Climate-Resilient Coastal Urban Planning through a Decision Support System (DSS)

Planification Urbaine Côtière Résiliente au Climat au Moyen d'un Système d'Aide à la Décision (SAD)

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RÉSUMÉ

Cette étude développe un Système d'Aide à la Décision (SAD) pour la planification urbaine côtière résiliente au climat, en intégrant la modélisation hydrodynamique, l'apprentissage automatique et l'analyse multicritère afin de hiérarchiser les stratégies d'adaptation urbaine face aux risques d'inondation et d'érosion. Le SAD opère dans des contextes à faible disponibilité de données, en combinant des informations physiques, environnementales et territoriales pour produire des cartes probabilistes de risque et des zonages stratégiques. La méthodologie inclut la modélisation couplée FLOW+SWAN, un Random Forest et une Réseau de Neurones Convolutionnel RNC pour les projections d'occupation du sol, la normalisation par logique floue, ainsi que la méthode TOPSIS associée à des simulations Monte Carlo pour classer des stratégies telles que les solutions fondées sur la nature, l'ingénierie douce, l'adaptation du bâti ou le repli planifié. Appliqués à Tumaco (Colombie), les résultats montrent que l'absence de modélisation physique surestime les zones à haut risque d'environ 284 ha, tandis que l'intégration des scénarios d'élévation du niveau de la mer identifie 52 ha supplémentaires nécessitant une intervention à long terme. Le SAD soutient une régulation du sol fondée sur l'évidence, anticipe les transformations spatiales liées au changement climatique et place l'eau au centre de la planification stratégique dans les villes côtières vulnérables.

ABSTRACT

This study develops a Decision Support System (DSS) for climate-resilient coastal urban planning by integrating hydrodynamic modeling, machine learning and multicriteria analysis to prioritize urban adaptation strategies under flood and erosion risk. The DSS operates in data-scarce environments, combining physical, environmental and territorial information to generate probabilistic risk maps and strategic zoning layers. Methods include coupled FLOW+SWAN modeling, Random Forest and Convolutional Neural Network CNN-based land cover projections, fuzzy logic normalization, and TOPSIS with Monte Carlo simulations to rank adaptation pathways such as nature-based solutions, soft engineering, built-environment adaptation and planned retreat. Applied to Tumaco (Colombia), results show that omitting physically based modeling overestimates high-risk areas by ~284 ha, while incorporating sea-level-rise scenarios identifies an additional 52 ha requiring long-term intervention. The DSS supports evidence-based land-use regulation, anticipates spatial transformations driven by climate change, and positions water as a central element for strategic urban planning in vulnerable coastal cities.

KEYWORDS

Adaptation strategies, Coastal urban planning, Decision Support System, Flood and erosion risk, Machine learning

1 INTRODUCTION

Coastal cities are increasingly exposed to flooding and erosion as a result of sea-level rise, wave climate intensification and morphological changes influenced by climate and urban transformation (Cruz-Ramírez et al. 2024; Hoque et al. 2021). In data-scarce regions, these dynamics hinder the development of strategic zoning and the prioritization of urban adaptation measures. To address this gap, a Decision Support System (DSS) is developed, integrating hydrodynamic modeling, machine learning, fuzzy logic and multicriteria analysis to characterize coastal risk and prioritize adaptation strategies under climate uncertainty (Glavovic et al. 2022; Narne et al. 2024; Rangel-Buitrago et al. 2018). This approach aligns with current calls to place water at the center of urban planning and land-use regulation in vulnerable coastal environments (Enríquez-Hidalgo et al. 2025; Narne et al. 2024; Terribile et al. 2024).

2 STUDY AREA

The study was conducted in Tumaco, a coastal city on the Colombian Pacific composed of low-lying islands highly susceptible to flooding and erosion. Urban expansion over intertidal and reclaimed zones has increased the exposure of population and infrastructure. Figure 1 shows the location of the study area, including Tumaco and El Morro islands, as well as the distribution of hydrometeorological stations and wave buoys used for the calibration and validation of the hydrodynamic and wave models.

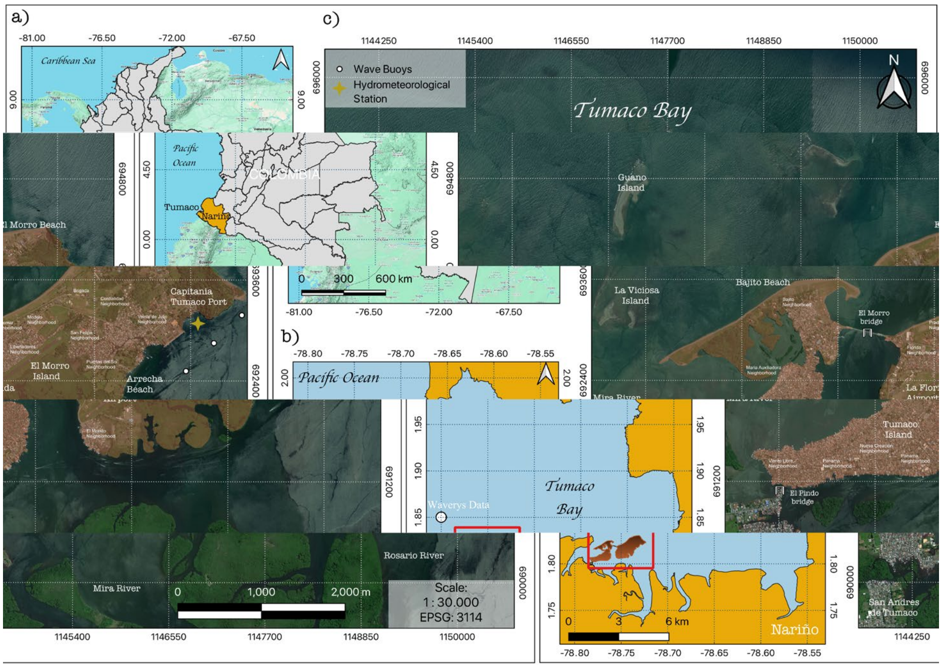

Figure 1. Study area location: a) Nariño department - Colombia, b) Tumaco-Nariño and c) Tumaco City

3 MATERIALS AND METHODS

The DSS is structured into four methodological components, with the overall framework presented in Figure 2.

3.1 Hydrodynamic and wave modeling

The coupled FLOW+SWAN model was used to simulate water levels, significant wave height, peak wave period and wave direction. These variables supported the generation of flood and erosion forcing scenarios under present and future conditions.

3.2 Remote sensing and machine learning

Thirty years of shoreline displacement were analyzed using CoastSat, complemented by a Random Forest model relating shoreline change rate to oceanic variables. Land use, human settlements and vegetation cover were classified using a ResNet convolutional neural network applied to Sentinel-2 imagery.

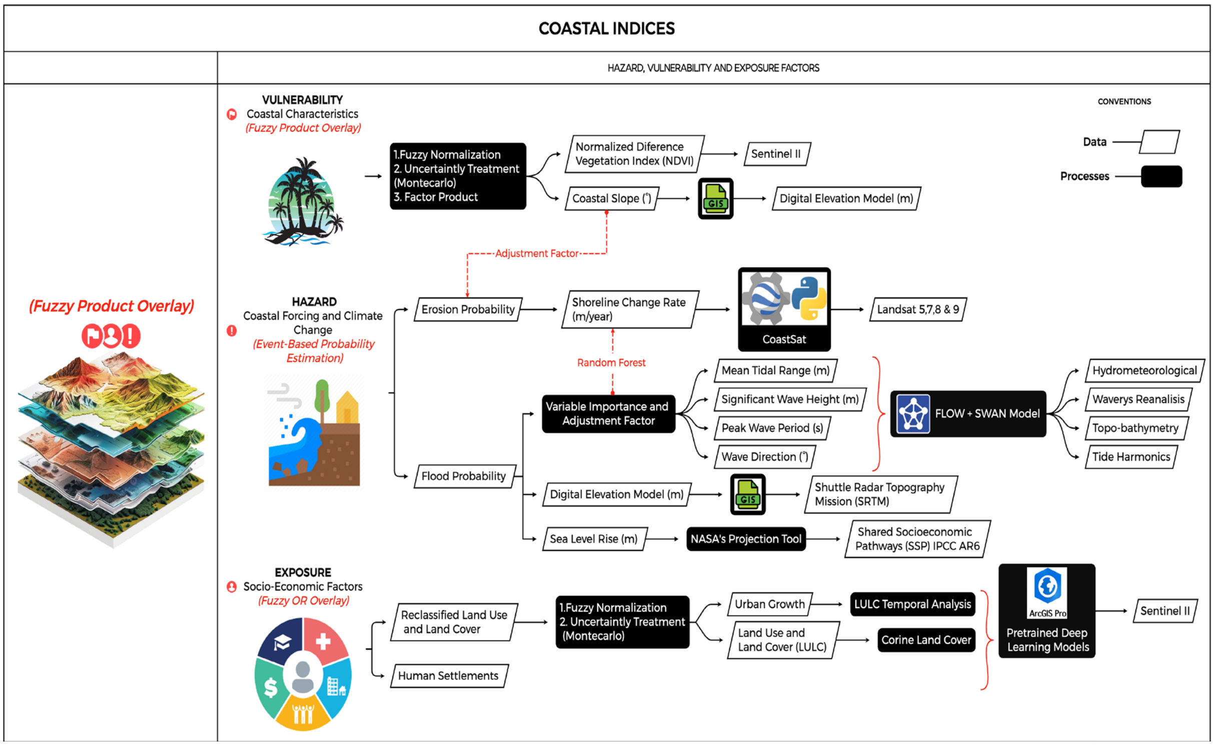

Figure 2. Framework for the characterization of coastal flood and erosion risk in data-limited context

3.3 Probabilistic risk index

Flooding and erosion risk were estimated using fuzzy normalization of vulnerability and exposure factors, combined through Monte Carlo simulations to represent uncertainty. The resulting continuous probabilistic index allows identification of spatial risk gradients based on shoreline retreat and island elevation.

3.4 Prioritization of urban adaptation strategies

Five strategies were evaluated: nature-based solutions, soft engineering, built-environment adaptation, planned retreat or advance, and hard engineering. Prioritization was performed using TOPSIS combined with Monte Carlo sampling, and strategies were spatially allocated according to risk levels, sea-level rise projections (SSP1-2.6, SSP2-4.5, SSP5-8.5) and expected land-use transitions.

4 RESULTS

The omission of physically based hazard modeling produces an overestimation of approximately 284 ha of land classified as high risk, confirming the importance of incorporating hydrodynamic processes into territorial planning. Table 1 summarizes the spatial distribution of urban adaptation strategies derived from the DSS. Nature-based solutions and built-environment adaptation dominate due to their suitability in densely populated areas and degraded but recoverable ecosystems. Under current conditions, approximately 4.6% of the territory requires intervention. By 2050 this increases to 12.7% (SSP2), and by 2100 ranges between 14.2% and 16% depending on sea-level-rise scenario. Figure 3 illustrates the spatial progression of areas requiring intervention under the SSP5 scenario for 2050 and 2100. These results allow anticipating significant urban transformations, informing land-use regulation and guiding investment in adaptation infrastructure.

Table 1. Spatial Allocation of Adaptation Solutions Across Scenarios Based on DSS Output

Scenario	**Nature Based**		**Soft Engineering**		**Built Environment**		**Do- Noting**	**Total Intervention Area**
	Area (ha)	% Area	Area (ha)	%Area	Area (ha)	% Area	Area (ha)	
Actual - 2024	1.70	0.22%	3.49	0.45%	30.92	4.00%	741.81	4.64%
SSP1 - 2050	3.31	0.43%	0.00	0.00%	58.00	7.50%	680.50	12.52%
SSP2 - 2050	3.37	0.43%	0.00	0.00%	59.41	7.64%	679.03	12.71%
SSP5 - 2050	3.41	0.44%	0.00	0.00%	61.14	7.86%	677.26	12.94%
SSP1 - 2100	4.05	0.52%	0.00	0.00%	64.57	8.30%	667.10	14.25%
SSP2 - 2100	4.51	0.58%	6.35	0.82%	70.45	9.10%	660.50	15.10%
SSP5 - 2100	4.91	0.63%	6.64	0.85%	76.71	9.86%	653.55	16.00%

Note: Each percentage refers to the share of total area (777.92 ha) assigned to a specific solution or to the aggregated intervention category under each scenario.

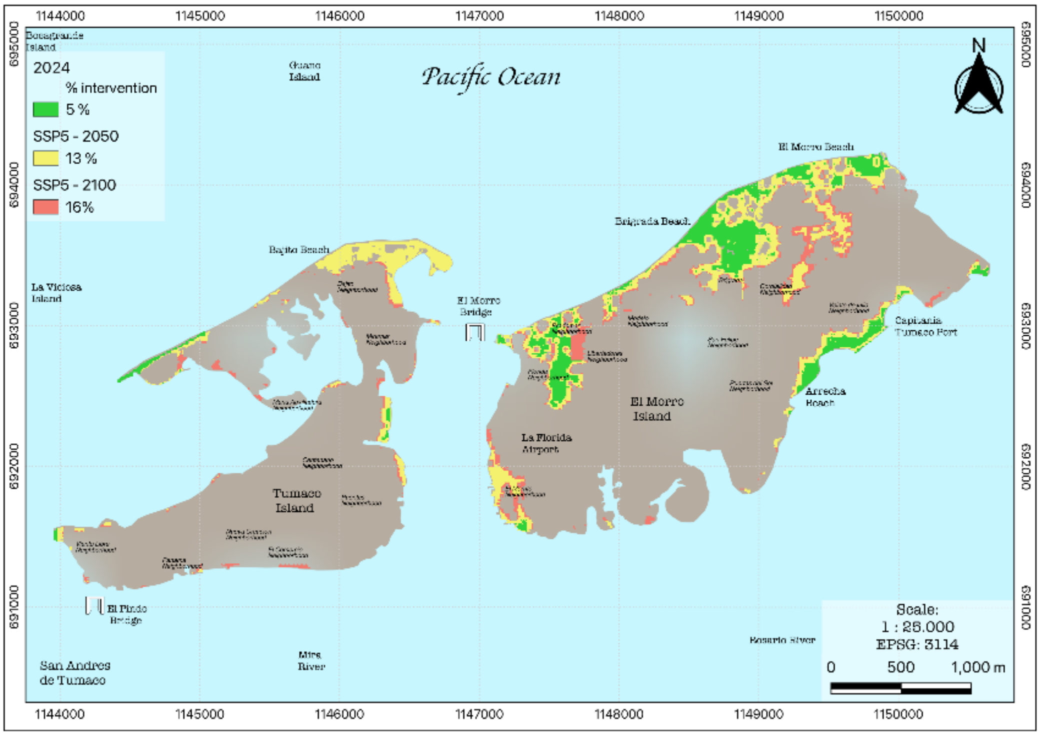

Figure 3. Spatial progression of critical areas requiring intervention under the SSP5 scenario for 2050 and 2100.

5 CONCLUSIONS

The DSS developed in this study provides an operational and flexible tool to integrate coastal dynamics and climate uncertainty into urban planning in data-limited contexts. The combination of hydrodynamic modeling, machine learning and multicriteria analysis enhances the identification of critical zones, supports evidence-based adaptation planning and strengthens land-use management under climate-change scenarios. Results demonstrate that placing water at the center of planning improves consistency between zoning, urban regulation and short-, medium- and long-term adaptation measures.

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