



Spatial Planning and Settlement Resilience for Disaster Mitigation in Coastal Banda Aceh: A Perception-Based SEM-PLS Assessment

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ABSTRACT

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Banda Aceh City is a coastal urban area with high exposure to tsunami, coastal flooding, abrasion, and earthquake-related hazards. Settlement expansion following the 2004 tsunami has increased spatial pressure in the northern coastal districts, creating a need for more risk-sensitive spatial planning and development control. This study examines how coastal households perceive the relationship between disaster potential (X1), settlement arrangement (X2), settlement resilience (X3), community participation (X4), climate change (X5), ecosystem-based coastal protection (X6), public education (N1), and disaster mitigation effectiveness (Y). A theoretical model was first specified from disaster mitigation and spatial planning theory and then estimated with Structural Equation Modeling–Partial Least Squares (SEM-PLS) in SmartPLS 4.0 using data from 400 household heads or household representatives in five coastal districts of Banda Aceh; a separate pilot sample of 150 respondents was used only for instrument testing and was excluded from the final estimation. Geographic Information System (GIS)-based disaster risk and coastal buffer maps were used to describe the spatial context of the study area; no spatial variable was entered as a numerical indicator in the structural model. X3 is the only construct with a statistically significant relationship with Y at the 5% level ($\beta = 0.620$; $t = 11.147$; $p < 0.001$). X6, measured through household perceptions rather than field measurement of ecosystem condition, is negative and non-significant ($\beta = -0.111$; $t = 1.950$; $p = 0.051$), and the direct and indirect effects of N1 are also non-significant. The model explains 53.6% of the variance in Y. The findings are perception-based, cross-sectional evidence from one coastal city and should be read as such: they support prioritising resilient settlement infrastructure, evacuation access, and preparedness within the Regional Spatial Plan (RSP) and Detailed Spatial Plan (DSP), while X2, X4, N1, X5, and X6 are retained as theory- and policy-based planning implications rather than empirically confirmed determinants.

1. INTRODUCTION

Banda Aceh City is a coastal urban area with high exposure to tsunami, coastal flooding, abrasion, and earthquake-related hazards. Settlement expansion following the 2004 tsunami has increased spatial pressure in northern coastal districts, creating a need for more risk-sensitive spatial planning and development control.

Previous studies on coastal disaster mitigation in Banda Aceh and comparable tsunami-prone settlements have generally treated hazard mapping, structural coastal protection, spatial planning regulation, and community preparedness as separate analytical domains. Hazard-based studies [1-3] identify tsunami inundation zones and physical exposure but stop short of linking exposure to settlement-level resilience outcomes. Regulatory and land-use studies [4-6] evaluate zoning compliance and urbanization pressure without incorporating participation or education as explanatory

mechanisms, and comparable regulatory analysis has also been applied to spatial planning in tsunami-prone zones [7]. Structural and ecosystem-oriented studies [8-10] emphasize infrastructure and coastal buffers, and related work on integrated, community-based coastal management [11, 12] similarly emphasizes these measures, but such studies rarely test these dimensions against psychosocial and governance factors using a validated causal model. Spatial studies of coastal flooding also demonstrate the value of hazard mapping for evaluating settlement planning [13]. Existing models thus remain fragmented, limiting their use for prioritizing planning and budgetary resources such as the Regional Spatial Plan (RSP) and Detailed Spatial Plan (DSP). This study instead combines disaster potential (X1), settlement arrangement (X2), settlement resilience (X3), community participation (X4), climate change (X5), ecosystem-based coastal protection (X6), and public education (N1) in one structural framework so their relative relationships with disaster

mitigation effectiveness (Y) can be examined together.

Beyond structural and regulatory measures, coastal ecosystems play a direct role in reducing disaster exposure. In particular, mangrove systems provide ecosystem-related benefits for coastal settlements by buffering wave energy, stabilizing shorelines against abrasion, and supporting fisheries-based livelihoods. These functions make mangrove restoration a nature-based solution that can complement engineered protection such as seawalls [8]. In this context, the role of coastal ecosystems extends beyond hazard reduction to supporting the ecological and livelihood conditions of coastal communities. In Banda Aceh, this ecological buffering capacity is unevenly distributed: protective structures are concentrated in areas such as Ulee Lheue, while mangrove cover in Alue Naga remains limited, leaving parts of the coastline more exposed to abrasion and tidal flooding [14, 15].

Effective disaster mitigation requires integrating spatial planning, resilient infrastructure, and hazard-sensitive development controls [16], an approach echoed in other urbanizing coastal contexts where modelling projects future growth and its environmental consequences [17]. Coastal settlement vulnerability is further shaped by population density, poverty, and lack of protective vegetation, as well as flooding compounded by alluvial soils and flat topography [15]. This study addresses this gap by integrating theoretical spatial planning principles with empirical evidence on Y. The analysis combines a theoretical model, Structural Equation Modeling–Partial Least Squares (SEM-PLS) validation using respondent data, and an empirical model developed from the validated relationships. The empirical model is based on data from the doctoral dissertation underlying this study.

This structural model draws on several complementary theoretical perspectives. The Pressure and Release (PAR) framework explains disaster risk as the interaction of root causes, dynamic pressures, unsafe conditions, and triggering hazards, which is reflected in X1. Community and settlement resilience theory, which emphasizes the capacity of social and physical systems to absorb disturbance, self-organize, and adapt, underlies X3, X4, and N1 as capacity-related constructs. X2 and X5 are grounded in spatial planning theory, particularly its treatment of land-use control and climate-related risks as determinants of exposure. X6 extends the framework by representing household perceptions of the effectiveness and benefits of nature-based coastal measures. These strands are combined to justify modeling all eight constructs together as a single testable structure (X1–X6, N1, Y).

Within this framework, N1 was originally hypothesized to operate as a mediator rather than a parallel predictor, on the reasoning that household knowledge and awareness form the mechanism through which X1, X2, X4, and X5 are translated into concrete mitigation behavior. The mediation test reported in Section 3.2 indicates that this translation mechanism is not supported in the present sample, since none of the indirect paths through N1 reach significance. The revised model therefore treats N1 as a direct explanatory construct operating in parallel with X3 rather than as a mediator. N1 and X3 represent two distinct capacity dimensions: X3 represents the physical and institutional capacity of a settlement to withstand and recover from hazards, whereas N1 represents the cognitive and behavioral capacity of households. X6 is included as a separate construct using the dedicated ecological indicators in the questionnaire. This distinction prevents X6 from being treated merely as a general perception of environmental

quality and allows its relationship with Y to be tested explicitly in the revised SEM-PLS model.

Two scope limitations are stated at the outset. First, X6 is measured through household perceptions of the effectiveness and the ecological and socioeconomic benefits of nature-based coastal measures. It does not measure mangrove extent, mangrove condition, or ecosystem service delivery in the field, and this study therefore does not empirically test coastal ecosystem resilience as an ecological state. Second, the Geographic Information System (GIS) material presented below provides spatial context for describing the study area and interpreting the survey results; no spatial variable is entered as a numerical indicator in the SEM-PLS estimation and no quantitative spatial analysis is performed. The study is accordingly described throughout as a spatial-planning-oriented, perception-based mitigation assessment rather than as a spatially integrated model.

2. MATERIAL AND METHODS

The article employs three connected stages detailed in Table 1: formulating a theoretical model from disaster mitigation and planning theory, validating relationships through SEM-PLS analysis [18], and translating validated results into empirical recommendations for coastal mitigation in Banda Aceh.

Table 1. Stages of theoretical and empirical model development

Stage	Main Function	Output
Theoretical Model	Formulates the conceptual structure of X1–X6, N1, and Y based on planning, mitigation, and X6 considerations. Tests validity, reliability, discriminant validity, coefficient of determination (R^2), bootstrapping, and model fit using SmartPLS 4.0.	Initial causal framework and research hypotheses
SEM-PLS Validation	Interprets statistically supported paths together with Geographic Information System (GIS)-based spatial context and translates them into planning implications.	Validated structural and measurement model
Empirical Model		Spatial-planning-oriented mitigation priorities for coastal settlements (spatial data used as context, not as model input)

Note: Structural Equation Modeling–Partial Least Squares (SEM-PLS).

Table 1 therefore establishes the analytical sequence carried through the remainder of the manuscript, from theoretical formulation to SEM-PLS validation and empirical interpretation.

2.1 Study area and boundary

The research was conducted in the coastal settlement zone of Banda Aceh City. The study area covers five coastal districts: Syiah Kuala, Kuta Raja, Kuta Alam, Jaya Baru, and Meuraxa. The operational coastal boundary was defined as land within approximately 2–3 km from the coastline. This boundary was based on the historical 2004 tsunami inundation zone, the relevance of coastal border regulation, and the need

to extend the analysis for tsunami mitigation purposes. The selected districts represent areas where settlement growth, coastal hazards, and disaster mitigation infrastructure intersect most directly. District-level evidence confirms that post-tsunami settlements in Meuraxa, Kuta Alam, and Syiah Kuala remain classified as high-risk zones despite existing regulations, with inadequate mangrove buffers and residential vulnerability to tsunami and liquefaction [10].

Figure 1 presents the disaster risk zoning map of Banda

Aceh City, illustrating the spatial distribution of disaster risk levels across the five coastal districts included in the study: Syiah Kuala, Kuta Raja, Kuta Alam, Jaya Baru, and Meuraxa. The spatial analysis was used to define the coastal study context and to identify locations where settlement exposure and disaster risk overlap. These spatial results were not entered as numerical indicators in the SEM-PLS model; instead, they were used to complement the household perception data and to support the interpretation of spatial-planning implications.

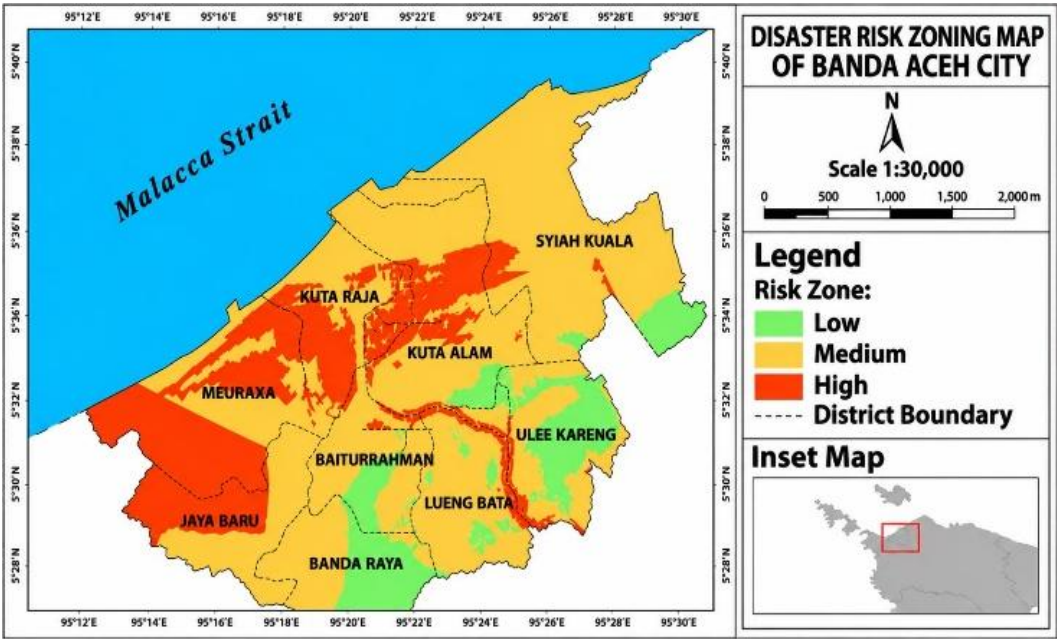


Figure 1. Disaster risk zoning map of Banda Aceh City
Source: Author’s overlay analysis (2026).

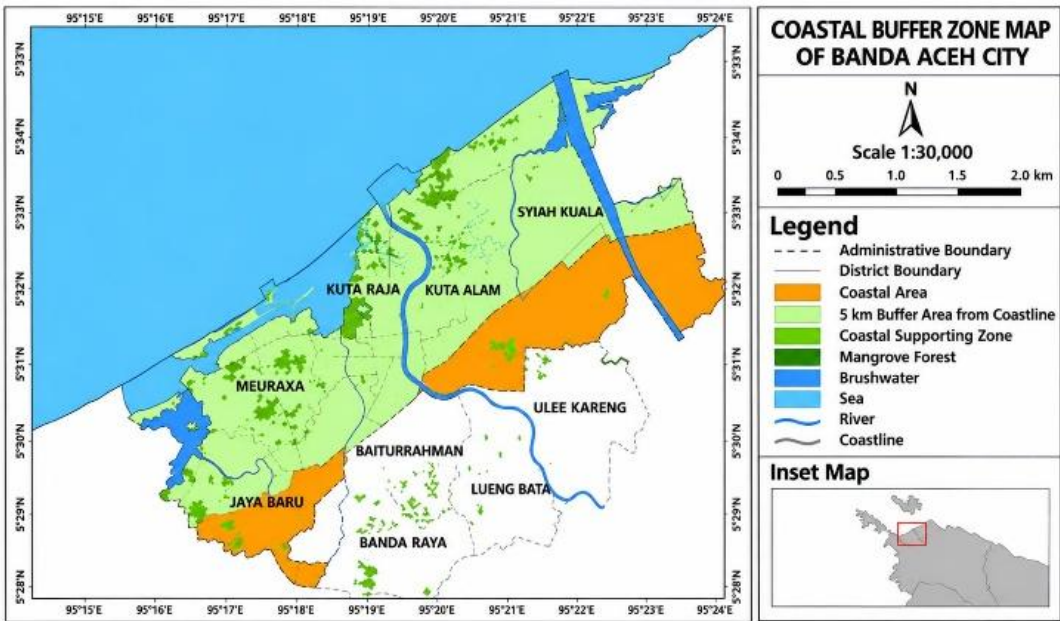


Figure 2. Coastal buffer zone map of Banda Aceh City
Source: Author’s overlay analysis (2026).

Figure 1 confirms that disaster risk is concentrated along the coastal fringe of the five study districts, providing the spatial rationale for selecting these areas as the survey population. Figure 2 shows the coastal buffer zone used as the spatial reference for defining the coastal study context and interpreting settlement exposure.

The map indicates that the coastal buffer zone extends across the northern part of Banda Aceh City, covering the main coastal areas and settlement zones included in this study. The spatial distribution of these zones was used as a geographic reference for interpreting the household survey results. Thus, GIS-based spatial analysis and SEM-PLS serve

complementary functions: GIS identifies the spatial context of risk and exposure, whereas SEM-PLS tests relationships among perception-based constructs measured through the questionnaire.

No quantitative spatial analysis was carried out on these maps: no spatial regression, overlay scoring, geostatistical test, or spatial weighting was applied, and neither risk class nor distance to the shoreline was coded as a variable in the structural model. Figures 1 and 2 are used to define and describe the study area and to locate the surveyed settlements relative to hazard zones. The integration between the spatial and the statistical component is therefore interpretive: the maps establish the exposure context in which the perception data were collected, and the SEM-PLS results are read against that context when planning implications are drawn in Section 3.4.

2.2 Population, sample size, and sampling technique

The study population consisted of 102,643 residents living in the five coastal districts of Banda Aceh City: Syiah Kuala, Meuraxa, Kuta Alam, Kuta Raja, and Jaya Baru. The operational study area comprised coastal residential areas located approximately 2–3 km from the coastline. Respondents were household heads or household representatives residing within the defined coastal residential areas.

The main sample size was determined using the Slovin formula with a 5% margin of error, resulting in 400 respondents. An area-based household sampling approach was applied across the five coastal districts. The 400 respondents were distributed across the study districts according to the sampling plan, consisting of 143 respondents in Syiah Kuala, 107 in Meuraxa, 70 in Kuta Alam, 60 in Kuta Raja, and 20 in Jaya Baru. This distribution ensured that the household survey covered all five coastal districts included in the study. Each questionnaire was administered individually to the selected respondents, with one completed questionnaire recorded for each respondent. The collected responses were checked for completeness and consistency before analysis.

Households were selected within each district using a systematic area-based procedure rather than simple random sampling. Coastal villages (gampong) located within the 2–3 km coastal boundary were first identified. The online questionnaire was then distributed to residents living within the identified coastal villages through online channels, with respondents screened based on their residential location and eligibility criteria. One household head or household representative was invited to complete the questionnaire per household.

The district quotas (143 Syiah Kuala, 107 Meuraxa, 70 Kuta

Alam, 60 Kuta Raja, and 20 Jaya Baru) were allocated approximately in proportion to the number of households living within the coastal boundary of each district. Thus, districts with larger coastal settlement populations contributed more respondents, while Jaya Baru, which has a relatively narrow coastal strip, contributed the fewest respondents. The sample was intended to represent coastal households across the five districts taken together and was not designed or powered for separate district-level estimation. The sample is therefore representative of coastal households in the five districts taken together; it is not powered for separate district-level estimation, and the results are not disaggregated by district.

Before the main survey, a separate pilot test involving 150 respondents was conducted to assess the questionnaire. The pilot respondents were treated separately from the main survey and were not included in the 400 respondents used for the final SEM-PLS analysis. The 150 pilot respondents were drawn from the same five coastal districts but from different households, and none of them appear among the 400 respondents analysed in the final SEM-PLS model. Pilot responses were used only to check item wording, comprehension, and preliminary item-total consistency, and were not pooled with the main data set at any stage of estimation.

Data and Model Consistency Note: The questionnaire instrument used in the final SEM-PLS analysis is identical to the one administered during the original data collection; no items were added, removed, or reworded between the earlier and the current manuscript version. No respondents or data records were removed from the analysis: all 400 collected responses were retained in the final SEM-PLS model. The raw dataset contained no missing values and no duplicate respondent entries, so no additional data screening, outlier removal, or respondent exclusion was required beyond the pilot-sample separation described above.

2.3 Data collection

Primary data were collected through household questionnaires, field observation, documentation of settlement conditions, and stakeholder interviews. The questionnaire measured respondents' perceptions regarding X1–X6, N1, and Y. Secondary data were obtained from spatial planning documents such as the RSP and DSP, hazard maps, population statistics, land-use maps, government policy documents, and previous research. The GIS analysis provided the spatial context for interpreting the survey-based SEM-PLS results rather than serving as a direct numerical input to the structural model.

Table 2. Research variables and their operational definitions

Code	Variable	Role in Model	Operational Meaning
X1	Disaster Potential	Explanatory variable	Coastal hazard exposure and tsunami/earthquake/flood risk.
X2	Settlement Arrangement	Explanatory variable	Land-use control and infrastructure adequacy for mitigation.
X3	Settlement Resilience	Explanatory variable	Housing quality, evacuation access, shelter, and recovery capacity.
X4	Community Participation	Explanatory variable	Community involvement in preparedness and mitigation action.
X5	Climate Change	Explanatory variable	Perceived sea-level rise, flooding, abrasion, and climate vulnerability.
X6	Ecosystem-Based Coastal Protection	Explanatory variable	Perceived effectiveness and ecological and socioeconomic benefits of ecosystem-based coastal protection, including mangrove restoration and other nature-based measures.
N1	Public Education	Explanatory variable	Education and awareness that strengthen preparedness.
Y	Disaster Mitigation Effectiveness	Dependent variable	Perceived effectiveness of spatial-planning-based mitigation.

2.4 Research variables

The research variables were arranged into explanatory constructs and one dependent construct. The dependent construct is Y. The explanatory constructs are X1–X6 and N1. X6 was added because the questionnaire contains a dedicated set of indicators addressing X6, including its role in reducing coastal hazards and its ecological and socioeconomic benefits. N1 was initially examined as a possible mediator; however, the mediation results were not significant, so N1 is retained as a direct explanatory construct in the revised interpretation.

Table 2 summarises the constructs, their role in the model, and their operational meaning.

Table 2 therefore defines the operational meaning of each construct used in the subsequent measurement and structural analysis.

3. RESULTS AND DISCUSSION

3.1 Measurement model validation

The theoretical model assumes that Y in coastal settlements depends on interacting physical, social, spatial, climatic, educational, and ecosystem-based dimensions. The revised model therefore examines X1–X6 as explanatory constructs, with N1 representing household knowledge and preparedness and Y representing disaster mitigation effectiveness. The SEM-PLS analysis tests the validity and reliability of these constructs and the significance of their hypothesized relationships. The GIS-based spatial analysis is used alongside the SEM-PLS results to provide geographic context for

interpreting the implications of the statistically tested relationships.

The revised measurement model reports the outer loadings of all retained indicators together with convergent and discriminant validity. The three indicators of X6 have outer loadings of 0.842, 0.872, and 0.855, respectively, and an average variance extracted (AVE) of 0.733. These results support the convergent validity of the X6 construct. The HTMT assessment also shows that the X6 ratios with the other constructs are below 0.90, with the highest value observed for X6 and X5 (0.843), supporting discriminant validity.

The SEM-PLS analysis was performed using SmartPLS 4.0. The measurement model was evaluated through convergent validity, discriminant validity, and reliability. Tables 3–10 present the measurement and structural results supporting the transition from the theoretical model to the empirical model.

To verify that the reported results originate from the intended model and dataset, the final structural model was cross-checked directly against the SmartPLS 4.0 output. The imported dataset comprised exactly 400 observations, consistent with the sample size reported in Section 2.2. Figure 3 presents the complete structural model exported from SmartPLS, showing all eight constructs, their indicators, and the corresponding outer loadings and path coefficients. Because the SmartPLS diagram uses single-letter construct labels (A–F, N, Y) for display purposes, Table 3 provides the correspondence between these labels and the construct codes (X1–X6, N1, Y) used throughout this manuscript.

Figure 3 confirms that the exported SmartPLS model reflects the full set of eight constructs and their indicator structure used throughout the measurement and structural analysis reported below.

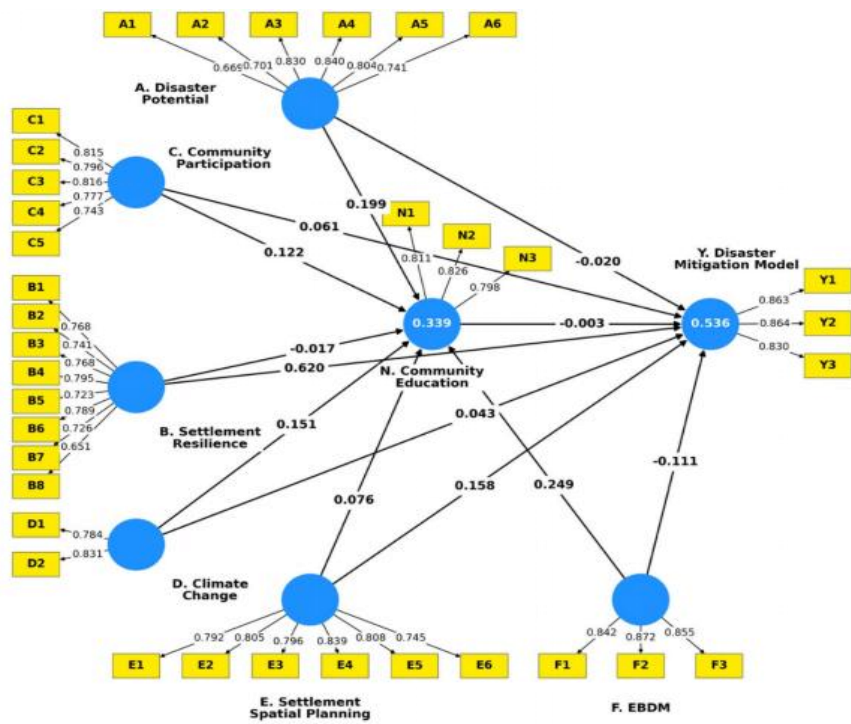


Figure 3. Final structural model (SmartPLS 4.0 output, n = 400)
Source: SmartPLS 4.0 output (2026).

The path coefficients shown in Figure 3 match those reported in Table 8: $A \rightarrow Y = -0.020$ ($X1 \rightarrow Y$); $B \rightarrow Y = 0.620$ ($X3 \rightarrow Y$); $C \rightarrow Y = 0.061$ ($X4 \rightarrow Y$); $D \rightarrow Y = 0.043$ ($X5 \rightarrow Y$); $E \rightarrow Y = 0.103$ ($X2 \rightarrow Y$); $F \rightarrow Y = -0.111$ ($X6$

$\rightarrow Y$); $N \rightarrow Y = -0.003$ ($N1 \rightarrow Y$). This confirms that the diagram originates from the same model and dataset reported throughout this manuscript. Table 4 reports the outer loadings of all retained indicators for each construct.

Table 3. Correspondence between SmartPLS diagram labels and manuscript construct codes

SmartPLS Diagram Label	Manuscript Code	Construct Name in Manuscript
A. Disaster Potential	X1	Disaster Potential
B. Settlement Resilience	X3	Settlement Resilience
C. Community Participation	X4	Community Participation
D. Climate Change	X5	Climate Change
E. Settlement Spatial Planning	X2	Settlement Arrangement
F. Ecosystem-Based Disaster Management	X6	Ecosystem-Based Coastal Protection
N. Community Education	N1	Public Education
Y. Disaster Mitigation Model	Y	Disaster Mitigation Effectiveness

Note: Partial Least Squares (PLS).

Table 4. Outer loadings of the retained indicators

Indicator	Construct	Outer Loading
A1	X1	0.669
A2	X1	0.701
A3	X1	0.830
A4	X1	0.840
A5	X1	0.804
A6	X1	0.741
B1	X3	0.768
B2	X3	0.741
B3	X3	0.768
B4	X3	0.795
B5	X3	0.723
B6	X3	0.789
B7	X3	0.726
B8	X3	0.651
C1	X4	0.815
C2	X4	0.796
C3	X4	0.816
C4	X4	0.777
C5	X4	0.743
D1	X5	0.784
D2	X5	0.831
E1	X2	0.792
E2	X2	0.805
E3	X2	0.796
E4	X2	0.839
E5	X2	0.808
E6	X2	0.745
F1	X6	0.842
F2	X6	0.872
F3	X6	0.855
N1	N1	0.811
N2	N1	0.826
N3	N1	0.798
Y1	Y	0.863
Y2	Y	0.864
Y3	Y	0.830

Table 5. Average variance extracted (AVE) for each construct

Construct Variable	AVE
Y	0.727
X4	0.624
X2	0.636
X5	0.634
X1	0.563
X3	0.556
X6	0.733

All outer loadings exceed the 0.60 threshold, supporting the indicator reliability of the retained measurement items. Table 5 reports AVE for each construct to assess convergent validity.

Table 5 shows that all constructs meet the AVE criterion of 0.50. The AVE values are 0.727 for Y, 0.624 for X4, 0.636 for X2, 0.634 for X5, 0.563 for X1, 0.556 for X3, and 0.733 for X6. The X6 value is therefore above the recommended threshold and supports convergent validity for the X6 construct. Table 6 reports the reliability coefficients, including Cronbach's alpha, rho_A, and rho_C, for each construct.

Table 6. Reliability values for each construct

Construct Variable	Cronbach's Alpha	rho_A (pA)	rho_C (Composite Reliability)
Y	0.812	0.812	0.889
X1	0.859	0.913	0.883
X2	0.885	0.887	0.913
X3	0.886	0.897	0.909
X4	0.849	0.851	0.892
X5	0.465	0.609	0.771
X6	0.818	0.818	0.891

Table 6 shows that the constructs generally meet the reliability criteria, with rho_C (pC) values above 0.70. However, Cronbach's alpha for X5 (0.465) is below the commonly accepted threshold. Because X5 is measured with only two indicators, Cronbach's alpha may underestimate its internal consistency. Although its rho_A (pA) is 0.609, its rho_C (pC) remains acceptable at 0.771. X6 shows Cronbach's alpha = 0.818, rho_A (pA) = 0.818, and rho_C (pC) = 0.891, indicating acceptable internal consistency and reliability.

X5 requires a specific justification. It is measured by two indicators, D1 and D2, covering perceived sea-level rise, tidal flooding, abrasion, and general climate vulnerability as defined in Table 2. Their outer loadings are 0.784 and 0.831 (Table 4), the construct AVE is 0.634 (Table 5), and its reliability coefficients are Cronbach's alpha = 0.465, rho_A (pA) = 0.609, and rho_C (pC) = 0.771 (Table 6). Convergent validity is therefore satisfied, but internal consistency is weak. Cronbach's alpha is downward-biased for a two-item construct because it is a function of item count, yet rho_A (pA) also remains below 0.70 here, so the weakness cannot be attributed to item count alone. X5 is retained for two reasons: removing it would eliminate the climate dimension from a coastal-hazard model in which climate pressure is a stated planning concern, and its structural path to Y is in any case non-significant, so retention does not inflate any supported conclusion. Given the measurement quality, X5 is treated as an exploratory construct throughout: its coefficient is not interpreted substantively, no comparison of effect sizes involving X5 is made, and no climate-related recommendation in Section 3.4 rests on it. Strengthening this construct with additional items is identified as a requirement for future work.

3.2 Structural model validation

The coefficient of determination (R^2) was evaluated to assess the explanatory power of the revised structural model. With X6 included as an explanatory construct, the revised SmartPLS estimation gives an R^2 of 0.536 and an adjusted R^2 of 0.528 for Y.

Table 7 reports the R^2 and adjusted R^2 values for the dependent construct.

Table 7. Coefficient of determination (R^2) for disaster mitigation effectiveness (Y)

Model	R^2	Adjusted R^2
Y	0.536	0.528

The R^2 value of 0.536 means that 53.6% of the variance in Y can be explained by the predictors in the revised model. The remaining 46.4% may be associated with factors outside the model, including economic capacity, institutional and government support, emergency response capability, objective ecosystem condition, and changes in coastal land use. These factors were not included as explanatory constructs in the present SEM-PLS model and therefore represent potential directions for further model development. The revised model thus provides a moderate level of explanatory power for the perception-based evidence from coastal households.

Table 8 presents the bootstrapping results of the revised structural model. The results include path coefficients, t -statistics, and p -values used to assess the significance of the relationships between the explanatory variables and Y.

The bootstrapping results in Table 8 show that X3 has the strongest statistically significant relationship with Y ($\beta = 0.620$; $t = 11.147$; $p < 0.001$). The relationships for X1, X2, X4, X5, X6, and N1 are not statistically significant at the 5% level. X6 has a negative coefficient of -0.111 with $p = 0.051$, which is slightly above the 0.05 threshold. Therefore, X6 is retained as an empirically tested construct, but its relationship with Y should be interpreted as non-significant at the 5% level rather than as a confirmed determinant.

To evaluate whether N1 functions as a mediator, indirect effects from X1, X2, X4, X5, and X6 to Y through N1 were assessed using bootstrapping in SmartPLS 4.0 with 5000 resamples. The results are presented in Table 9.

All five indirect paths are not significant, since every p -value is above 0.05. This indicates that N1 does not mediate the relationships between X1, X2, X4, X5, or X6 and Y. The direct path from N1 to Y is also not significant ($\beta = -0.003$; $t = 0.062$; $p = 0.950$). Therefore, N1 is retained in the structural framework as a direct explanatory construct, but the present sample does not provide statistical evidence of either a mediating or direct effect.

Table 8. Bootstrapping results of the structural model

Variable Relationship	Original Sample (O)	Sample Mean (M)	Standard Deviation	t -Statistics	p -Values
X1 $\rightarrow$ Y	-0.020	-0.018	0.046	0.431	0.667
X2 $\rightarrow$ Y	0.103	0.102	0.061	1.692	0.091
X3 $\rightarrow$ Y	0.620	0.621	0.056	11.147	<0.001
X4 $\rightarrow$ Y	0.061	0.064	0.064	0.951	0.342
X5 $\rightarrow$ Y	0.043	0.045	0.058	0.746	0.455
X6 $\rightarrow$ Y	-0.111	-0.111	0.057	1.950	0.051
N1 $\rightarrow$ Y	-0.003	-0.006	0.051	0.062	0.950

Table 9. Bootstrapping results of indirect effects through public education (N1)

Variable Relationship	Original Sample (O)	Sample Mean (M)	Standard Deviation	t -Statistics	p -Values
X4 $\rightarrow$ N1 $\rightarrow$ Y	-0.004	-0.004	0.009	0.403	0.687
X2 $\rightarrow$ N1 $\rightarrow$ Y	-0.004	-0.004	0.009	0.412	0.680
X5 $\rightarrow$ N1 $\rightarrow$ Y	-0.005	-0.006	0.011	0.414	0.679
X1 $\rightarrow$ N1 $\rightarrow$ Y	-0.006	-0.007	0.013	0.440	0.660
X6 $\rightarrow$ N1 $\rightarrow$ Y	-0.001	-0.001	0.013	0.060	0.952

Table 10 reports the goodness-of-fit statistics for the revised model. The Standardized Root Mean Square Residual (SRMR) value is 0.065 for both the saturated and estimated models. The Normed Fit Index (NFI) is 0.752, while d_{ULS} , d_G , and chi-square are 2.817, 0.867, and 2041.676, respectively. These values represent the model after the inclusion of X6 and should be interpreted together with the measurement and structural results.

Table 10. Model fit results

Indicator	Saturated Model	Estimated Model
SRMR	0.065	0.065
d_{ULS}	2.817	2.817
d_G	0.867	0.867
Chi-square	2041.676	2041.676
NFI	0.752	0.752

Note: Standardized Root Mean Square Residual (SRMR); Normed Fit Index (NFI).

The non-significance of X1, X2, X4, X5, and X6 means that statistically significant relationships with Y were not established for these constructs in the present sample at the 5%

level. This does not imply that these dimensions are unimportant in disaster mitigation practice. Their interpretation should instead consider the way they were operationalized through household perceptions and the spatial context of Banda Aceh. X3, by contrast, is the only construct that shows a statistically significant relationship with Y and therefore provides the strongest empirical basis for the current planning recommendations.

The non-significance of X1 may partly reflect measurement design: it was captured through perception-based survey items rather than objective hazard-exposure indicators, and perceived risk can vary independently of a household's actual spatial exposure across the five coastal districts. This may introduce measurement noise that attenuates the statistical relationship. Similar caution applies to X2, X4, and X5 because the present analysis measures perceptions rather than direct observations of land-use compliance, participation intensity, or physical climate impacts.

3.3 Empirical model and comparative positioning

Based on the revised SEM-PLS results, the empirical model

identifies X3 as the strongest statistically supported determinant of Y. The path coefficients represent standardized structural relationships rather than a predictive regression equation. The revised model can be summarized as: $Y = -0.020X1 + 0.103X2 + 0.620X3 + 0.061X4 + 0.043X5 - 0.111X6 - 0.003N1 + \zeta$. X6 is included explicitly because X6 was measured through dedicated questionnaire indicators and tested as an explanatory construct in the revised model

The empirical model translates the SEM-PLS results into priorities for disaster mitigation in coastal settlements. X1 remains a contextual hazard variable, but merely recognizing it is insufficient. Y depends more on whether settlements are physically and socially resilient-road access to evacuation routes, vertical evacuation buildings, disaster-resistant housing, and integration of mitigation infrastructure into statutory spatial plans.

Table 11. Comparative positioning of this study relative to prior coastal mitigation research

Research Strand	Studies	Approach	Position vs. This Study
Hazard mapping / physical exposure	[1-3]	Descriptive hazard and inundation mapping	Does not test whether X1 predicts outcomes; this study finds X1 non-significant.
Regulatory / land-use compliance	[4-6]	Zoning and urbanization-policy evaluation	Evaluates compliance qualitatively; this study's X2 is positive but non-significant ($\beta = 0.103$; $p = 0.091$).
Structural mitigation measures	[8-11]	Case-based evaluation of mangroves, seawalls, early-warning systems	Prioritizes structural measures; this study finds X3 the strongest determinant ($\beta = 0.620$; $p < 0.001$).
Community preparedness assessment	[19]	Bottom-up/top-down composite resilience index	Reports low preparedness (index = 36.97); this finding is consistent with the strong role of X3 in the model.
Participatory spatial planning	[20]	Qualitative case study, single Banda Aceh sub-district	Finds participation poorly accommodated; this study confirms X4 non-significant ($\beta = 0.061$; $p = 0.342$).

Table 11 positions the present SEM-PLS findings against the four strands of prior Banda Aceh and comparable coastal-mitigation research already discussed above (hazard mapping, regulation, structural/coastal protection, and community or ecosystem-based management). The revised comparison also reflects the explicit inclusion of X6 as a construct.

Read across the comparison, prior studies emphasize hazard exposure, regulation, and structural protection [10, 19]. Related studies further address community preparedness and risk-sensitive planning [7, 11, 20], while other work emphasizes integrated coastal management [12, 13] and highlights the importance of considering social and psychological consequences in spatial planning [21]. Unlike these predominantly hazard-planning or case-study-centered approaches, this study uses a household-based SEM-PLS framework to test several of these dimensions together through a perception-based model, with X6 tested explicitly rather than discussed only descriptively. X3 is statistically significant, whereas X1, X2, X4, X5, and X6 are not statistically significant at the 5% level. The X6 result should therefore be interpreted as empirical evidence from household perceptions of X6, but not as a statistically confirmed determinant of Y.

3.4 Implications for spatial planning

It should be emphasized that, based on the revised structural results, X3 is the only statistically significant determinant of Y at the 5% level. X6 has a negative but non-significant relationship with Y ($\beta = -0.111$; $t = 1.950$; $p = 0.051$). Recommendations concerning spatial planning enforcement, N1, X4, climate adaptation, and ecosystem-based protection are therefore presented as planning and policy implications rather than as claims of statistically significant effects.

The empirical model therefore recommends strengthening X3 as the main empirically supported intervention area, while continuing to consider spatial planning enforcement, N1, X4, climate adaptation, and X6 in coastal mitigation planning. These dimensions are presented as complementary planning considerations unless supported by statistically significant relationships in the present model. For X6 specifically, the non-significant result at the 5% level does not remove its

relevance as a planning consideration; rather, it indicates that the household-perception data do not establish a statistically significant direct relationship with Y. Research on spatial impacts in dense hazard-prone settlements further supports attention to social and psychological dimensions when planning recovery and risk reduction [21].

N1 remains part of the conceptual framework as a direct explanatory construct representing household knowledge and awareness. The direct path from N1 to Y is not statistically significant ($\beta = -0.003$; $t = 0.062$; $p = 0.950$), and its indirect effects are also not significant. Therefore, N1 is not presented as a confirmed determinant or mediator in the current empirical evidence. Instead, N1 is retained as a practical planning consideration that may support preparedness, participation, and appropriate responses when implemented together with physical and institutional measures [12].

The role of N1 is specified consistently across the model, the tables, and the structural equation. N1 enters the final model as a direct explanatory construct in parallel with X1–X6; its direct path to Y is reported in Table 8 ($\beta = -0.003$; $t = 0.062$; $p = 0.950$), its indirect paths are reported in Table 9, and it appears in the structural equation as the $-0.003N1$ term. Both the direct and the indirect effects of N1 are non-significant in this sample. N1 is therefore retained in the conceptual framework and in the reported model for completeness, but it is not claimed as a determinant or as a mediator of Y.

These findings align with prior research emphasizing hazard-sensitive zoning, structural measures, integrated coastal management, and differentiated spatial controls [7, 12, 13]. The empirical model therefore yields five planning priorities: (1) stricter regulation of disaster-prone coastal zones near the shoreline and within historical tsunami inundation areas; (2) integrated evacuation infrastructure, including improved roads, signage, vertical evacuation buildings, and gathering points; (3) strengthened X3 through better building quality, disaster-resistant construction, and public facility preparedness; (4) institutionalized X4 and education through regular training and local disaster forums; and (5) consideration of X6, including mangrove restoration and other nature-based measures, within the RSP and DSP. These

recommendations are framed as planning implications, while the SEM-PLS result for X6 is reported as non-significant at the 5% level.

4. CONCLUSIONS

The findings provide perception-based evidence from households in the coastal settlements of Banda Aceh. In the revised structural model, X3 shows the strongest statistically significant relationship with Y ($\beta = 0.620$; $t = 11.147$; $p < 0.001$). X6 was incorporated through dedicated questionnaire indicators and was evaluated explicitly in the SEM-PLS model; its direct relationship with Y was negative but not statistically significant at the 5% level ($\beta = -0.111$; $t = 1.950$; $p = 0.051$). The revised model explains 53.6% of the variance in Y. GIS analysis complements the SEM-PLS results by identifying the spatial distribution of disaster risk and coastal buffer zones, while SEM-PLS provides evidence on relationships among the survey-based constructs.

The revised measurement model reports the complete outer-loadings table, AVE, reliability values, and HTMT assessment. X6 demonstrates acceptable measurement properties, with outer loadings of 0.842, 0.872, and 0.855, AVE = 0.733, Cronbach's alpha = 0.818, $\rho_A = 0.818$, and $\rho_C = 0.891$. The HTMT values involving X6 are below 0.90, with the highest value of 0.843 observed in relation to X5. X5 remains a measurement limitation because its Cronbach's alpha is 0.465, although its composite reliability is 0.771; interpretation of this construct should therefore remain cautious.

The findings support strengthening resilient settlement infrastructure, evacuation access, and preparedness within spatial planning. In addition, N1, X4, X5, and X6 are retained as complementary planning considerations. In particular, the non-significant X6 result should not be interpreted as evidence that X6 is ineffective in practice; rather, the present perception-based household survey does not establish a statistically significant direct relationship between X6 and Y at the 5% level.

This study has several limitations. The empirical evidence is based on a cross-sectional, perception-based household survey conducted in one coastal city, Banda Aceh, which limits generalization to other coastal settings. The GIS analysis provides spatial context but was not statistically integrated as numerical indicators in the SEM-PLS model. The newly added X6 construct is also perception-based rather than a direct field measurement of mangrove condition or ecosystem services. Future research should combine objective ecological and spatial indicators with longitudinal household data to strengthen validation and transferability.

These results should be read as perception-based, cross-sectional evidence from coastal households in a single city. The analysis tests how households perceive X1, X2, X3, X4, X5, X6, and N1 in relation to Y. It does not validate an operating disaster mitigation system, does not measure ecological or physical performance in the field, and does not establish the direction of causality. Only the relationship between X3 and Y is statistically supported at the 5% level; the recommendations concerning X2, X4, X5, N1, and X6 are offered as theory- and policy-based planning implications, not as relationships confirmed by this model.

DECLARATION OF COMPETING INTERESTS

The authors declare that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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