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Beyond Recovery: Land Use and Land Cover Change and the Shifting Value of Coastal Ecosystems in Banda Aceh

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ABSTRACT

Coastal landscapes represent some of the planet's most ecologically significant environments due to the wide range of ecosystem services they provide, including climate regulation, carbon sequestration, and flood mitigation. However, these landscapes are increasingly threatened by rapid urbanization and post-disaster reconstruction, which have led to environmental degradation and diminished sustainability. This study examines spatiotemporal changes in land use and land cover (LULC) and their implications for ecosystem service value (ESV) in the coastal zone of Banda Aceh, Indonesia, from 2015 to 2024, with projections to 2040. Using Sentinel-2 imagery, LULC classes were identified through supervised classification and assessed for change accuracy. Future landscape patterns were simulated using the CA–Markov model to estimate transitions among vegetation, wetland, and built-up areas. ESV was calculated, incorporating spatial and temporal dynamics. Results reveal a decline in built-up area, accompanied by reductions in wetland and vegetation cover, resulting in an estimated 10.5% reduction in total ESV between 2015 and 2024. Sensitivity analysis indicates that conversions from wetlands and vegetation to built-up land result in the most significant losses in ESV. Projections to 2040 suggest the potential for partial ecological recovery through the re-expansion of wetland areas. The study highlights the importance of integrating ecosystem-service valuation into spatial planning and coastal resilience strategies. More broadly, the findings provide an empirical framework for guiding sustainable land-use decision-making in post-disaster coastal cities across the Global South. This study provides a coastal-specific application integrating ESV estimation with CA–Markov-based projections, offering insights to support spatial planning in post-disaster coastal contexts.

1. INTRODUCTION

Coastal environments represent highly productive and biologically critical ecological systems. Shoreline protection, climate regulation, water and nutrient recycling, and the provision of fishery resources that local populations depend on are just a few of the ecosystem services they offer [1]. Both environmental stability and human well-being depend on these ecosystem services. Nevertheless, ecosystems of all types, including coastal ecosystems, are increasingly experiencing degradation as a result of extensive alterations to land use and land cover (LULC), driven by expanding urban sprawl, agricultural intensification, population growth, and a range of other anthropogenic stressors [2, 3]. Many coastal zones and ecosystems are losing functional capacity and biodiversity, resulting in diminished delivery of essential ecosystem services.

Due to limited spatial governance, the intense economic dependence on coastal ecosystems, and the prevalence of damaging environmental events, the transformation of coastal ecosystems in tropical developing countries has taken a paradigm shift more than in other regions [4]. Banda Aceh, which is located at the northern tip of Sumatra, Indonesia, is an interesting case. The Banda Aceh coastal Bashan landscape underwent drastic changes after the 2004 Indian Ocean tsunami, which had devastating effects on both the built and natural environments [5, 6]. In the following decades, extensive rebuilding and urban growth significantly altered the coast's landscape. These kinds of changes likely put increased stress on flood control, carbon storage, and biodiversity preservation, which, in turn, makes the ecosystem services people usually depend on and expect less reliable [7, 8].

Unfortunately, sustainable spatial planning and post-disaster recovery hinge on understanding how the changing coastal landscape is valued (in terms of the ecosystem services it provides). Most studies at the global to regional scales [9-11] have looked at the value of ecosystem services (ES) and LULC change, but integrating the smaller coastal area, both in terms of spatial and temporal scales, is still relatively absent. Every landscape responds to various development pressures in different ways [12]. Many existing studies focus on static assessments of ecosystem services, often overlooking the temporal dimensions of ecosystem service decline and recovery, thereby limiting understanding of long-term ecosystem service dynamics.

In the early stages of post-tsunami urbanization in Banda Aceh, many mangrove forests, wetlands, and other naturally vegetated areas have been turned into urban corridors [5, 13]. Furthermore, urbanization in the remaining naturally vegetated areas of the city has diminished the city's ecological capacity and weakened the natural barriers against coastal flooding and other extreme weather events [14]. These natural defenses are likely to worsen if there is no systematic research examining and comparing the links between changes in coastal land use and changes in ecosystem services. Consequently, the need for integrated approaches to spatially analyze various land-use patterns, value ecological systems, and use forecasting instruments for urban development and environmental policy remains.

This research addresses these gaps by examining how the coastal environment changes across time and space, and how these changes affect the value of ecosystem services in Banda Aceh over the period 2015 to 2040. The study employs high-resolution satellite imagery, CA-Markov modelling, and the economic valuation of ecosystem services to present the first comprehensive framework for evaluating and forecasting the ecological consequences of land-use changes in post-disaster coastal areas. More precisely, the objectives of the study were to: (1) ascertain the pattern of spatial LULC change from 2015 to 2024, (2) analyze the change in ESV over the same time frame, (3) forecast the land cover and ESV configuration for 2040, and (4) analyze the ESV land conversion impact and land cover scenario for 2040. The novelty of this research lies in its application of dynamic, multi-temporal modeling in a coastal city that natural disasters and socio-economic recovery have significantly shaped. The results enhance our understanding of how coastal ecosystems can recover and provide valuable guidance on utilizing ESV measurements in Indonesia and other developing coastal areas.

2. MATERIAL AND METHODS

2.1 Study location

The study area encompasses Banda Aceh City's coastal area and one of its newly developed peri-urban zones, the Banda Aceh Growth (Figure 1). Located in the northernmost part of the island of Sumatra, Indonesia, the research area extends between 5° 16' 15" - 5° 36' 16" N and 95° 16'15" - 95° 22' 35" E. The area is flat, with an average elevation of 0.8 meters above sea level, making it more vulnerable to tsunamis and tidal flooding. Banda Aceh's population was approximately 257,635 in 2022 (BPS, 2022), and it has grown over the past few decades, placing pressure on land development. The region's tropical monsoonal climate, characterized by coastal wetlands, mangroves, and riparian vegetation, supports a rich biodiversity. However, much of this natural vegetation has been converted to urban and barren land, mainly due to urban development and post-tsunami reconstruction.

Moreover, Banda Aceh is situated within an ecotone, integrating land and sea. The city's coastal lowlands and plains comprise a complex, ecologically important system of wetlands, estuaries, reclaimed land, and rivers. This landscape is environmentally important and sensitive to human impacts. Banda Aceh thus offers a valuable opportunity to examine the effects of rapid LULC change on the ESV, particularly in a post-disaster coastal environment.

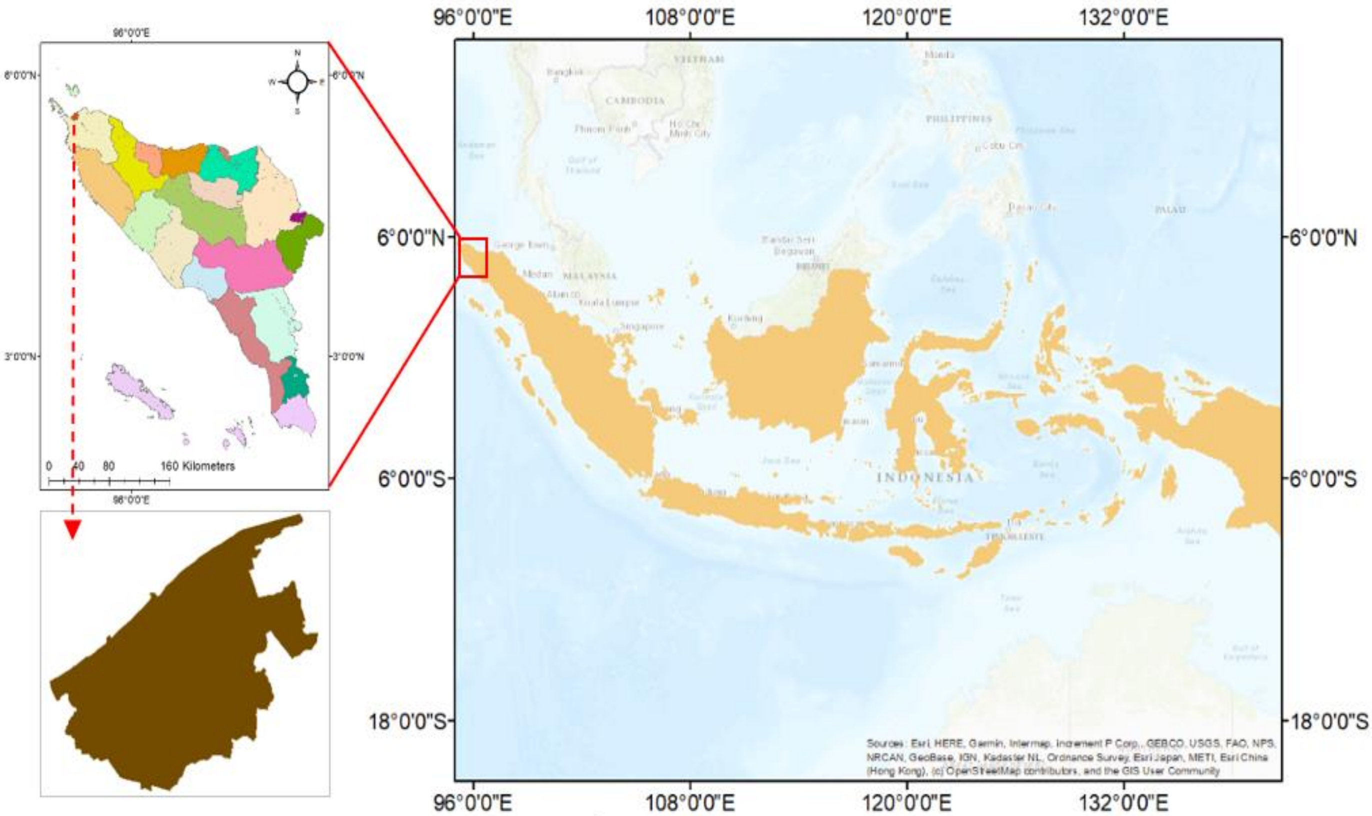

Figure 1. Study location

2.2 Data sources and materials

The study employed multi-temporal remote sensing data combined with socio-economic and ecological information. Satellite Imagery: High-resolution optical imagery from 2005 and 2024 was used as the primary data source. Sentinel-2A imagery (10–20 m resolution) captured detailed LULC dynamics. Image acquisition and pre-processing were performed using the Google Earth Engine (GEE) platform, applying a cloud cover threshold of less than 10% to ensure image quality and minimize atmospheric interference. It offers enhanced spectral differentiation through 13 bands, particularly effective in identifying vegetation, water bodies, and built-up surfaces. Supporting Data:

(1) Statistical datasets (population, built-up growth, and GDP) from BPS Banda Aceh (2022).
(2) Reference data for ecosystem service coefficients [15, 16], and updated regional studies [17, 18].
(3) Software: All geographic studies were conducted using geographic monitoring and modeling (GMM) software, augmented by ArcGIS Pro 3.0 for visualization and Excel/SPSS for descriptive statistics and sensitivity analysis.

2.3 Land use and land cover classification and accuracy assessment

Generally, LULC classification was accomplished using supervised classification with the maximum likelihood and multi-temporal analysis technique [19]. Following visual interpretation and field verification, five primary LULC categories were established: built-up area (BA), vegetation (V), wetland (WL), bareland (BL), and waterbody (WB). However, small waterbodies with limited spatial extent and spectral similarity to adjacent LULC were incorporated inti wetland and/or vegetation classes. Training samples were created from composite spectral signatures and later confirmed against reference data and Google Earth images. A stratified sampling approach was applied to ensure representative training samples for each LULC class.

To assess classification reliability, an error matrix was generated and validated for each temporal period (2015 and 2024) using stratified random sampling [20]. The two principal accuracy measurements were:

$$Overall\ accuracy = \frac{\mathrm{N_{AA} + N_{BB} + N_{CC}}}{\mathrm{N}} \times 100\% \tag{1}$$

where, N_{AA}, N_{BB}, and N_{CC} are the correctly classified samples for classes A, B, C, respectively, and N is the total number of validation samples.

$$Kappa = \frac{\mathrm{N}\ \sum_{j=1}^{k} \mathrm{N_{jj}} - \sum_{j=1}^{k} \mathrm{N_{jR} N_{Pj}}}{\mathrm{N}^2 - \sum_{j=1}^{k} \mathrm{N_{jR} N_{Pj}}} \tag{2}$$

where, K is the Kappa coefficient, N is the total number of validation samples, N_{jj} is the number of correctly classified samples in class j, N_{jR} is the row total for class j, and N_{pj} is the column total for class j.

All years displayed overall accuracy of more than 90%, while Kappa values indicated "substantial agreement," indicating that the classification results were appropriate for the planned geographical and statistical analysis. Kappa values above 0.8 indicate strong agreement and confirm the robustness of the classification results. The most substantial classification errors occurred between marshes and woody vegetation, likely due to their spectral overlap during transitional seasons.

2.4 Ecosystem services assessment

Costanza et al. [15] established the foundational framework for ecosystem service valuation, which was later elaborated and advanced [16, 21]. Each LULC classification was assigned an ecosystem service valuation coefficient (USD ha^{-1} yr^{-1}), indicating the approximate annual monetary value of the associated ecosystem services. Valuation focused on nine primary ecosystem functions: gas regulation, climatic regulation, water supply, soil formation, waste disposal, biodiversity protection, food provision, provision of raw materials, and recreation/culture.

The ESV coefficients applied in this study were adapted from global valuation studies and adjusted to reflect regional conditions, with each LULC category matched to its closest equivalent ecosystem type (e.g., vegetation to forest, wetlands to coastal/wetland systems, and water bodies to aquatic systems).

To compute the total ESV for each LULC category, the following formula was used:

$$\mathrm{ESVi} = \Sigma\ (\mathrm{Vij} \times \mathrm{Ai}) \tag{3}$$

where, *ESVi* represents the ecosystem service value associated with LULC category i, *Vj* denotes the value coefficient of ecosystem service function j, and *Ai* refers to the area of LULC category i expressed in hectares.

The value of services provided by each ecosystem function is calculated by multiplying the respective ES coefficient by the corresponding land area for each period (Eq. (4)).

$$\mathrm{ESVf} = \Sigma\ (\mathrm{Ai} \times \mathrm{Vfi}) \tag{4}$$

where, *ESVf* is represents the ecosystem service value generated by ecosystem service function f, *Ai* refers to the area of LULC category i, and *Vf* denotes the corresponding value coefficient value coefficient for ecosystem service function f associated with LULC category i.

The change in ESV is determined by calculating the difference between the estimated ESV values for each reference year. ESV is expressed in rupiah and as a percentage for a comprehensive understanding of the changes that occur. All monetary values were standardized to a consistent unit and period to ensure comparability across time. The change in ESV is calculated based on Eq. (5).

$$\text{Change of ESV (\%)} = \frac{\mathrm{ESV_{t2}} - \mathrm{ESV_{t1}}}{\mathrm{ESV_{t1}}} \tag{5}$$

where, ESV_{t1} and ESV_{t2} denote the ecosystem service values (ESV) at the initial and subsequent assessment periods, respectively.

2.5 Prediction to land use and land cover 2040

To estimate future LULC dynamics, the CA-Markov model was applied [22, 23]. This hybrid model combines the Markov chain's capacity to predict transition probabilities between classes with the spatial contiguity principles of cellular automata, creating spatially explicit LULC maps. The transition probability matrix was derived from observed LULC changes between 2015 and 2024. The probability of transition between land cover states was defined as Eq. (6).

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1k} \\ p_{21} & p_{22} & \cdots & p_{2k} \\ \cdots & \cdots & \cdots & \cdots \\ p_{k1} & p_{k2} & \cdots & p_{kk} \end{bmatrix} \quad (6)$$

where, P represents the transition probability matrix, P_{11}, P_{12}, …, P_{kk} indicates the probability of transition among LULC classes, and k is the total number of LULC classes.

2.6 Cross-sensitivity

To assess ESV's sensitivity to specific forms of land-use change, a cross-sensitivity index (CSI) [24] was used.

$$\mathrm{CSI}_{jk} = \frac{\Delta \mathrm{ESV}/\mathrm{ESV}}{\Delta \mathrm{Ajk}/(\frac{\mathrm{Aj}+\mathrm{Ak}}{2})} \quad (7)$$

where, CSI_{jk} represents the cross-sensitivity index, ΔESV is the change in ecosystem service value, ΔAjk is the converted area between LULC classes j and k, and Aj and Ak denote the areas of the respective classes. ESV will increase due to net conversion from land use type j to k, while a negative CSI_{jk} implies the opposite relationship. The larger the CSI_{jk}, the more sensitive the ESV response to LULC changes.

3. RESULT

3.1 Accuracy assessment of land use and land cover classification

As a primary starting point for all spatial and valuation studies, assessing the accuracy and reliability of the LULC classification, along with its implementations, was performed for the years 2015 and 2024 through stratified random sampling and a confusion matrix framework, achieving an overall accuracy of 90.53% and 94.12% (Table 1) respectively, both of which lie within the acceptable range for high quality analysis of remote sensing data [25]. Kappa coefficients revealed high levels of agreement (substantial:> 0.85) and significant correspondence between the categorized and reference data. The primary misclassification occurred between the wetland and vegetation classes due to their similar spectral signatures, particularly during the transition period between the dry and wet seasons. Conversely, the built-up and waterbody classes were slightly confused, demonstrating precise spectral separation in Sentinel-2A imagery, notably in the NIR and SWIR bands.

These findings further demonstrate that the Geospatial Monitoring and Modelling (GMM) platform's supervised classification produced reliable data for spatiotemporal analysis of coastal change during the specified period. The resulting overall accuracy values validate the classification outputs as appropriate for assessing land-cover transformations and for estimating the corresponding shifts in ESV arising from these changes.

Table 1. Error matrix

Classified Data	Reference Data					Total	Error
	Vegetation	Waterbody	Built-up Area	Bareland	Wetland		
			(a) 2015				
Vegetation	51	0	0	0	0	51	0.000
Waterbody	0	45	0	0	3	48	0.063
Built-up area	0	0	18	2	0	20	0.042
Bareland	0	0	5	23	1	29	0.207
Wetland	3	0	1	1	16	21	0.238
Total	54	45	24	26	20	169	
Error	0.056	0.000	0.250	0.115	0.200		
Overall classified accuracy (%)						**= 90.5325444**	
			(b) 2024				
Vegetation	53	0	0	0	0	53	0.000
Waterbody	0	42	0	0	0	42	0.000
Built-up area	0	0	20	1	0	21	0.024
Bareland	0	1	3	25	2	31	0.194
Wetland	1	1	1	0	20	23	0.130
Total	54	44	24	26	22	170	
Error	0.019	0.045	0.167	0.038	0.091		
Overall classified accuracy (%)						**= 94.1176471**	

3.2 Spatial dynamics of coastal land use (2015–2024)

Banda Aceh's coastal landscape underwent significant developments from 2015 to 2024. LULC change analysis indicates that the most significant changes over the 2015-2024 period were the extensive conversion of natural environments to developed urban landscapes and the ongoing expansion of built-up areas, as shown in Figures 2 and 3. The built-up area increased from 659.29 ha to 711.42 ha, indicating continued urban expansion. In contrast, natural environments experienced substantial decline. Vegetation cover decreased from 375.18 ha to 305.28 ha, representing a reduction of approximately 19%. Similarly, wetland areas declined from 394.14 ha to 286.08 ha, corresponding to a decrease of 27.4% over the study period.

Moreover, the increase from 210.54 ha to 274.35 ha in land cleared of woody vegetation indicates an increase in land under active or significant approval for use as operational land for construction and other purposes. The rise of 536.15 ha to 598.35 ha in the waterbody category was moderate. The increase resulted from artificially constructed waterbodies, including post-tsunami flood basins and other constructed waterbodies.

From a spatial perspective, persistence mapping revealed that waterbody and wetland classes remained largely stable in the western and northern portions of the study area. In contrast, the southern and central urban zones were characterized by a rapid transformation of vegetated land into built-up areas. These findings were also supported by the cross-tabulation map, which showed that the most prevalent conversions were from vegetation to built-up areas and from wetlands to built-up areas, underscoring urbanization as the primary driver of land transformation. Such transitions illustrate a gradual yet persistent shift from ecological to anthropogenic land uses, a trajectory commonly observed in coastal cities undergoing early stages of post-disaster recovery.

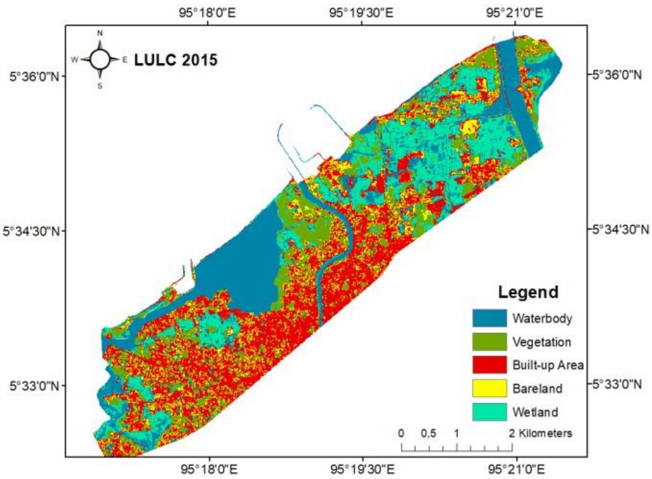

Figure 2. Land use and land cover (LULC) in 2015

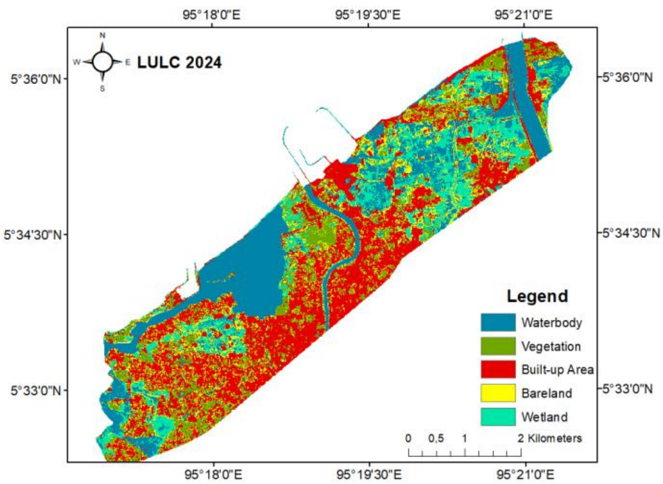

Figure 3. Land use and land cover (LULC) in 2024

3.3 Land use and land cover projections for 2040

According to the CA–Markov projections for 2040, urban expansion is anticipated to continue and increasingly dominate the spatial pattern of land usage, as shown in Figure 4. Predicted area classifications indicate that built-up areas will extend to about 745 ha, while vegetated areas will decline to 236 ha. Notably, wetland area recovery is expected to reach 395 ha, which may be attributable to sedimentation or to local authority restoration initiatives. This indicates that the ecological functions of some wetland patches are reactivated through ecological rebalancing following previous disturbances. However, the total proportion of ecological land cover remains below 2015 levels, indicating that urban expansion continues to exceed the capacity of natural regeneration to replenish it (Figure 5).

Predictions for 2040 indicate that built-up urban areas are spatially clustering along the coast near the Ulee Lheue and Meuraxa sub-districts. However, some remnants of verdant patches are retained along the northern coastal margins. The validated simulation Kappa score of greater than 0.85 indicates that the simulation results are reliable, providing a reasonable expectation that the landscape contours will follow these predictions if the current pace of development continues.

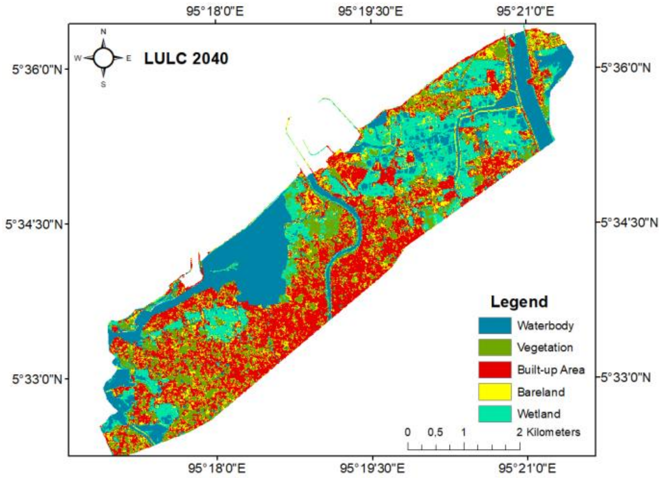

Figure 4. Land use and land cover (LULC) for 2040

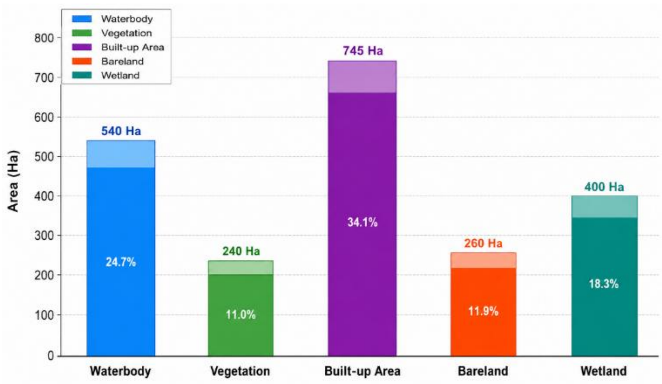

Figure 5. Prediction of land use and land cover (LULC) for 2040

3.4 Changes in ecosystem service value

ESV assigned to each LULC class demonstrates, and is replicated at total scales, a significant decline in ecological benefits during 2015-2024, which correlates with the loss of vegetated areas and wetlands. The estimated value for the coastal zone of Banda Aceh was $13.03 million in 2015, $11.47 million in 2024, and $12.11 million in 2040, resulting from partial wetland recovery. The predictions for 2040 indicate a partial wetland recovery, as the value remained stable over these years.

According to the breakdown by LULC category, wetlands made the most significant contribution to total ESV (approximately 45–50%), followed by vegetation (25–30%) and water bodies (20–22%). In contrast, built-up and bareland areas had negligible contributions to total ESV, further demonstrating the ecological cost of urban sprawl. The total ESV decline of 10.5% from 2015 to 2024 amounts to approximately $1.56 million per year in lost ecosystem services, primarily due to the loss of flood regulation, carbon sequestration, and habitat protection. The partial recovery in 2040 indicates the potential for ecosystem restoration, provided that strategically vegetated and wetland areas are maintained through adaptive land management practices.

These results clearly demonstrate the inverse relationship between urban expansion and the decline in ecosystem service capacity, reinforcing the urgency of integrating ESV-based metrics into the criteria and thresholds used for land-use planning and environmental management.

3.5 Cross-sensitivity analysis of land conversion impacts

The cross-sensitivity (CS) analysis quantified the impact of different land conversions on Banda Aceh's coastal landscape from 2015 to 2024. Negative sensitivity coefficients indicate that the conversions cause a loss in ESV, and positive sensitivity coefficients indicate an ESV gain.

The transition from vegetation to built-up land had the most substantial negative KSS value of -0.911, indicating the greatest reduction in overall ESV among all land-use conversions. A wetland-to-built-up conversion also yielded a KSS of -0.600, reflecting a severe loss of ecosystem function. The remaining two conversions, vegetation to bareland at 0.421 and wetland to waterbody at -0.444, had more moderate adverse effects on ESV, but still had negative impacts.

These results confirm findings from other areas of the world where urban development is the most important factor driving loss of ESV [14, 26]. In Banda Aceh, other scarce conversion opportunities, such as fully vegetated land or wetland ecosystems, were utilized to support ESV recovery.

The loss of vegetation and wetland cover is the most destructive form of land conversion in low-lying coastal areas, where these ecosystems play a significant role in flood storage, carbon sequestration, and habitat provision.

4. DISCUSSION

4.1 Linking land use and land cover dynamics and coastal urbanisation

This study's findings reveal that a substantial portion of the Banda Aceh coast is undergoing rapid change, characterized by the expansion of the developed environment and the loss of vegetation and wetlands. These shifts are congruent with global patterns of coastal urbanization, in which towns in the developing world face the dilemma of rapid coastal development alongside demands for economic growth and environmental conservation [3].

The 7.9% increase in built-up land area between 2015 and 2024 reflects the ongoing post-disaster reconstruction trajectory of Banda Aceh, which has continued to evolve since the 2004 tsunami. In the immediate post-disaster recovery period, land reclamation and housing development were key priorities to accommodate the displaced population and stimulate the economy [5, 13]. However, such urban growth has been accompanied by a steady decline in natural landscapes that previously functioned as buffers against coastal hazards.

Transforming multiple patches of wetlands and vegetation into urban uses reduces ecological resilience by altering hydrological interconnections, degrading soil hydrological properties and firmness, and increasing surface runoff [27, 28]. It can lead to increased flood risk, higher temperatures, and a possible intensification of the urban heat island effect [29-31]. The loss of 19% of vegetation and approximately 27% of wetlands in less than 10 years indicates severe pressure from post-disaster urban recovery, which can undermine the long-term prospects for environmental recovery [32].

4.2 Ecosystem service value losses and their impacts on the environment

The estimated 10.5% decline in total ESV between 2015 and 2024 underscores the significant economic and ecological consequences of urban sprawl. The associated loss of approximately 1.56 million USD per year in ecosystem services due to urban sprawl reflects the diminished capacity of coastal ecosystems to deliver critical functions, including flood regulation, carbon sequestration, and habitat protection [1].

The high contribution of wetlands and vegetation to total ESV is consistent with findings in the global literature [15-17], attributing high ecological productivity to multifunctionality. In Banda Aceh, these land types have historically served as natural drains and filters to remove and mitigate floods and tides; their degradation means, among other things, the loss of ecosystems. It also contributes to the significant socio-economic burdens faced by urban populations in low-lying areas.

The slight expected ESV rebound in 2040, due to partial wetland regeneration, demonstrates ecological self-recovery, albeit minimal, within the context of natural sedimentation or community-based restoration activities. However, this recovery is likely unregulated, lacking systematic policy initiatives, and insufficient to offset prevailing urban development. The phenomenon has been well documented in other tropical deltas, where opposing spontaneous ecosystem regeneration and development are substantial [4].

The changes in LULC and ESV over time in Banda Aceh align with prior regional works [33], which describe a decrease in vegetation cover and an increase in surface temperature within the post-tsunami urban core. Likewise, a significant spatial link has been found between the intensity of land conversion and the loss of carbon stocks in the coastal areas of Aceh [34].

In a global context, Banda Aceh's ESV decline (10.5%) is modest, yet significant enough to indicate that urbanization has increased. However, the remaining ecological capacity is available for urbanization to some extent. A 23% loss in the ESV of the Ethiopian Rift Valley due to extensive agriculture [12], while a 12–14% loss in ESV in peri-urban areas of Europe [9]. Ongoing restoration activities, natural sediment accumulation, and the biosphere of the wetland ecosystem along protected estuarine corridors may explain Banda Aceh's comparatively lower ESV decline.

Rapid biophysical feedbacks are observed in Banda Aceh, a tropical coastal city. Consequently, rational land-use changes may lead to disproportionate environmental impacts. Hence, understanding the ecological changes in ESV in the region, influenced simultaneously by climate change, urbanization, and sea-level rise, requires continued observation [4].

4.3 Policy implications for spatial planning

This research greatly adds to Indonesia's environmental and spatial policies. Spatial planning regulatory papers, such as Regional Spatial Plan of Banda Aceh City 2009-2029 and Detailed Spatial Plan of Banda Aceh City 2021-2041. and incorporating ESV evaluations will help create a balance between ecological protection and economic development. Currently, many Indonesian spatial plans prioritize land allocation for development and infrastructure, often with limited consideration for the environmental consequences of land conversion. Incorporating ESV into planning processes can help planners and decision-makers more effectively recognize the trade-offs inherent in alternative land-use options. For instance, sensitivity and cross-impact analyses can support the delineation of "no-conversion zones" in wetlands or vegetated areas that are essential for maintaining critical ecological functions.

Furthermore, the combined use of CA-Markov modelling and ESV quantification methods offers a decision-support system in practice. It allows planners to assess potential land-use changes and analyze the ESV consequences before implementing spatial policies. Predictive modelling of this nature aligns with the low-carbon development and coastal resilience priorities outlined in Indonesia's 2025–2029 National Medium-Term Development Plan.

This is also true within the United Nations' Sustainable Development Goals (SDGs) global policy framework, specifically Goals 11 (Sustainable Cities and Communities) and 15 (Life on Land). Integrating ESV into the spatial planning process supports evidence-based decision-making to achieve a reasonable level of ecological equilibrium during urban development [35].

4.4 Limitations and future research

Despite this study's excellent marriage of spatial modelling and ecological valuation, certain limitations should be acknowledged. The ecological valuation and modelling used valuation factors derived mostly from global datasets [15], which may not fully capture local economic and cultural contexts. Future studies should focus on constructing those coefficients using localised socio-ecological datasets.

Second, while the CA–Markov model has demonstrated strong performance in capturing land-use dynamics within defined spatial boundaries and temporal sequences, it remains constrained by its reliance on replication. In reality, land-use changes are driven by a complex interplay of regulatory frameworks, economic shifts, and community behaviors, many of which fall outside the model's capacity to capture. Incorporating agent-based models (ABMs) or machine learning approaches could better simulate the underlying decision-making processes, thereby improving the model's predictive power.

Third, the ESV estimation in this study has provided an analysis and value primarily for ecosystem services in the provisioning and regulating domains, with limited attention given to cultural and supporting services, such as aesthetic, spiritual, and recreational values within and surrounding the study area. These underrepresented service categories are nonetheless critical to holistic and comprehensive ecosystem service valuation and should therefore be systematically incorporated in future studies.

Finally, long-term ecosystem assessment will be strengthened through the continuous monitoring afforded by multi-sensor observation systems, thereby enhancing the precision with which land-cover changes are detected and characterized. Revitalized traditional methods, alongside contemporary approaches, should be utilized to assess the effectiveness of different monitoring techniques and to enhance their efficiency within adaptive management frameworks.

Dual transitions characterise the coastal system of Banda Aceh: rapid changes in the urban landscape occur alongside slower changes in the ecosystems. The decline in ESV provides evidence that the balance has tilted toward ecological post-disaster reconstruction; however, the soft recovery of the wetlands suggests some level of resilience.

This duality highlights a broader pattern across coastal Southeast Asia, underscoring the need for development and conservation to work in tandem within the constraints of space and institutional limitations. The combination of spatial modelling and ecosystem valuation provides a way to address some of this conflict. After all, the only way to maintain the coastal landscape of Banda Aceh while preserving its ecological integrity is to adopt ESV-informed, constrained spatial governance that incorporates ecological metrics into zoning and land-use decisions.

5. CONCLUSIONS

This study evaluated the patterns and implications of LULC changes and the dynamics of ESV in Banda Aceh's coastal area from 2015 to 2040. It integrates remote sensing analysis, CA-Markov modelling, and economic evaluation to demonstrate the significant impact of rapid spatial and functional disasters on post-disaster urbanisation in the coastal area of Banda Aceh.

Between 2015 and 2024, the impacts of urbanisation were evident. Built-up environments decreased by nearly 8%, while vegetation and wetlands declined by approximately 19% and 27%, respectively. Overall, the spatial changes resulted in a 10.5% decline in ESV functional capacity. The average annual loss from ecosystem services is 1.56 million USD. It is no surprise that regulating wetlands and vegetation yielded the most outstanding total ESV, and that the most significant losses occurred in areas that provide critical climate regulation, flood control, and support for emergent biodiversity.

The CA–Markov projection for 2040 continues to show potential urban expansion, but wetland areas will also recover, suggesting limited ecological self-regulation. Moreover, the CS analysis revealed that transitions from vegetation and wetlands to built-up land have the most significant negative impact on ecosystem services, reinforcing the need for strengthened land-use regulation to safeguard ecologically high-value areas.

The findings depict a picture of Banda Aceh's coastal environment undergoing physical development of the metropolis, accompanied by a degree of further ecological self-regulation. This fact necessitates the inclusion of ESV-centric metrics in spatial plans, including the spatial regional plan and detailed spatial plan of Banda Aceh City, to address development challenges and facilitate strategic planning for urban expansion and urban-rural connections.

From a different perspective, this study demonstrates that spatial simulation models incorporating ESV are viable tools for informing coastal resilience and post-disaster coastal management strategies. Future efforts could further integrate local ecological data to enhance value coefficients, examine land-use patterns for cultural and supporting services, and apply advanced modelling tools to incorporate policies and land-use change behaviours.

This study further establishes the groundwork for the sustainable spatial planning of ecosystem services by integrating the ecological and economic impacts of transformative landscape changes. Ecosystem services should be regarded as important infrastructure sustaining the resilience and livability of urban coastal areas, such as Banda Aceh.

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REFERENCES

[1] Lester, S.E., Dubel, A.K., Hernán, G., McHenry, J., Rassweiler, A. (2020). Spatial planning principles for marine ecosystem restoration. Frontiers in Marine Science, 7: 328. https://doi.org/10.3389/fmars.2020.00328

[2] Gunnell, K., Mulligan, M., Francis, R.A., Hole, D.G. (2019). Evaluating natural infrastructure for flood management within the watersheds of selected global cities. Science of the Total Environment, 670: 411-424. https://doi.org/10.1016/j.scitotenv.2019.03.212

[3] Liu, Z.H., Huang, Q.D., Yang, H.Y. (2021). Supply-demand spatial patterns of park cultural services in megalopolis area of Shenzhen, China. Ecological Indicators, 121: 107066. https://doi.org/10.1016/j.ecolind.2020.107066

[4] Bhowmik, K., Padmanaban, R., Cabral, P., Romeiras, M.M. (2022). Global mangrove deforestation and its interacting social-ecological drivers: A systematic review and synthesis. Sustainability, 14(8): 4433. https://doi.org/10.3390/su14084433

[5] Achmad, A., Hasyim, S., Rangkuti, B., Aulia, D.N. (2015). Spatial relationship between city center and economic activity center on urban growth in tsunami-prone city: The case of Banda Aceh, Indonesia. Jurnal Teknologi, 75(1): 47-53. https://doi.org/10.11113/jt.v75.2653

[6] Wardana, M., Achmad, A., Idawati, D.E. (2021). Coastal residential landscape model to support disaster risk reduction. Journal of Physics: Conference Series, 1882(1): 012160. https://doi.org/10.1088/1742-6596/1882/1/012160

[7] Achmad, A., Burhan, I.M., Zuraidi, E., Ramli, I. (2020). Determination of recharge areas to optimize the function of urban protected areas on a small island. IOP Conference Series: Earth and Environmental Science, 452(1): 012104. https://doi.org/10.1088/1755-1315/452/1/012104

[8] Wang, Q., Xu, Y.P., Cai, X.T., Tang, J.Y., Yang, L. (2021). Role of underlying surface, rainstorm and antecedent wetness condition on flood responses in small and medium sized watersheds in the Yangtze River Delta region, China. Catena, 206: 105489. https://doi.org/10.1016/j.catena.2021.105489

[9] Van De Voorde, T., van der Kwast, J., Poelmans, L., Canters, F., et al. (2016). Projecting alternative urban growth patterns: The development and application of a remote sensing assisted calibration framework for the Greater Dublin Area. Ecological Indicators, 60: 1056-1069. https://doi.org/10.1016/j.ecolind.2015.08.035

[10] Xie, Z.L., Li, X.Z., Chi, Y., Jiang, D.G., Zhang, Y.Q., Ma, Y.X., Chen, S.L. (2021). Ecosystem service value decreases more rapidly under the dual pressures of land use change and ecological vulnerability: A case study in Zhujiajian Island. Ocean & Coastal Management, 201: 105493. https://doi.org/10.1016/j.ocecoaman.2020.105493

[11] Basconi, L., Rova, S., Stocco, A., Pranovi, F. (2023). Ecosystem services for supporting coastal and marine resources management, an example from the Adriatic Sea (Central Mediterranean Sea). Ocean & Coastal Management, 235: 106486. https://doi.org/10.1016/j.ocecoaman.2023.106486

[12] Assefa, W.W., Eneyew, B.G., Wondie, A. (2021). The impacts of land-use and land-cover change on wetland ecosystem service values in peri-urban and urban area of Bahir Dar City, Upper Blue Nile Basin, Northwestern Ethiopia. Ecological Processes, 10: 39. https://doi.org/10.1186/s13717-021-00310-8

[13] Syamsidik, Rasyif, T.M., Kato, S. (2015). Development of accurate tsunami estimated times of arrival for tsunami-prone cities in Aceh, Indonesia. International Journal of Disaster Risk Reduction, 14: 403-410. https://doi.org/10.1016/j.ijdrr.2015.09.006

[14] Rahman, M., Szabó, G. (2021). Impact of land use and land cover changes on urban ecosystem service value in Dhaka, Bangladesh. Land, 10(8): 793. https://doi.org/10.3390/land10080793

[15] Costanza, R., d'Arge, R., de Groot, R., Farber, S., et al. (1997). The value of the world's ecosystem services and natural capital. Nature, 387: 253-260. https://doi.org/10.1038/387253a0

[16] de Groot, R.S., Alkemade, R., Braat, L., Hein, L., Willemen, L. (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecological Complexity, 7(3): 260-272. https://doi.org/10.1016/j.ecocom.2009.10.006

[17] Guo, R.Z., Lin, L., Xu, J.F., Dai, W.H., Song, Y.B., Dong, M. (2023). Spatio-temporal characteristics of cultural ecosystem services and their relations to landscape factors in Hangzhou Xixi National Wetland Park, China. Ecological Indicators, 154: 110910. https://doi.org/10.1016/j.ecolind.2023.110910

[18] Simeon, M., Wana, D. (2024). Impacts of land use land cover dynamics on ecosystem services in Maze National Park and its environs, southwestern Ethiopia. Heliyon, 10(9): e30704. https://doi.org/10.1016/j.heliyon.2024.e30704

[19] Tadesse, T., Berhanu, Y., Gitima, G., Kassie, M., Jakubus, M. (2024). Impacts of land use and cover changes on ecosystem service values from 1992 to 2052 in Gena District, Southwest Ethiopia. Scientific African, 24: e02244. https://doi.org/10.1016/j.sciaf.2024.e02244

[20] Olofsson, P., Foody, G.M., Herold, M., Stehman, S.V., Woodcock, C.E., Wulder, M.A. (2014). Good practices for estimating area and assessing accuracy of land change. Remote Sensing of Environment, 148: 42-57. https://doi.org/10.1016/j.rse.2014.02.015

[21] Costanza, R., Kubiszewski, I. (2012). The authorship structure of 'ecosystem services' as a transdisciplinary field of scholarship. Ecosystem Services, 1: 16-25. https://doi.org/10.1016/j.ecoser.2012.06.002

[22] Janizadeh, S., Pal, S.C., Saha, A., Chowdhuri, I., Ahmadi, K., Mirzaei, S., Mosavi, A.H., Tiefenbacher, J.P. (2021). Mapping the spatial and temporal variability of flood hazard affected by climate and land-use changes in the future. Journal of Environmental Management, 298: 113551. https://doi.org/10.1016/j.jenvman.2021.113551

[23] Mathewos, Y., Abate, B., Dadi, M., Mathewos, M. (2024). The nexus between spatiotemporal land use/land cover dynamics and ecosystem service values in the Wabe River catchment, Omo Gibe River Basin, Ethiopia. Environmental Challenges, 17: 101053. https://doi.org/10.1016/j.envc.2024.101053

[24] Li, X.Y., Wu, C.S. (2025). Sensitivity assessment and simulation of ecosystem services in response to land use change in arid regions: Empirical evidence from Xinjiang, China. Ecological Indicators, 171: 113150. https://doi.org/10.1016/j.ecolind.2025.113150

[25] Congalton, R.G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. Remote Sensing of Environment, 37(1): 35-46. https://doi.org/10.1016/0034-4257(91)90048-B

[26] Cheng, Y.H., Kang, Q., Liu, K.W., Cui, P., Zhao, K.X., Li, J.W., Ma, X., Ni, Q.S. (2023). Impact of urbanization on ecosystem service value from the perspective of spatio-temporal heterogeneity: A case study from the Yellow River Basin. Land, 12(7): 1301. https://doi.org/10.3390/land12071301

[27] Umair, M., Kim, D., Ray, R.L., Choi, M. (2018). Estimating land surface variables and sensitivity analysis for CLM and VIC simulations using remote sensing products. Science of the Total Environment, 633: 470-483. https://doi.org/10.1016/j.scitotenv.2018.03.138

[28] Leta, M.K., Demissie, T.A., Tränckner, J. (2021). Hydrological responses of watershed to historical and future land use land cover change dynamics of Nashe Watershed, Ethiopia. Water, 13(17): 2372. https://doi.org/10.3390/w13172372

[29] Nguyen, Q., Shrestha, S., Ghimire, S., Sundaram, S.M., Xue, W.C., Virdis, S.G.P., Maharjan, M. (2023). Application of machine learning models in assessing the hydrological changes under climate change in the transboundary 3S River Basin. Journal of Water and Climate Change, 14(8): 2902-2918. https://doi.org/10.2166/wcc.2023.313

[30] Abulibdeh, A. (2021). Analysis of urban heat island characteristics and mitigation strategies for eight arid and semi-arid Gulf Region cities. Environmental Earth Sciences, 80: 259. https://doi.org/10.1007/s12665-021-09540-7

[31] Mulatu, T., Desta, H. (2023). Surface temperature variation among traditional and modern residential forms in Addis Ababa, Ethiopia: Implications for land use planning. City and Environment Interactions, 20: 100126. https://doi.org/10.1016/j.cacint.2023.100126

[32] Fernandes, M.M., Fernandes, M.R.M., Garcia, J.R., Matricardi, E.A.T., et al. (2021). Land use and land cover changes and carbon stock valuation in the São Francisco River Basin, Brazil. Environmental Challenges, 5: 100247. https://doi.org/10.1016/j.envc.2021.100247

[33] Achmad, A., Ramli, I., Nizamuddin, N., Gunawan, A., Fakhrana, S.Z. (2024). The impact of land use and land cover changes on ecosystem service value in Aceh Besar Regency, Aceh, Indonesia. Bulletin of Geography. Physical Geography Series, 26: 69-76. https://doi.org/10.12775/bgeo-2024-0005

[34] Achmad, A., Ramli, I., Nizamuddin, N. (2023). Impact of land use and land cover changes on carbon stock in Aceh Besar District, Aceh, Indonesia. Journal of Water and Land Development, 57: 159-166. https://doi.org/10.24425/jwld.2023.145346

[35] Li, R.Q., Li, Y.F., van den Brink, M., Woltjer, J. (2015). The capacities of institutions for the integration of ecosystem services in coastal strategic planning: The case of Jiaozhou Bay. Ocean & Coastal Management, 107: 1-15. https://doi.org/10.1016/j.ocecoaman.2015.02.001