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Sea Level Rise and Artisanal Port Vulnerability in Panama: Projected Operational Disruption and Economic Losses by 2050 Under SSP5-8.5

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Abstract. Artisanal fishing ports in low-lying tropical coasts face disproportionate exposure to sea level rise (SLR), yet port-level operational and economic impact assessments remain scarce for Central America. This study quantifies the projected inoperability and direct economic losses of four state-administered artisanal fishing ports—Aguadulce, El Agallito, El Salado, and Boca Parita—in Parita Bay, Panama, under the SSP2-4.5 and SSP5-8.5 emissions scenarios for the 2050 planning horizon. Freeboard vulnerability was assessed using empirical overflow formulae following Spanish ROM 2.0-11 maritime design standards, incorporating Total Water Level (TWL) projections of up to 2.96 m derived from Panama's national coastal vulnerability database. Port operability thresholds were combined with significant wave height exceedance probabilities to estimate annual inoperability periods, while economic losses were quantified through a direct impact assessment model integrating compound annual growth rate (CAGR) revenue projections and historically calibrated revenue sensitivity factors. Results show that all four terminals will become inoperable under both SSP scenarios by 2050, with projected annual inoperability reaching approximately 215 days (≈59% of the year). Direct annual losses are projected to reach USD 29,493 at Aguadulce (15.5% of 2050 projected revenue) and USD 22,376 at Boca Parita (24.2% of projected revenue), with El Agallito exhibiting the most severe operational fragility despite lower absolute losses (59.7% revenue reduction factor). More than 10,000 residents—predominantly dependent on artisanal fishing for income and subsistence—face exposure to permanent coastal inundation. Cumulatively discounted at a 5% social discount rate, the present value of inaction across the three economically quantified terminals (excluding El Salado due to data limitations) approaches USD 770,000 by 2050, excluding indirect multiplier effects. These findings provide a replicable, data-driven framework for prioritising differentiated coastal adaptation investments at the terminal level and demonstrate that modest-revenue artisanal ports represent critical social infrastructure whose functional loss carries costs that conventional national-scale assessments consistently underestimate.

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1 Introduction

Coastal communities worldwide face escalating risks from sea level rise (SLR), a threat that disproportionately affects low-income, subsistence-dependent populations in developing regions (Hauer et al., 2019). Among coastal economic assets, port infrastructure is particularly exposed: combined SLR and storm surge scenarios could impose costs of up to USD 690 billion in Tokyo Bay alone (Hoshino et al., 2016), while global annual coastal damages are projected to reach USD 27 trillion by 2100 (Jevrejeva et al., 2012). Existing port vulnerability assessments have advanced considerably at the global scale (Albert et al., 2016; Monioudi et al., 2018), yet these studies necessarily operate at coarse spatial resolutions and focus predominantly on commercial container and bulk cargo facilities in high-income countries. Artisanal fishing ports in the Global South—which anchor the food security and livelihoods of millions—remain largely absent from the quantitative SLR impact literature. Regional assessments for Latin America and the Caribbean (Instituto de Hidráulica Ambiental de la Universidad de Cantabria & CEPAL, 2015) similarly characterize exposure at the national or coastal-segment scale, without delivering the port-level operability and revenue data required to justify and prioritize infrastructure investment. This gap is consequential: the absence of facility-level economic impact data for small-scale ports systematically depresses the estimated cost of inaction, undermining the economic case for adaptation investment in precisely the communities most vulnerable to climate change.

In Panama, the Ministry of Environment (MiAmbiente) has documented progressive coastline erosion and increased flooding in urban centers, with consequent damage to critical infrastructure (Ministerio de Ambiente de Panamá, 2019). In collaboration with the Instituto de Hidráulica Ambiental de la Universidad de Cantabria, MiAmbiente developed a national coastal vulnerability database extending to the 2050 horizon, which identifies Parita Bay as a high-risk area (Instituto de Hidráulica Ambiental de la Universidad de Cantabria & CEPAL, 2015). Parita Bay is a macrotidal wetland system of recognized conservation value and constitutes a regional economic engine supporting artisanal fishing, aquaculture, and tourism (Sociedad Audubon de Panamá, 2023). The artisanal fishing sector is both economically vital and highly vulnerable to environmental stressors such as pollution and climate variability (Vergara, 2017). However, existing national assessments characterize inundation risk at the district scale and do not provide the port-level operational and economic detail necessary to justify and prioritize infrastructure investment. Addressing this methodological gap, the present study evaluates the impacts of SLR on four critical state-administered ports—Aguadulce, El Agallito, El Salado, and Boca Parita—selected for their economic relevance and their central role in sustaining surrounding coastal communities. Specifically, we (i) assess freeboard vulnerability under the SSP2-4.5 and SSP5-8.5 scenarios using ROM 2.0-11 design standards; (ii) estimate annual operational inoperability periods; (iii) quantify direct economic losses through the 2050 horizon; and (iv) derive adaptation investment thresholds grounded in revenue-based risk metrics.

2 Study Area

Parita Bay is situated within the Republic of Panama, spanning the provinces of Coclé, Herrera, and Los Santos, at coordinates 8°06′N, 80°24′W (Figure 1). According to 2023 census data, the population of the study region is approximately 341,670 inhabitants, distributed across the districts of Aguadulce, Antón, Natá, Penonomé, Chitré, Parita, Santa María, and Los Santos (INEC, 2023).

Geographically, the bay occupies a low-lying coastal plain characterized by Alfisol soils—indicative of moderate fertility and restricted drainage—and extends along approximately 150 km of coastline (Smithsonian Tropical Research Institute, 2022). The area is classified as a macrotidal zone, with tidal ranges of 5–6 m, and receives freshwater inputs from several riverine sources, including the Parita River, the Estero Salado River, and the Palo Blanco estuary.

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This pronounced macrotidal regime — among the largest on Panama's Pacific coast — amplifies Total Water Level variability and renders the TWL-based freeboard assessment framework particularly appropriate for this setting: tidal oscillation constitutes the dominant water level driver, meaning that even modest SLR increments can rapidly erode the structural safety margins quantified in the following section.

The regional economy exhibits strong dependence on coastal activities, with artisanal fishing constituting the most significant livelihood sector. This activity provides economic sustenance to more than 5,000 individuals who are directly reliant on the operational functionality of port infrastructure at the key nodes of Aguadulce, El Salado, Boca Parita, and El Agallito (Figure 1).

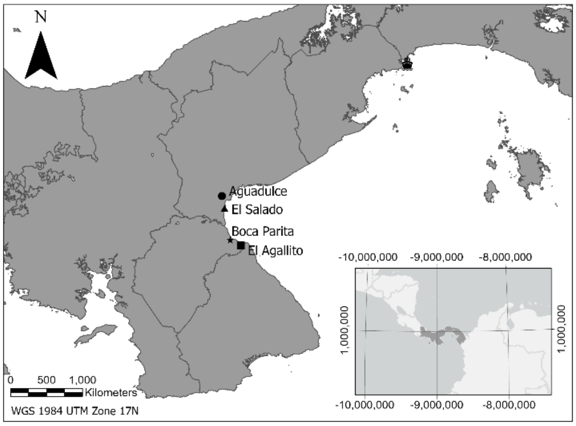

Figure 1: Regional location of Parita Bay.

3 Methods

This study employs a multi-source methodological framework grounded in international technical standards and official Panamanian institutional data. Marine dynamics parameters, including tide levels and wave characteristics, were obtained from MiAmbiente to establish site-specific oceanographic conditions. Economic data pertaining to port operations were provided by the Panama Maritime Authority (AMP), while housing and demographic statistics were sourced from the National Institute of Statistics and Census (INEC) to characterize local socioeconomic vulnerability. Geospatial analyses were conducted using ArcGIS Pro to generate spatial data layers and delineate potential flood inundation zones across the four study sites: Aguadulce, El Salado, Boca Parita, and El Agallito. Structural safety thresholds were subsequently defined in accordance with Spanish ROM standards, and the resulting variables were integrated to project operational and economic impacts through the 2050 projection horizon.

3.1 Data collection

Sea level rise projections under the SSP2-4.5 and SSP5-8.5 scenarios, provided by MiAmbiente (Figure 2), were used to estimate potential coastal inundation depths across the study area.

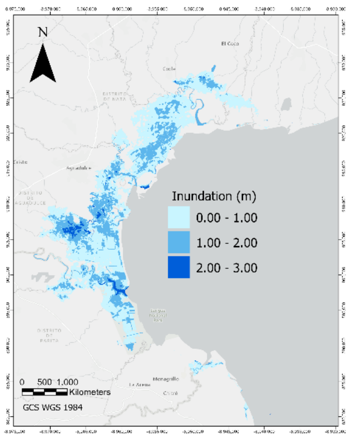

Figure 2: Climate projections for the study area under SSP2-4.5 and SSP5-8.5 scenarios.

The resulting Total Water Level (TWL) values, summarized in Table 1, indicate that permanent TWL could approach 3.00 m under the most severe scenario by 2050.

Table 1: Estimated mean total water level values for 2050.

Condition	2050 Horizon SSP2-4.5 P50 (m)	2050 Horizon SSP5-8.5 P50 (m)
Total Water Level (TWL)	2.94	2.96

Source: (Instituto de Hidráulica Ambiental & Ministerio de Ambiente de Panamá, 2023a).

Field surveys were conducted at each port site in November 2024 to collect site-specific structural data. Freeboard—defined as the vertical distance between the water surface and the top of the pier—was measured at each location, along with the total structural depth (H), which quantifies the flood tolerance capacity of each installation (Table 2).

Table 2: Freeboard measurements (m). h* denotes structural flood tolerance depth (vertical distance from pier crest to invert level); values below 0.5 m trigger inoperability under ROM 2.0-11.

Port	Freeboard (m)	h (m)
El Salado	2.10	1.00
Aguadulce	1.73	1.20
Boca Parita	1.00	0.50
El Agallito	1.20	0.20

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These physical vulnerability parameters directly affect the region's operational and economic stability. Historical revenue data for the period July 2019–June 2024, provided by the Panama Maritime Authority (AMP), are presented in Table 3.

Table 3: Port revenues for study sites (July 2019–June 2024).

Year	Aguadulce (USD)	Boca Parita (USD)	El Agallito (USD)	El Salado (USD)
2019	57,547.00	22,219.00	1,305.00	0.00
2020	45,991.00	17,334.00	5,379.00	0.00
2021	78,952.00	45,557.00	3,665.00	0.00
2022	42,062.00	38,375.00	1,301.00	0.00
2023	67,150.00	32,613.00	2,604.00	0.00
2024 (June)	35,481.00	19,182.00	313.00	0.00

Source: Autoridad Marítima de Panamá (2024).

The port of El Salado was excluded from financial projections due to the complete absence of official revenue records from the Panama Maritime Authority (AMP), reflecting its operation through informal, subsistence-based activities without administrative oversight.

Although structural deterioration precludes derivation of a reliable CAGR for this site, it is retained throughout as a qualitative vulnerability benchmark, with its physical risk profile quantified through freeboard analysis. The absence of economic data for El Salado constitutes a recognized limitation of this study: the true aggregate cost of SLR across Parita Bay is therefore underestimated, as the subsistence losses and social welfare costs associated with this terminal are not captured in the quantitative totals. Future assessments should prioritize the establishment of formal revenue tracking mechanisms at El Salado to enable its inclusion in economic impact models. These empirical measurements constitute the foundational inputs for the operational risk models developed in the following section.

3.2 Data analysis

According to MiAmbiente projections, several areas of Panama are expected to experience permanent inundation by 2050. Accordingly, a geospatial analysis was conducted using a Digital Elevation Model (DEM) to delineate the 3-meter inundation extent across the study area. Operational capacity of the berthing structures was evaluated by examining the effect of projected sea level rise on quay freeboard using Eq. (1).

This methodology follows the ROM 2.0-11: Recomendaciones para el Proyecto y Ejecución en Obras de Atraque y Amarre (Puertos del Estado, 2012). For each scenario, the projected sea level rise increment is summed with the 50th-percentile astronomical and meteorological tide values, as expressed in Eq. (1):

$$F_f = F_i - (SLR + MT_{50}) \tag{1}$$

where F_f is the final freeboard, F_i is the initial freeboard, SLR denotes sea level rise and MT_{50} represents astronomical and meteorological tides at the 50th percentile. This methodology establishes a minimum fixed berthing crest elevation threshold of 0.5 m for artisanal fishing ports, in accordance with ROM 2.0-11 (Figure 3).

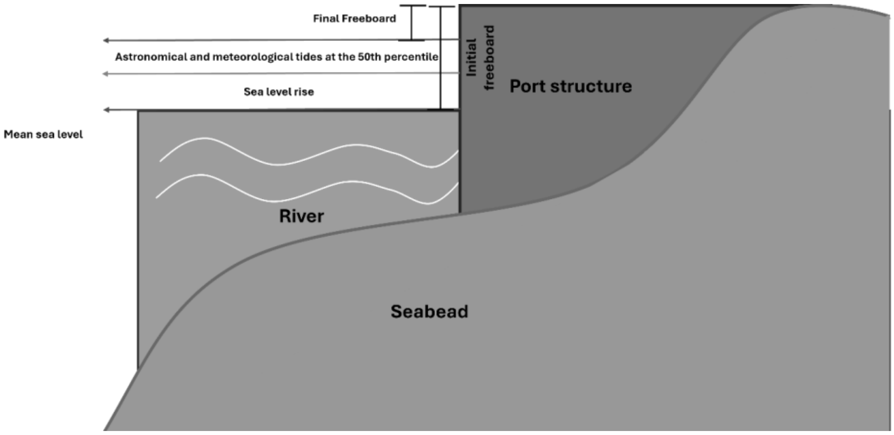

Figure 3: Simplified cross-sectional diagram of a typical small fishing port structure. Adapted from Riera Guevara (2023).

3.2.1 Economic Impact and Financial Risk Framework

To quantify the financial impact of projected inundation, the analysis was structured around three principal components:

Revenue projection. Port revenues for the 2050 horizon were estimated using the compound annual growth rate (CAGR), computed from the 2019–2023 revenue series. The CAGR was computed from the 2019–2023 revenue series using Eq. (2):

$$CAGR = \left(\frac{V_f}{V_i}\right)^{\frac{1}{n}} - 1 \tag{2}$$

Here, n denotes the number of years between the initial (2019) and final (2023) revenue observations (V_i and V_f, respectively). The resulting rate was applied to project revenues to 2050 using Eq. (3):

$$V_{2050} = V_{2023} \times (1 + CAGR)^n \tag{3}$$

Where V_{2050} represents the projected revenue for the year 2050, V_{2023} is the baseline revenue from the final historical observation year (2023), CAGR is the compound annual growth rate calculated in Eq. (2), and n denotes the number of projection years between 2023 and 2050.

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Operational downtime and port accessibility. Following criteria established by Puertos del Estado (2000) and Instituto de Hidráulica Ambiental de la Universidad de Cantabria & CEPAL (2015), port accessibility is determined by the probability that significant wave height (Hs) exceeds the 1.5 m navigation safety threshold. A uniform regional *Hs* exceedance probability was applied across all four ports based on the MiAmbiente marine dynamics database, which provides a single composite wave climate series for the macrotidal embayment of Parita Bay; site-to-site variation within the bay is small relative to the inter-annual variability captured by the historical record, justifying this regionalisation. This regional Hs parameter was locally validated to ensure its applicability across all study sites. The exceedance duration is detailed in Eq. (4):

$$H_{yr} = P_{(H_s>1.5)} \times 8640 \tag{4}$$

Where H_{yr} is the is the cumulative downtime in hours per year and $P_{(H_s>1.5)}$ represents the statistical exceedance probability where the significant wave height exceeds 1.5 m. This expression converts the statistical exceedance probability into an annual temporal metric using a fixed operational standard of 8640 hours per year, following the methodological framework established by Comisión Económica para América Latina y el Caribe (2012) , thereby quantifying the cumulative duration during which navigation and docking operations are rendered unsafe.

3.2.2 Economic Loss Quantification

The economic impact of inundation on port operations was estimated using a direct impact assessment model that distinguishes between direct losses attributable to physical infrastructure damage and indirect losses arising from operational interruptions. This approach is well-established in the literature on risk assessment and the resilience of critical infrastructure.

To ensure spatial precision in the 2050 revenue projections, a site-specific exponential growth rate was derived by comparing population and economic activity data from the two most recent national censuses (2010 and 2023), yielding a customized growth trajectory for each port's catchment area. Indirect losses were quantified using Eqs. (5) and (6), which estimate the annual revenue deficit attributable to port operational downtime:

$$L_{an} = (\frac{R_{an}}{365}) \times R_f \times D_{flood} \tag{5}$$

$$R_f = 1 - (\frac{R_{min}}{R_{avg}}) \tag{6}$$

Where L_{an} is the annual economic loss, R_{an} represents the project annual revenue, R_f is the operational reduction factor, D_{flood} denotes the number of flooded or inoperable days, R_{min} is the minimum daily revenue, and R_{avg} is the average dailey revenue.

The annual financial risk for each terminal (Eq. 5) is obtained by combining its 2050 revenue projection with the corresponding reduction factor (Eq. 6) and the 215-day inoperability constant. It should be noted that the 2020 revenue observations—used as the historical minimum for all three terminals (Table 6)—may reflect COVID-19-related disruptions rather than climate-driven losses, introducing a conservative bias in the reduction factors. Given the limited historical data available for these artisanal terminals, incorporating the 2020 downturn establishes a highly conservative financial baseline, as the lower revenues recorded during the pandemic prevent overestimating typical port earnings. A sensitivity analysis excluding 2020 would likely yield marginally lower projected annual losses, confirming that the present estimates represent a conservative upper bound of operational fragility.

4 Results

The operational status of each port terminal was determined by comparing projected sea levels against the structure's design freeboard (Eq. 1). This threshold defines a binary operational classification: a terminal is considered operational when prevailing marine conditions remain below the established safety threshold, and inoperative when wave height exceedance or flooding occurs (Table 4).

Table 4. Operational status results under the present and projected 2050 scenarios. "Present" Freeboard = structural freeboard (Table 2) minus current mean total water level (SLR + MT_{50} under present conditions); negative 2050 values indicate full inundation above pier crest.

Parameter	Scenario	Aguadulce (●)	El Salado (▲)	Boca Parita (★)	El Agallito (■)
Initial Freeboard (m)	**Present**	**1.73**	**2.10**	**1.00**	**1.20**
TWL (m)	Present	1.20	1.00	0.50	0.20
	2050 (SSP2-4.5)	2.32	2.32	2.32	2.32
	2050 (SSP5-8.5)	2.35	2.35	2.35	2.35
Final Freeboard (m)	Present	0.53	1.10	0.50	1.00
	2050 (SSP2-4.5)	−0.59	−0.22	−1.32	−1.12
	2050 (SSP5-8.5)	−0.62	−0.25	−1.35	−1.15
Condition	Present	Operational	Operational	Inoperative	Operational
	2050 (both scenarios)	Flooded	Flooded	Flooded	Flooded

Vulnerability Assessment and Loss Quantification

To quantify the physical inoperability of the ports, we conducted a statistical analysis of the MiAmbiente wave climate database, specifically targeting the annual duration in which marine conditions exceed defined structural safety thresholds (Hs >1.5 m). Based on this analysis, we derived an exceedance probability of 0.60, which serves as the core operational parameter for our assessment. Applying this probability to the total annual operational window (8640 hours) yields an annual risk period of approximately 5153 hours. This duration represents the critical link between physical coastal dynamics and port vulnerability, equating to 215 days of projected inoperability per year, or 58.8 % of the annual cycle. This temporal metric serves as the foundational input for the subsequent economic impact analysis, allowing for the direct quantification of potential losses resulting from sea-level rise and wave-driven inundation.

The economic quantification accounts for the inherent revenue volatility characteristic of artisanal and commercial port activities. The reduction factor (Eq. 6) captures each terminal's daily cash flow sensitivity to external shocks, ensuring that the annual loss estimate reflects not merely a linear function of inoperable days, but rather the true operational risk grounded in historically recorded minimum revenues between 2019 and 2023.

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To avoid statistical bias arising from short-term revenue volatility at Boca Parita and El Agallito, a regional CAGR of 0.0393 (derived from Aguadulce data) was applied as a stable benchmark for these terminals. This normalization yields a conservative and regionally representative 2050 revenue forecast, as presented in Table 5.

Table 5. Projected annual revenue by 2050.

Port	2023 Annual Revenue (USD)	Projected Revenue by 2050 (USD)
Aguadulce	67,150.00	190,306.44
Boca Parita	32,613.00	92,426.86
El Agallito	2,604.00	7,379.87

Operational risk was further quantified by integrating historical revenue sensitivity (Table 6) with the projected 215-day inundation period.

Table 6. Revenue reduction factors by port.

Port	Historical Mean Annual Revenue 2019–2023 (USD)	Historical Minimum Annual Revenue (USD)	Reduction Factor (%)
Aguadulce	62,410.00	45,991.00	26.30%
Boca Parita	29,430.75	17,334.00	41.10%
El Agallito	3,238.25	1,305.00	59.70%

The final phase of this analysis quantifies annual financial risk (Eq. 5) by integrating the 2050 revenue forecast with the operational sensitivity factor for each terminal. A central component of this calculation is the 215-day projected inoperability period—representing the total annual duration during which port infrastructure will remain submerged or unsafe for operations. This value, derived from the 5,153.14 annual hours of threshold exceedance, translates physical coastal dynamics into a direct measure of business interruption. The estimated economic impacts for each terminal under the SSP5-8.5 scenario are detailed in Table 7.

Table 7. Estimated annual economic losses for 2050.

Port	Projected Revenue by 2050 (USD)	Reduction Factor (%)	Projected Inoperable Days	Projected Annual Loss by 2050 (USD)
Aguadulce	190,306.44	26.31%	215	29,493.07
Boca Parita	92,426.86	41.10%	215	22,376.16

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El Agallito	7,379.87	59.70%	215	2,595.19

5 Discussion

The projected 215-day annual inoperability across all four Parita Bay terminals constitutes one of the most severe operational disruption scenarios documented for artisanal fishing port infrastructure in Central America, and directly addresses the methodological gap identified in the introduction: the systematic underrepresentation of small-scale port systems in SLR impact literature. This outcome is consistent with, yet more acute than, comparable assessments of small-scale coastal port systems in other Pacific-facing regions. Amer (2024) identified analogous bifurcated risk profiles in southeast Texas port systems under SLR projections, where terminals with higher revenue bases face the greatest absolute capital exposure while lower-revenue facilities exhibit the greatest proportional operational fragility. The present findings mirror this pattern with notable clarity: Aguadulce registers the highest absolute projected annual loss (USD 29,493), while El Agallito presents the most severe reduction factor (59.7%), confirming that infrastructure scale and revenue concentration jointly determine the dominant risk pathway. At the global scale, (Jevrejeva et al., 2012) project annual coastal damages reaching USD 27 trillion by 2100, and Hoshino et al. (2016) estimate losses of up to USD 690 billion in Tokyo Bay alone under combined SLR and storm surge scenarios. While these figures reflect large commercial port systems that are incomparable in absolute scale to Parita Bay, they establish the systemic nature of port vulnerability to SLR and underscore that artisanal facilities—though economically modest in national accounts—can represent proportionally catastrophic losses for the communities that depend on them.

When contextualized against current operating revenues, the projected economic losses reveal a sustainability threshold that warrants urgent policy attention. Aguadulce's projected annual loss of USD 29,493 represents approximately 43% of its 2023 recorded revenue—a loss-to-revenue ratio that would render continued operation economically untenable without structural intervention. Boca Parita, with a projected annual loss of USD 22,376 against a 2023 revenue of USD 32,613, faces an even more precarious ratio of approximately 69%. Magnan et al. (2022) demonstrate that proactive coastal adaptation in low-lying areas generates benefit-cost ratios substantially exceeding unity even under conservative SLR projections. Applying this principle to the present findings, the combined projected annual loss across the three quantified terminals (USD 54,464) represents a recurring avoidable cost against which adaptation investment can be measured. Discounted over the 25-year horizon to 2050 at a conservative social discount rate of 5%, the cumulative present value of inaction approaches USD 770,000—a threshold that supports the economic justification for moderately costly structural interventions. This estimate is conservative, as it excludes indirect losses arising from supply chain disruption, reduced fishing yields, and social welfare costs, which the literature suggests can amplify direct losses by a factor of 2–3 in artisanal fisheries economies (Instituto de Hidráulica Ambiental de la Universidad de Cantabria & CEPAL, 2015). Taken together, these figures reveal a dual risk profile across the bay: Aguadulce presents the greatest absolute capital exposure, while El Agallito exhibits the most acute operational fragility, as reflected in its 59.7% revenue reduction factor. This divergence is analytically significant — it confirms that vulnerability in this system is not uniform and that adaptation responses must be differentiated accordingly, a point developed further below.

Several methodological assumptions merit critical examination in assessing the robustness of these projections. The 60% wave exceedance probability applied in Eq. (4) is derived from the MiAmbiente marine dynamics database and reflects historical significant wave height (Hs) distributions at the study sites; however, this parameter does not incorporate projected changes in wave climate under SSP5-8.5, which the Intergovernmental Panel on Climate Change (IPCC) (2023) projects may intensify storm activity in the eastern Pacific by mid-century. If wave exceedance probabilities increase beyond 60%, the 215-day inoperability estimate would be proportionally higher, suggesting that the present results represent a conservative lower bound. Similarly, applying Aguadulce's CAGR (0.0393) as a regional revenue benchmark for Boca Parita and El Agallito introduces deliberate conservatism: the actual growth trajectories of these terminals post-2023 may diverge significantly depending on post-pandemic recovery patterns and fisheries management decisions. The binary operability model—classifying ports as either fully operational or fully inoperative—is an additional simplification; in practice, partial operability at reduced capacity during marginal flooding is likely, implying that the model may underestimate cumulative economic disruption by excluding partial-service losses. Future iterations of this methodology should incorporate a graduated operability function sensitive to flood depth increments above the minimum freeboard threshold.

The social dimensions of port inoperability in Parita Bay exhibit structural parallels with Small Island Developing States (SIDS), where port loss represents an existential threat to community livelihoods (Albert et al., 2016). Unlike insular contexts, Parita Bay's continental setting offers greater feasibility for structural adaptation, yet coastal degradation continuously erodes community adaptive capacity (Yee et al. 2022). Therefore, mitigating the erosion of port viability is a policy imperative to safeguard local food security, shifting the focus from infrastructure repair to integrated social resilience strategies

The European experience with dynamic coastal risk management offers a transferable framework for differentiating adaptation strategies across Parita Bay's four terminals. The paradigm shift away from rigid coastal defenses in the Netherlands and Germany's Halligen islands (Schleswig-Holstein)—driven by the long-term unsustainability of hard engineering under accelerating SLR—has converged on integrated approaches combining structural upgrading, operational protocols, and managed retreat where protection costs exceed benefits (Amer, 2024; Magnan et al., 2022). Applied to the present findings, this framework suggests a differentiated portfolio of responses. Aguadulce, with the highest revenue base and the greatest structural freeboard (1.73 m), presents the strongest economic case for capital investment in quay elevation and structural reinforcement; the projected annual loss of USD 29,493 against a 2050 revenue of USD 190,306 implies a loss rate of approximately 15.5%, which likely falls within acceptable thresholds for infrastructure investment justification. Boca Parita and El Agallito, by contrast, exhibit revenue structures too thin to sustain large capital expenditures, suggesting that demand-side interventions—development of alternative landing sites, livelihood diversification programmes, and targeted social protection mechanisms—may generate higher social returns per unit of investment than structural protection alone. El Salado, excluded from financial projections due to the absence of AMP records, warrants priority attention as a qualitative vulnerability benchmark: its subsistence function and structural deterioration represent a compound social risk that conventional economic impact models do not capture.

These findings carry direct implications for Panama's national coastal planning framework. MiAmbiente's existing coastal vulnerability database (Instituto de Hidráulica Ambiental & Ministerio de Ambiente de Panamá, 2023b) provides the essential spatial foundation for adaptation planning, but the present study demonstrates that generic inundation mapping must be complemented by port-level operability modeling and revenue-based economic impact assessment to generate investment priorities that are both technically grounded and economically defensible. A significant gap in the current analysis—and a priority for future research—is the integration of input-output modeling to trace how port inoperability propagates through the regional economy via upstream and downstream linkages in fish processing, transportation, cold chain logistics, and retail distribution. Such an extended analysis would likely reveal that the USD 54,464 in direct annual losses identified here represent only a fraction of the total economic disruption attributable to SLR in the Parita Bay coastal system, strengthening the economic case for early and sustained adaptation investment.

6 Conclusions

This study integrated oceanographic, structural, and socioeconomic data within a GIS-based analytical framework to quantify the operational and economic impacts of sea level rise on four artisanal fishing ports in Parita Bay, Panama, by 2050. The results establish three principal findings. First, freeboard analysis confirms that all four terminals will be fully inundated under both SSP2-4.5 and SSP5-8.5 scenarios by 2050, with projected annual inoperability reaching approximately 215 days—roughly 59% of the year—representing a near-total functional collapse of port infrastructure across the bay. Aguadulce, while structurally the most resilient port owing to its 1.73 m freeboard, is not exempt: negative freeboard values under both scenarios confirm that structural advantage alone is insufficient without targeted intervention.

Second, the economic analysis reveals that direct annual losses are financially unsustainable relative to current revenue baselines. Aguadulce faces a loss-to-revenue ratio of approximately 43% against 2023 revenue, and Boca Parita approximately 69%—thresholds that would render continued operation economically untenable without structural protection. Cumulatively, the present value of inaction across the three quantified terminals approaches USD 770,000 by 2050, a figure that excludes indirect supply chain, fisheries, and welfare losses, which the literature suggests may amplify direct losses by a factor of 2–3.

Third, risk profiles are terminal-specific and require differentiated policy responses: Aguadulce warrants capital investment in quay elevation and structural reinforcement, while Boca Parita and El Agallito are better served by alternative landing site development, livelihood diversification, and targeted social protection programmes. El Salado, absent from financial projections due to data unavailability, represents an additional unquantified vulnerability with high social risk. These findings provide a replicable methodological framework—combining ROM 2.0-11 freeboard standards, CAGR revenue projection, and direct impact modelling—applicable to other artisanal port systems across Central America and the wider Caribbean. For national planners, the results reinforce the imperative to complement existing district-scale inundation mapping with port-level operability and economic assessments, and to establish formal revenue tracking at informal facilities such as El Salado, thereby closing the data gap that currently causes national adaptation cost estimates to be systematically underestimated.

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