	01 Nov 2009	Bathymetry, Turbidity
2010	Spring-Summer	Landsat 7	07 Sep 2010	Bathymetry, Turbidity
2014	Autumn-Winter	Landsat 7	30 Oct 2014	Bathymetry, Turbidity
2015	Spring-Summer	Landsat 7	29 Jul 2015	Bathymetry, Turbidity
2016	Pre-Hurricane Newton	Sentinel-2	25 Aug 2016	Event Impact
2016	Post-Hurricane Newton (1)	Sentinel-2	14 Sep 2016	Event Impact
2016	Post-Hurricane Newton (2)	Sentinel-2	24 Oct 2016	Event Impact
2019	Pre-Hurricane Lorena	Sentinel-2	10 Aug 2019	Event Impact
2019	Post-Hurricane Lorena (1)	Sentinel-2	24 Sep 2019	Event Impact
2019	Post-Hurricane Lorena (2)	Sentinel-2	03 Nov 2019	Event Impact
2020	Spring-Summer	Sentinel-2	10 Jul 2020	Bathymetry, Turbidity
2020	Autumn-Winter	Sentinel-2	23 Oct 2020	Bathymetry, Turbidity
2024	Autumn-Winter	Sentinel-2	27 Oct 2024	Bathymetry, Turbidity
2025	Spring-Summer	Sentinel-2	13 Mar 2025	Bathymetry, Turbidity

For the precise delineation of the shoreline, we acquired four commercial VHR pan-sharpened images (QuickBird, WorldView-1, WorldView-3, Pleiades-1A) with sub-meter spatial resolution (30–60 cm) (Table 3). These 16-bit, geometrically corrected images provide the necessary detail for detecting fine-scale erosion and accretion patterns over key dates, including the periods before and after Hurricane Lorena.

70 Landsat and Sentinel images were downloaded from USGS Earth Explorer and Copernicus Browser, respectively, at the L1TP processing level (georeferenced and radiometrically corrected). Atmospheric correction was performed externally using the ACOLITE satellite image processing software, which combines atmospheric correction algorithms for aquatic applications



from various satellite missions developed at RBINS (Vanhellemont and Ruddick (2018)). Additionally, the satellite images were cropped and individually validated.

Table 3. Very high-resolution (VHR) satellite images used for shoreline change analysis.

Year	Satellite	Resolution	Acquisition Date	Purpose
2006	QuickBird	60 cm	23 Apr 2006	Baseline Shoreline (20-yr)
2019	WorldView-1	50 cm	29 Aug 2019	Pre-Hurricane Lorena Shoreline
2019	WorldView-3	30 cm	15 Dec 2019	Post-Hurricane Lorena Shoreline
2024	Pleiades-1A	50 cm	10 Nov 2024	Recent Shoreline

75 2.3 Derivation of Environmental Variables

All environmental variables were derived exclusively from satellite imagery. It is therefore critical to state that these results represent reliable approximations rather than absolute truths. The following sections detail the algorithms, their application, and the associated validation context for each variable.

2.3.1 Satellite-Derived Bathymetry (SDB)

80 Relative water depth was estimated using a physically based analytical model that leverages the differential attenuation of light in water. We applied the two-stage semiempirical log-ratio reflectance model (Lamas-Torres et al. (2025)) which integrates the optical properties of green/blue and red/blue band ratios within a parametric regression framework.

The model estimates depth z using log-ratio reflectance indices defined as:

$$X_1 = \log\left(\frac{R_G}{R_B}\right), \quad X_2 = \log\left(\frac{R_R}{R_B}\right)$$

85 where R_G , R_B , and R_R represent atmospherically corrected reflectance values in the green, blue, and red spectral bands, respectively. These indices are physically meaningful: the green/blue ratio captures depth-dependent penetration due to the moderate attenuation of green light, while the red/blue ratio enhances sensitivity in very shallow waters due to the rapid absorption of red wavelengths.

The model structure is formulated in two stages:

90 1. **First stage:** An exponential relationship between depth and the green/blue log-ratio:

$$z = \alpha_1 \cdot \exp(\beta_1 X_1) + \epsilon_1$$

where α_1 and β_1 are regression coefficients, and ϵ_1 represents the residual error.

2. **Second stage:** The residual ϵ_1 is modeled as a quadratic function of the red/blue log-ratio:

$$\epsilon_1 = \alpha_2 X_2^2 + \beta_2 X_2 + \gamma_2$$



95 where α_2 , β_2 , and γ_2 are additional regression parameters.

The final combined model is expressed as:

$$z = \alpha_1 \cdot \exp(\beta_1 X_1) + \alpha_2 X_2^2 + \beta_2 X_2 + \gamma_2$$

This formulation retains the interpretability of semiempirical models while improving stability and accuracy across diverse coastal environments—from turbid lagoon systems to clear coral reef waters.

100 Model calibration was performed using `fminsearch` in MATLAB, minimizing the squared error between predicted and observed depths. Calibration data were derived from depth soundings in the official nautical chart *Portulano MX 25110* (SEMAR, 1:20,000 scale, 2018 edition). A satellite image coincident with the chart's reference date was processed using the ACOLITE atmospheric correction algorithm to obtain water-leaving reflectance values. The model was fitted separately for Landsat 7 and Sentinel-2 band sets to ensure sensor-specific accuracy.

105 The calibrated model provides a quantitatively validated estimate of relative bathymetry, enabling the generation of bathymetric difference maps through temporal subtraction of depth rasters. This approach is particularly robust in data-scarce regions and supports scalable, cost-effective coastal monitoring (Aviña Hernández and Martínez Rincón (2018)).

2.3.2 Turbidity patterns

The long-term trends in water clarity within Ensenada de La Paz were assessed qualitatively using satellite-derived turbidity
110 estimates. Due to the lack of concurrent, in situ turbidity measurements for the study period, the analysis focuses on identifying relative changes in spatial patterns rather than providing absolute concentrations. Turbidity was estimated using the single-band Nechad (Nechad et al. (2016)) algorithm applied to the red spectral band (665 nm), which is sensitive to the scattering and absorption properties of suspended particulate matter in coastal waters. This method allows for the detection of relative differences in turbidity over time and across the lagoon.

115 2.3.3 Shoreline Delineation and Change Detection

Shorelines were manually digitized on the very high-resolution (VHR) imagery (Table 3) using QGIS software (QGIS Development Team (2024)). The land-water boundary was identified through meticulous human interpretation based on a consistent visual threshold, ensuring morphological coherence across all dates. This manual process, while time-intensive, is considered the most accurate method for delineating shorelines from VHR imagery in complex environments like mangrove fringes and
120 gentle beaches, where automated methods often fail.

Shoreline change was calculated by comparing the vectorized shorelines from different epochs (e.g., 2006 vs. 2024 for long-term change, and pre- vs. post-hurricane for event impacts). Erosion and accretion zones were identified by computing the area change between subsequent shoreline positions. As with all remotely sensed delineations, the absolute positional accuracy is subject to the geometric fidelity of the source imagery; however, the high quality of the orthorectified VHR products ensures
125 that the relative changes between dates are robust and meaningful for change detection analysis.

2.4 Analysis of Extreme Events

To evaluate the geomorphological and water quality impacts of tropical cyclones, we conducted a targeted pre- and post-event analysis for two major hurricanes: Hurricane Newton (Comisión Nacional del Agua, Servicio Meteorológico Nacional (2016) (September 2016) and Hurricane Lorena (September 2019) (Comisión Nacional del Agua, Servicio Meteorológico Nacional
130 (2019)). The methodology focused on detecting abrupt, event-driven changes by comparing satellite-derived variables from images acquired immediately before and after each hurricane's landfall near La Paz Bay.

Specifically, for each hurricane, we analyzed:

- **Bathymetric Variations:** We applied the Satellite-Derived Bathymetry (SDB) model to pre- and post-hurricane multi-spectral images. Difference maps were generated to quantify localized sediment deposition (shallowing) or scour (deep-
135 ening), particularly in shallow areas and near the mouths of major streams.
- **Turbidity Response:** We evaluated changes in water clarity as a proxy for sediment mobilization and resuspension. Using the Nechad algorithm, we generated pre- and post-storm turbidity maps to identify plumes of suspended sediment, their spatial extent, and their persistence in the days and weeks following each hurricane. This analysis helped distinguish between immediate storm-driven resuspension and longer-term changes in water quality.
- **Shoreline Changes:** Using the very high-resolution (VHR) imagery (for Lorena), we compared shoreline positions to
140 identify areas of acute *erosion* (retreat) or *accretion* (advance) directly attributable to storm surge, waves, and associated flooding.

Contextual Integration: To interpret the satellite-observed changes within the specific hydro-meteorological context of each storm, we complemented the remote sensing analysis with a review of official reports from Mexico's National Water
145 Commission (CONAGUA) and local news sources. This provided crucial data on rainfall intensity, spatial distribution, and documented on-the-ground impacts, helping to correlate satellite signals with the physical drivers of each hurricane.

2.5 Integration of Local Ecological Knowledge

A core innovative component of this study was the systematic integration of Local Ecological Knowledge to ground-truth
150 satellite observations and uncover drivers of change not discernible from space alone. This mixed-methods approach was implemented during the final project phase (March–May 2025).

We conducted semi-structured interviews and held two focused workshops with key stakeholders who possess long-term, place-based experience in La Paz Bay. Participants were selected to represent the primary user groups and knowledge-holders of the system:

- Artisanal fishers from communities in *El Manglito*.
- Representatives from local organizations, including the *Organización de Pescadores Rescatando la Ensenada (OPRE)*
155 and *Noroeste Sustentable (NOS)*.



– Specialists in oceanography and coastal management from academic and consultancy backgrounds.

3 Results

3.1 Multitemporal Bathymetric Trends

160 The analysis of satellite-derived bathymetry over the 2005–2025 period reveals a clear and progressive trend of depth reduction (shallowing) across La Paz Bay. Figure 4 illustrates the absolute bathymetric change for each five-year interval, showing consistent patterns of sediment accumulation, a slight dominance of the color green, which represents a decrease in depth. The most significant depth loss occurred during the 2005–2010 period, with an average reduction of 0.21 m, while the most recent interval (2020–2025) shows a continued decline of 0.17 m (Table 4).

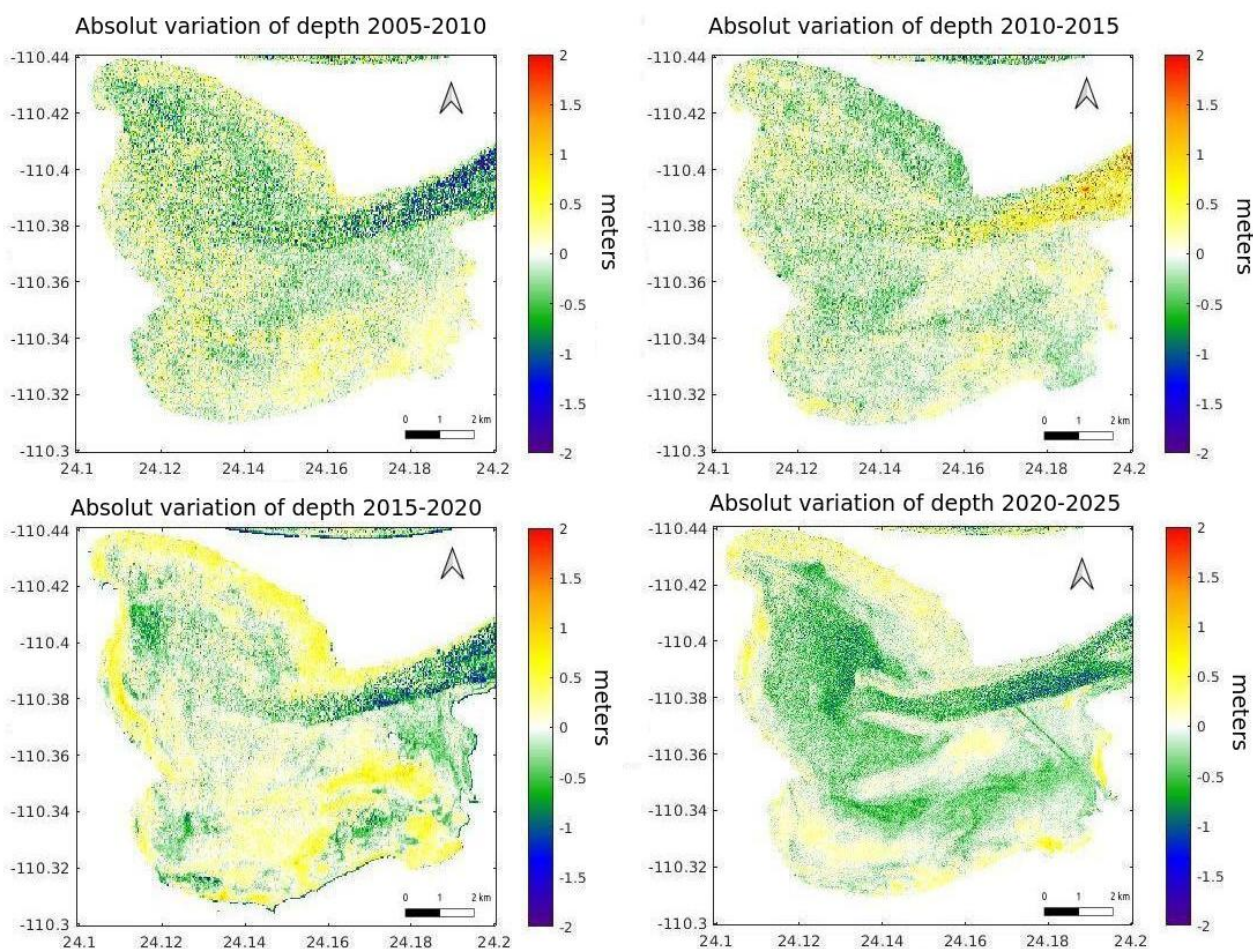


Figure 4. Absolute variation of the bathymetry in the Ensenada de La Paz in the periods: a) 2005-2010, b) 2010-2015, c) 2015-2020 and d) 2020-2025



Table 4. Average depth change per five-year interval in La Paz Bay (2005–2025). Positive values indicate deepening, negative values indicate shallowing.

Period	Avg. Depth Change (m)	Main Affected Zone
2005–2010	-0.21	Entire bay, esp. central channel
2010–2015	-0.02	Northern and northwestern areas
2015–2020	-0.004	Northwestern sector
2020–2025	-0.17	Widespread, except near streams
Average	-0.101	
Std. Dev.	0.094	

165 Seasonal comparisons consistently show greater depths during autumn-winter months compared to spring-summer (Table 5), with seasonal differences ranging from 0.03 to 0.21 m. The average seasonal variation across all analyzed periods is +0.11 m and can be show in Figure 5, indicating systematically deeper conditions during the colder months. This pattern aligns with expected hydrographic conditions: stronger vertical mixing and wind-driven resuspension during winter versus thermal stratification and potential fluvial sediment inputs during summer (Lizárraga-Arciniega et al. (2007)).

Table 5. Seasonal depth variation in La Paz Bay. Positive values indicate deeper conditions in autumn-winter compared to spring-summer.

Year Pair	Seasonal Δ Depth (m)	Autumn-Winter Date	Spring-Summer Date
2004/2005	+0.2128	19 Nov 2004	17 Jul 2005
2009/2010	+0.0499	01 Nov 2009	07 Sep 2010
2014/2015	+0.0308	30 Oct 2014	29 Jul 2015
2019/2020	+0.1358	23 Oct 2020	10 Jul 2020
2024/2025	+0.1253	27 Oct 2024	13 Mar 2025
Average	+0.1109		
Std. Dev.	0.075		

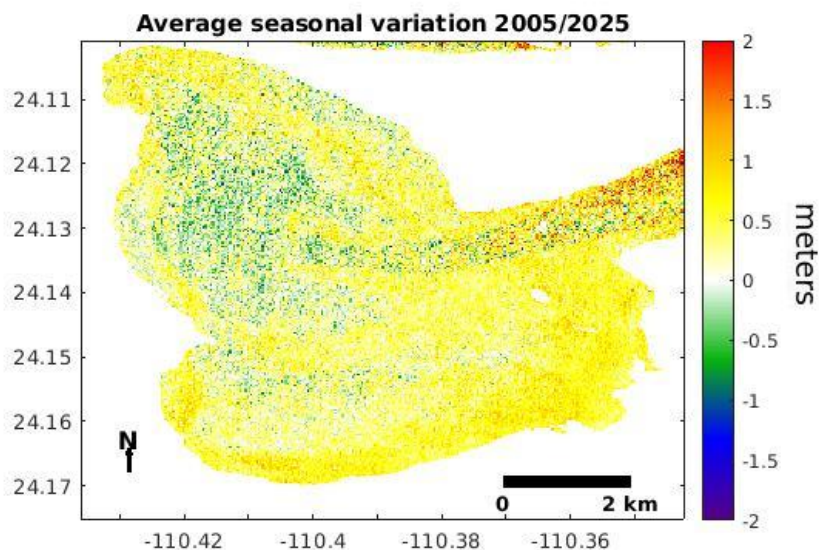


Figure 5. Average seasonal variation of the bathymetry in the Ensenada de La Paz in the Autumn-Winter season

170 The long-term trend analysis (Fig. 6, divided into two periods: 2004-2015 using imagery from Landsat 7 and 2015-2025 using Sentinel 2 imagery), confirms a generalized shallowing trend from 2004 to 2015. However, from 2015 onward, spatial heterogeneity increases, with notable sediment accumulation in the northwestern region and localized deepening near stream mouths, suggesting changes in sediment transport dynamics.

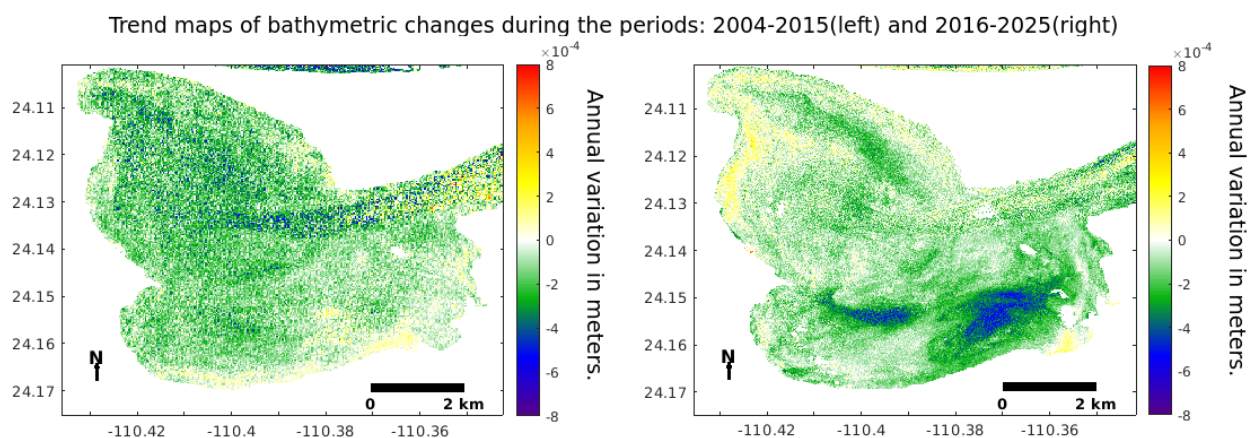


Figure 6. Map with the tendency of the bathymetric changes in the period 2004-2015 (using Landsat 7 imagery) and 2016-2025 (using Sentinel 2 imagery).



3.2 Shoreline Changes

175 The multi-temporal analysis of the shoreline of Ensenada de La Paz, conducted by comparing very high-resolution satellite
imagery (*Maxar Technologies*) from 2006 and 2024, revealed a predominantly erosive coastal dynamic over the 18-year study
period.

A detailed comparison quantified the areas of erosion and accretion (Figures 7). The results indicate a significant net loss of
coastal land. An estimated **21.34 hectares** of cumulative erosion were detected, widely distributed along the Ensenada but with
180 higher concentration in the northern and northwestern sectors. This loss aligns with documented reports of beach reduction
and the increase in nearshore water depth described in the bathymetric change analysis.

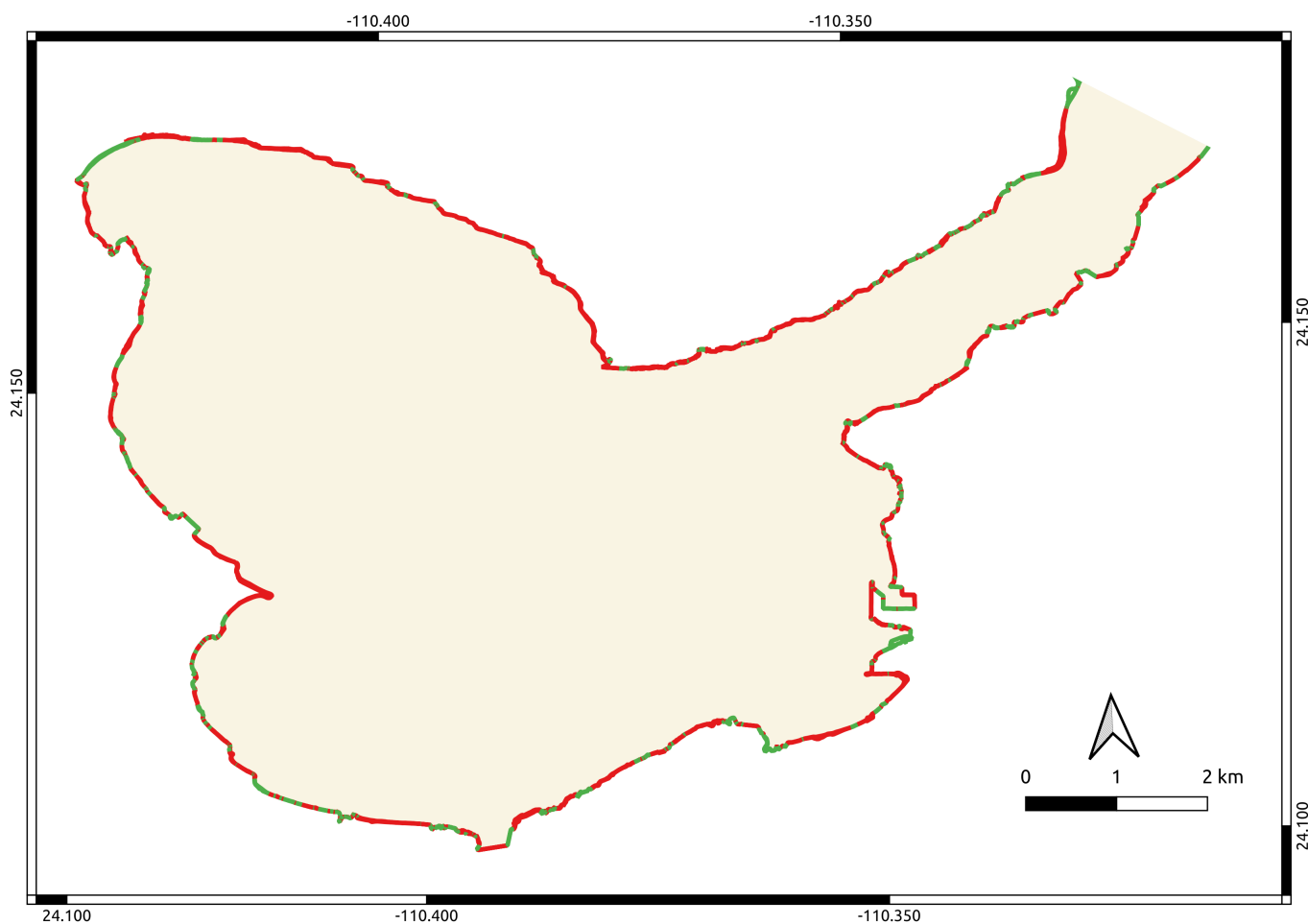


Figure 7. Map of the Ensenada de la Paz, highlighting in red the areas with erosion and in green the areas with accretion in the period 2006-2024.



In contrast, total accretion was estimated at only **5.71 hectares**. This gain was primarily concentrated at the tip of the El Mogote sand barrier and at the mouth of the El Cajoncito stream. Accretion observed in other areas, such as near CIBNOR or sections of the city's waterfront, is likely attributable to anthropogenic interventions (e.g., infrastructure, beach nourishment) rather than natural sedimentary processes.

3.3 Turbidity patterns

The comparison of composite images from the 2005 and the most recent period 2025 reveals a marked increase in nearshore turbidity. In the historical imagery, clearer waters (blue pixel values in the derived product) predominated close to the shoreline. In contrast, the recent composites consistently show higher turbidity signals (red pixel values) along significant stretches of the coast, particularly adjacent to urbanized areas, marinas, and modified shorelines. This suggests a potential increase in sediment resuspension or reduced flushing in these zones over the past two decades.

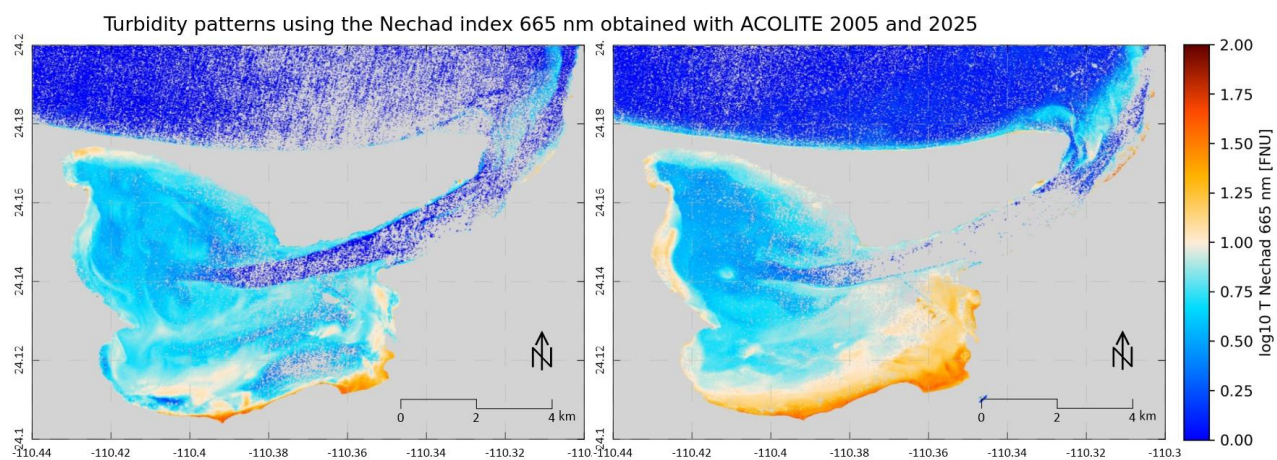


Figure 8. Map of the change in the nechad 665 nm index of the Ensenada de La Paz in the period 2004/2005 - 2024/2025.

3.4 Impact of Extreme Events

Hurricanes Newton (2016) and Lorena (2019) produced distinct morphological and sedimentary responses in La Paz Bay, reflecting differences in their rainfall distribution, intensity, and pathways. The following analysis details their individual impacts on bathymetry, turbidity, and shoreline dynamics.

3.4.1 Hurricane Newton (2016)

Hurricane Newton formed as a tropical depression on September 4, 2016, off the coast of Mexico, rapidly intensifying to a Category 1 hurricane. It reached its peak intensity with sustained winds of approximately 150 km/h (90 mph) and a minimum pressure of about 977 hPa, making landfall near Cabo San Lucas on September 6. Between September 4-7, it produced intense rainfall in the municipality of La Paz (87 mm in the capital, 95 mm in El Pescadero, and 91.9 mm in San Antonio), causing

power outages, temporary internet disruptions, and traffic issues due to fallen trees and signage according to CONAGUA (Comisión Nacional del Agua, Servicio Meteorológico Nacional (2016)) and BCS Noticias (Redacción BCS Noticias (2016)).

Bathymetric Impact: The analysis of satellite imagery revealed an immediate average depth reduction of 0.2832 m following Hurricane Newton. The most significant shallowing was concentrated in the northwestern sector and the central tidal channel as can be shown in (Fig. 9). However, two months post-event (24/10/2016), bathymetric data showed an average depth increase of 0.0614 m, indicating a partial recovery and sediment redistribution, particularly with shallowing now more pronounced near the mouths of the Cajoncito and La Palma streams.

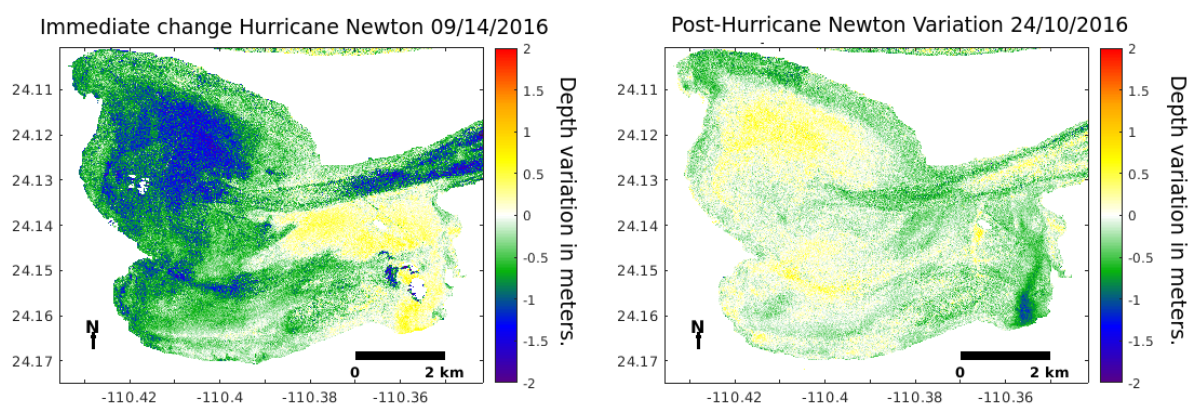


Figure 9. Bathymetric change map of La Paz Bay immediately following Hurricane Newton (2016), showing average depth reduction of 0.28 m, concentrated in the northwest and the tidal channel and after approximately two months, showing sediment redistribution.

Turbidity Impact: Ten days after the hurricane, a significant increase in turbidity (estimated via the Nechad 665 nm index) was observed, particularly near the Cajoncito, El Novillo, and La Palma streams in the south/southeastern part of the bay as can be shown in (Fig. 10). Approximately two months later, while turbidity remained concentrated in the same regions, a noticeable reduction in intensity was observed, suggesting a slow dissipation of the suspended sediment load.

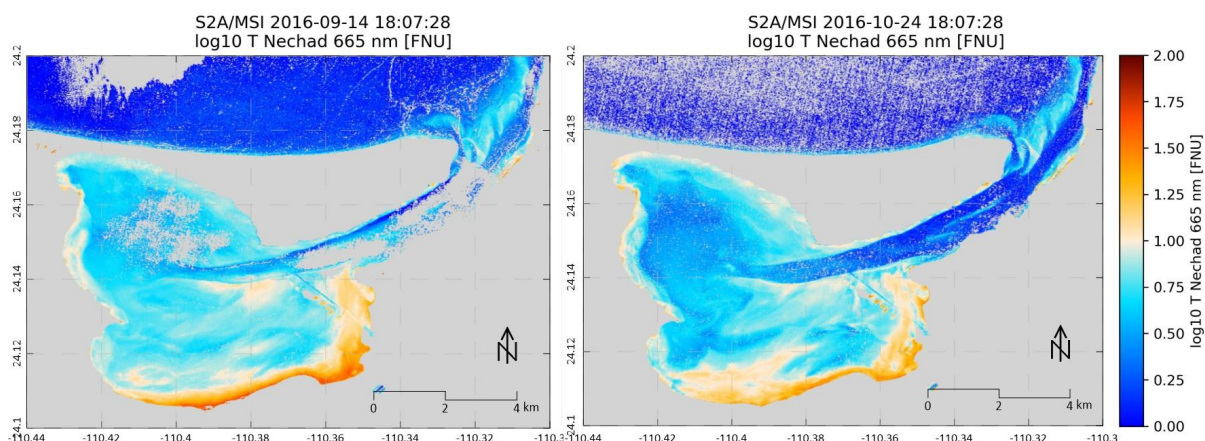


Figure 10. Turbidity map (Nechad 665 nm index) of La Paz Bay ten days after Hurricane Newton and approximately two months after, showing high sediment concentration near southern streams.

3.4.2 Hurricane Lorena (2019)

Hurricane Lorena originated as a tropical storm on September 17, 2019, south of the Mexican coast, quickly intensifying to a Category 1 hurricane. It made its first landfall in Jalisco on September 19, weakened overland, but re-intensified upon entering the warm Gulf of California before making a second landfall in Baja California Sur. Between September 20-21, it brought intense rainfall to La Paz (up to 174 mm in locations like La Ribera, Miraflores, and Los Planes), causing moderate impacts such as power and telephone service failures, fallen trees, poles, and flooding according to CONAGUA (Comisión Nacional del Agua, Servicio Meteorológico Nacional (2019)) and local newspapers (Redacción El Sudcaliforniano (2019)).

Bathymetric Impact: Following Hurricane Lorena, a more homogeneous average depth reduction of 0.1858 m was observed across the bay (Fig. 11). Two months later (03/11/2019), the system showed a notable recovery with an average depth increase of 0.20615 m, suggesting a rapid return towards a dynamic equilibrium compared to the more localized effects of Newton.

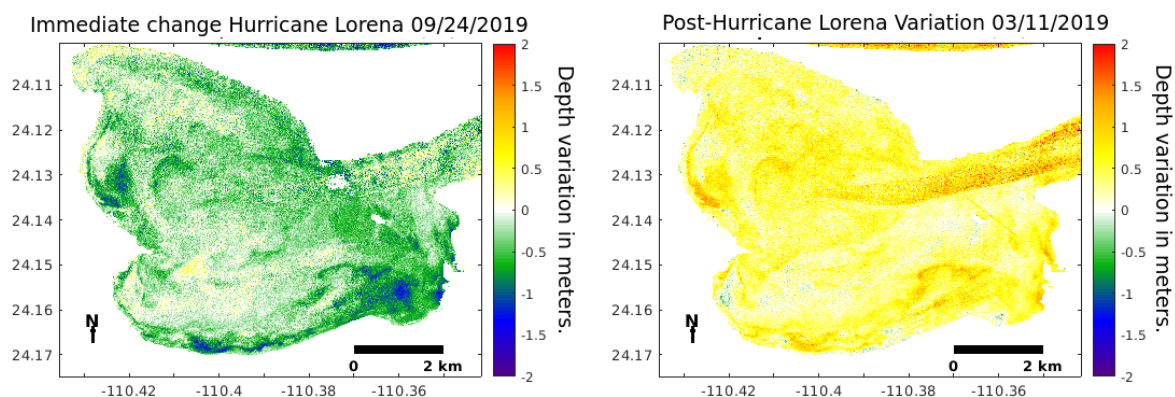


Figure 11. Bathymetric change map of La Paz Bay immediately following Hurricane Lorena (2019) and approximately two months after Hurricane Lorena, showing a relatively uniform average depth reduction and recovery

Shoreline Impact: Shoreline change analysis between August 29 and December 15, 2019, quantified approximately 3.4 hectares of erosion, primarily concentrated along the exposed northern shores and the western area near Comitán (Fig. 12). Concurrently, approximately 4.2 hectares of accretion were detected, mainly located in the south/southeastern areas adjacent to the mouths of the Cajoncito, El Novillo, and La Palma streams. This pattern indicates a net cross-bay sediment transport from wave-eroded areas to depositional zones influenced by fluvial inputs.

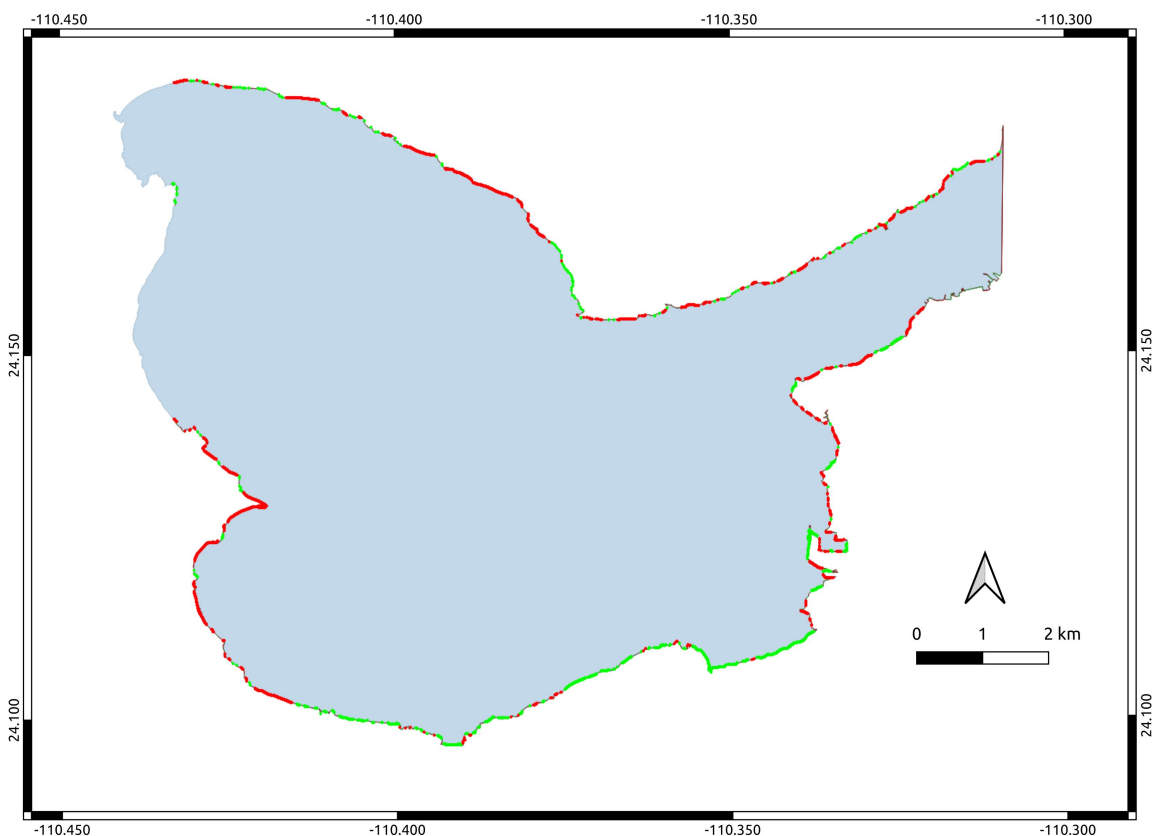


Figure 12. Shoreline change map of La Paz Bay following Hurricane Lorena (2019). Red areas indicate erosion (approx. 3.4 ha), primarily in the north and west. Green areas indicate accretion (approx. 4.2 ha), primarily near southern stream mouths.

Turbidity Impact: Analysis of turbidity patterns after Hurricane Lorena (Fig. 13) shows an expected increase in the Nechad index intensity near the main stream mouths immediately after the event, particularly in the south and southeastern parts of the bay. However, this increase was less pronounced and more spatially diffused compared to the sharp, highly localized spike
230 observed after Hurricane Newton. This pattern is likely attributable to Lorena's more widespread rainfall distribution and the absence of exceptionally intense, channelized runoff in the major streams, leading to a less concentrated sediment input into the bay.

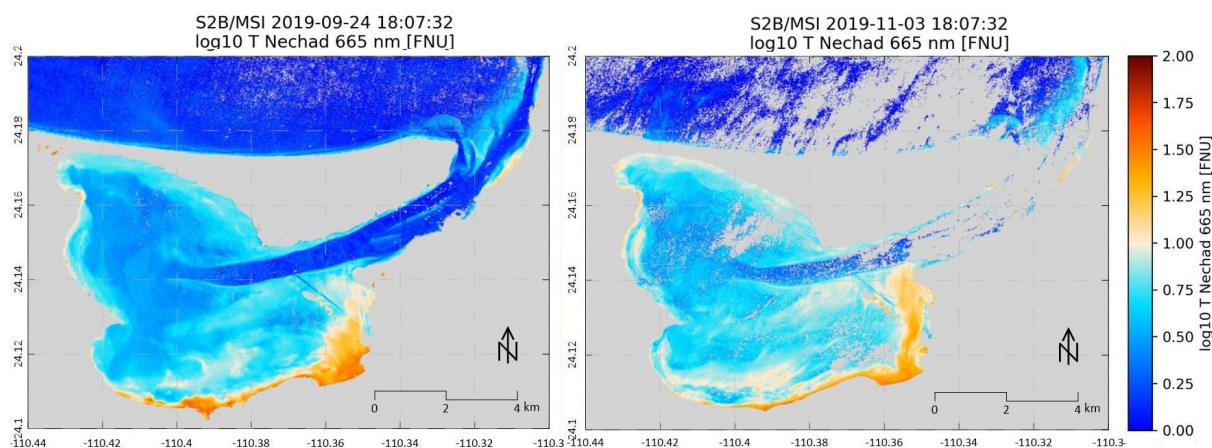


Figure 13. Turbidity maps (Nechad 665 nm index) of La Paz Bay one week and approximately two months after Hurricane Lorena, showing less pronounced variation compared to Hurricane Newton.

3.5 Local Stakeholder Reported Issues

The integration of local knowledge provided critical ground-truthing, contextualization, and insight into the drivers behind the remotely sensed observations. Artisanal fishers, members of the OPRE organization, and long-term residents consistently reported a suite of interconnected issues that directly inform management priorities:

- **Progressive shallowing and navigational hazards:** A widespread perception that the bay is "filling up," with specific reports of reduced depth in the northwestern sector and increasing difficulty for navigation in areas that were historically deeper. This aligns quantitatively with the observed bathymetric decline and sediment accumulation trends (Section 3.1).
Local knowledge pinpoints the area where sunken yachts adjacent to El Mogote have potentially altered current flows, contributing to this pattern.
- **Beach loss and coastal erosion:** A noticeable and concerning reduction of beach width along the northern and western shores, particularly in recreational areas like El Mogote. This aligns precisely with the erosional hotspots (21.34 ha lost) identified in the multidecadal shoreline change analysis (Section 3.2).
- **Anthropogenic pressures and resource conflicts:** Specific, recurring concerns include:
 - **Illegal and unsustainable fishing:** Reported illegal extraction of pen shell (*callo de hacha*) and oyster, along with the use of prohibited nets (*chinchorros*) in the northwest and south of the bay, impacting benthic habitats and legal concession holders like OPRE.
 - **Pollution and waste:** Visible solid waste accumulation and pollution in and around the main streams (especially Cajoncito), attributed to both stormwater runoff and direct discharge from vessels outside designated areas.



- **Unregulated tourism:** Intensive use of all-terrain vehicles (Razers) on the dune systems of El Mogote and high kayak traffic, contributing to habitat degradation in sensitive areas.
- **Vessel overcapacity:** A reported number of operating vessels that far exceeds official figures, indicating significant and unregulated pressure on the coastal ecosystem.

255 – **Proposed infrastructure and its perceived risks:** Strong opposition and concern were expressed regarding the proposed construction of a large pier. Stakeholders fear that such a rigid structure would disrupt natural sediment dynamics, potentially leading to artificial sedimentation patterns, increased local erosion, and negative impacts on bathymetry and navigability. The construction process itself is also seen as a major source of sediment resuspension and increased turbidity.

260 – **Ecological degradation and species loss:** Reports of the disappearance of key species like the manta ray and catarina clam from previously productive areas, signaling a decline in ecosystem health and biodiversity linked to the cumulative pressures described above.

This convergence between satellite-derived evidence and detailed local observations creates a robust, multi-perspective diagnosis. While remote sensing quantifies the *what* and *where* of change (shallowing, erosion, turbidity plumes), local knowledge
265 critically explains the *why* and *how* (specific anthropogenic drivers, historical context) and underscores the immediate social and economic implications of the Ensenada de La Paz transformation.

3.6 Management Recommendations

Based on the integrated analysis of satellite data, validated by local knowledge, the following multidimensional management recommendations are proposed to address the identified threats and guide the sustainable stewardship of La Paz Bay. These
270 actions are framed within an adaptive management approach that prioritizes monitoring, regulation, restoration, and inclusive governance.

3.6.1 Technical Monitoring and Research Recommendations

- **Enhanced Field Validation Campaigns:** Conduct periodic oceanographic campaigns to ground-truth and calibrate remote sensing products. These should include:

275 – High-resolution bathymetric surveys (e.g., using multibeam sonar) in areas identified as highly variable.

- Vertical profiles of turbidity, salinity, and temperature, particularly near stream mouths and areas of high human activity.

– **Installation of In-Situ Sensor Networks:** Deploy turbidimeters, water level gauges, and basic meteorological stations, with priority given to the southern part of the bay and the mouths of the main streams (Cajoncito, La Ardilla, La Palma,
280 El Novillo) to continuously monitor sediment and freshwater inputs.



– **Hydrodynamic and Sediment Transport Modeling:** Implement campaigns to measure current velocity and direction using Acoustic Doppler Current Profilers (ADCP), especially in the tidal channel and high-energy zones. This data should feed into numerical circulation models that integrate tides, winds, and fluvial contributions to robustly understand sediment transport pathways and predict morphological evolution.

285 – **Sedimentology and Geochemical Studies:** Perform systematic sampling for grain-size analysis and geochemical characterization of sediments. This is crucial to distinguish between natural and anthropogenic sediment sources, identify areas vulnerable to accumulation of fine or contaminated sediments, and better understand depositional dynamics.

– **Systematic Water Quality Monitoring:** Establish a regular monitoring program for key water quality parameters including nutrients (nitrates, phosphates), fecal coliforms, heavy metals, and microplastics to assess ecological health and risks to biodiversity and human health.

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– **Multitemporal Analysis of Vegetative Cover:** Monitor changes in mangrove, seagrass, and coastal vegetation cover both within the bay and in the upper watershed. This information is vital for modeling sediment retention, carbon capture potential, and designing effective ecological restoration strategies.

3.6.2 Water and Sediment Management Recommendations

295 – **Watershed Management and Runoff Control:** Implement rainwater harvesting and retention strategies in the upper parts of the catchment basin to reduce the volume and speed of direct runoff that carries sediments and waste into the bay during storm events.

– **Stream Restoration and Maintenance Programs:** Prioritize and execute cleaning and ecological restoration programs for the main stream channels (Cajoncito, La Ardilla, La Palma, El Novillo). This includes waste removal and bank stabilization to significantly reduce the garbage and sediment load reaching the bay after intense rains.

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3.6.3 Coastal Zone Management and Regulation Recommendations

– **Precautionary Approach to Coastal Infrastructure Development:** Implement a moratorium on all new large-scale, rigid coastal infrastructure projects (such as piers, breakwaters, or extensive shoreline hardening) until comprehensive, site-specific Environmental Impact Assessments (EIAs) are conducted and approved. These EIAs must include detailed sedimentological and hydrodynamic modeling to rigorously evaluate the project's potential to disrupt natural sediment transport pathways, alter current patterns, and trigger unforeseen erosion or accretion in adjacent areas. The principle of preventive action should guide decision-making, requiring proponents to demonstrate no significant adverse impact on the bay's morphodynamic equilibrium.

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– **Regulation of Maritime Traffic:** Establish and enforce regulations on the number, size, and operational zones of vessels within the bay, based on a scientifically determined carrying capacity. This should address the reported overcapacity and its cumulative effects on erosion (wake-induced), turbidity, and benthic habitat disturbance.

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- **Establishment of Protection and Exclusion Zones:** Designate and enforce marine protected areas, seasonal closures, or no-entry zones in critical habitats for beach regeneration, seagrass recovery, and key species conservation (e.g., former areas for manta rays, catarina clams).

- 315
- **Control of Coastal and Dune Degradation:** Regulate and, where necessary, prohibit the use of motorized vehicles (Razers) on sensitive dune systems like El Mogote to halt habitat destruction and associated sediment mobilization.

3.6.4 Social and Governance Recommendations

- **Participatory and Inclusive Governance:** Institutionalize the systematic inclusion of local communities (fishers, residents, tourism operators) in all coastal planning and decision-making processes. Their empirical knowledge and direct stake in the ecosystem's health are invaluable for designing effective and socially accepted management measures.

320

- **Development of an Integrated Coastal Management Plan:** Formulate and implement a comprehensive, ecosystem-based coastal management plan for La Paz Bay. This plan must be multi-actor, legally supported, and clearly articulate the integration of environmental monitoring, ecological restoration, and regulation of human activities.

- **Environmental Education and Citizen Stewardship:** Foster environmental education programs and campaigns promoting co-responsibility, specifically targeting vessel operators, tourism service providers, and residents in the direct zone of influence. Highlight the links between specific activities (e.g., waste disposal, illegal fishing) and the documented degradation of the bay.

325

- **Strengthening Surveillance and Enforcement:** Enhance the capacity of relevant authorities (e.g., PROFEPA, CONAPESCA) in collaboration with community surveillance committees (e.g., OPRE) to monitor and deter illegal fishing, unauthorized waste discharge, and other illicit activities reported by stakeholders.

330

The implementation of these recommendations requires a coordinated, interdisciplinary, and well-funded effort. The integrated diagnosis presented in this study provides a solid scientific and socio-ecological foundation for transitioning from observation to action, ensuring the long-term resilience and sustainability of the Ensenada de La Paz ecosystem.

4 Discussion

- 335
- The integrated analysis of La Paz Bay over the past two decades reveals a coastal system undergoing significant and multi-faceted physical transformation. The convergence of satellite-derived data with local knowledge provides not only a quantitative diagnosis of change but also critical insight into the complex interplay of natural and anthropogenic drivers shaping this transformation.



4.1 Decadal Geomorphic Trends: A System in Imbalance

340 The dominant long-term trend is a net loss of bathymetric depth, averaging -0.101 m over the 2005-2025 period. This "filling-in" of the bay aligns precisely with persistent reports from fishers and coastal users, validating the synergy between remote sensing and local knowledge. While episodic hurricane events contribute significant sediment pulses (e.g., -0.28 m after Newton), the sustained interannual shallowing suggests a chronic imbalance in the sediment budget. This is likely driven by a combination of reduced natural sediment inputs from increasingly urbanized and channelized watersheds (Chávez López
345 (2020)) and the continuous resuspension and internal redistribution of existing sediments by anthropogenic activities (e.g., vessel traffic, illegal bottom-fishing). The shift post-2015 towards more heterogeneous patterns—with notable sediment accumulation in the northwest coinciding with high recreational use and reported sunken vessels—highlights how localized human pressures can override broader natural trends.

The pronounced seasonal bathymetric signal ($+0.11$ m deeper in autumn-winter) is a key finding with implications for
350 monitoring. This pattern likely reflects stronger wind-driven vertical mixing and the export of fine sediments deposited during the stratified, fluviially-active summer months (Lizárraga-Arciniega et al. (2007)). It underscores that single-season surveys could misinterpret this natural cyclicity as net erosion or accretion, emphasizing the need for standardized, seasonal monitoring protocols.

4.2 Shoreline Dynamics: Erosion Dominance and Human Footprint

355 The stark contrast between 21.34 hectares of erosion and only 5.71 hectares of accretion over 18 years underscores a profound coastal imbalance. The concentration of erosion along the northern and western shores—areas exposed to predominant wave energy and heavily used for recreation—points to a deficit in sediment supply insufficient to counteract natural forcing. The work of Chavez López (Chavez L
'opez, [Nombre] (2020)) directly links this deficit to urbanization reducing effective runoff and sediment delivery from the
360 watershed. Conversely, localized accretion at the tip of El Mogote and near stream mouths (e.g., El Cajoncito) indicates zones of natural sediment convergence. However, accretion near urban infrastructure is almost certainly anthropogenic, resulting from shoreline hardening or beach nourishment, illustrating the direct human modification of sedimentary processes.

4.3 The Role of Extreme Events: Differing Hydrological Signatures

Hurricanes Newton (2016) and Lorena (2019) acted as powerful natural experiments, revealing the system's sensitivity to
365 rainfall distribution. Newton's intense, channelized runoff led to a sharp, localized increase in turbidity and bathymetric change near southern streams, with a slow recovery. In contrast, Lorena's more widespread rainfall produced a uniform but shallower depth reduction and a more diffuse turbidity signal, followed by a quicker systemic recovery. This divergence demonstrates that the impact of an extreme event is not a simple function of intensity but is critically mediated by its interaction with the watershed's geomorphology and land cover. Events that activate discrete fluvial pathways concentrate impacts and may lead to
370 longer-lasting sedimentary imprints.



4.4 Anthropogenic Pressures as Catalysts of Change

The local knowledge component was indispensable in moving from observing patterns to understanding proximate causes. Specific anthropogenic stressors reported by stakeholders—sunken vessels altering currents, propeller-driven resuspension from vessel overcapacity, illegal benthic fishing, waste discharge into streams, and dune degradation by off-road vehicles—provide
375 mechanistic explanations for the satellite-observed trends of localized shallowing, elevated nearshore turbidity, and beach loss.

4.5 Towards an Integrated Management Framework

The findings collectively argue for a paradigm shift from sectoral to integrated ecosystem-based management. The documented changes—shallowing, erosion, declining water clarity—are interconnected symptoms of a system under stress. Management actions must therefore be equally interconnected. The recommended actions form a logical hierarchy: **(1) Establish a robust**
380 **knowledge foundation** through enhanced monitoring (in-situ sensors, ADCP campaigns, seasonal surveys) and modeling to reduce uncertainty. **(2) Implement source-control measures** in the watershed (runoff management, stream restoration) to reduce sediment and pollutant loads. **(3) Regulate in-bay activities** (vessel capacity, fishing practices, coastal construction) to minimize pressures on sedimentary and ecological processes. **(4) Foster adaptive governance** that institutionalizes community participation, ensuring management is informed by both science and local knowledge. This integrated approach is essential to
385 address the root causes of degradation rather than its symptoms.

5 Conclusions

This study provides a comprehensive, two-decade assessment of the physical evolution of the Ensenada de La Paz, achieved through the synergistic integration of multi-temporal satellite remote sensing and Local Ecological Knowledge. The principal conclusions are as follows:

- 390 1. **The bay is undergoing active geomorphic transformation:** A consistent trend of net shallowing (average -0.101 m since 2005), coupled with dominant shoreline erosion (net loss of 15.63 hectares), signals a fundamental imbalance in the sedimentary budget of La Paz Bay, threatening navigability, coastal habitats, and infrastructure.
- 395 2. **Change is driven by a synergy of natural and anthropogenic forces:** Natural processes, including seasonal hydrographic cycles and sediment pulses from extreme events, set the baseline dynamic. However, these are being exacerbated and redirected by escalating anthropogenic pressures, including watershed modification, pollution, unsustainable resource extraction, and unregulated coastal/ maritime activities, as directly reported by local stakeholders.
3. **Extreme events act as punctuated disturbances with distinct signatures:** The geomorphic and turbidity response to hurricanes is highly dependent on rainfall spatial distribution and watershed connectivity, with channelized runoff (Newton) causing more persistent, localized impacts than widespread rainfall (Lorena).



400 4. **The integration of methodologies is a powerful diagnostic tool:** Satellite remote sensing successfully quantified the *what, where, and when* of change at a system scale, while local knowledge provided the indispensable *why and how*, identifying specific drivers and validating observed patterns. This combined approach offers a replicable model for data-scarce coastal regions worldwide.

405 5. **Urgent, integrated management action is required:** To halt and reverse current degradation trends, management must adopt a proactive, ecosystem-based strategy. Priorities include establishing a science-based participatory monitoring program, implementing stringent regulations on sediment-disrupting activities, restoring key watersheds (e.g., Arroyo El Cajoncito), and formally embedding local knowledge into coastal governance structures.

The Ensenada de La Paz stands at a critical juncture. The evidence presented here outlines a clear trajectory of decline but also provides the detailed scientific and social baseline necessary for corrective action. The future resilience of this ecologi-
410 cally and socio-economically vital system depends on the timely implementation of the recommended integrated management framework, ensuring its preservation as a functional coastal lagoon and a sustainable resource for future generations.

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415 *Data availability.* All data and images supporting the findings of this study are available in the extended technical document, which can be accessed on Zenodo (record 17905263).

Conflicts of interest

The authors declare no conflicts of interest.

Author contributions. Both authors contributed equally to the conceptualization and methodology of this project. Software implementation and original draft writing were carried out by J.A.M.V., while L.T.F. was responsible for review and editing.

420 *Competing interests.* The authors declare that they have no competing interests.



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