

Gendered Climate Vulnerability and Household Adaptation in Southwest Coastal Bangladesh: A Convergent Mixed-Methods Approach

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Research Article

Keywords: climate vulnerability, household adaptation, principal component analysis, Feminist Political Ecology, coastal Bangladesh

Posted Date: October 16th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10933771/v1>

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Additional Declarations: No competing interests reported.

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Abstract

Coastal households in Bangladesh face overlapping climatic hazards, but greater exposure does not necessarily translate into greater adaptation because material resources, gendered relations, and institutional access shape the capacity to act. This study examines how multidimensional and gender-sensitive household vulnerability is associated with the adoption and intensity of climate adaptation in Koyra Upazila, southwest coastal Bangladesh. A quantitatively dominant convergent mixed-methods design combined a survey of 383 households with 15 archived focus-group discussion records. Five dimensions: climate-related exposure, household sensitivity, gendered vulnerability, material capacity, and institutional access were constructed using dimension-specific principal component analysis, and a Gender-Sensitive Household Vulnerability Index (GSHVI) was developed from sensitivity, gendered vulnerability, and material-capacity deficit. Higher GSHVI was strongly associated with lower odds of adopting at least one substantive adaptation measure (OR=0.134, 95% CI 0.052–0.344, $p<0.001$) and a lower adaptation count (IRR=0.611, 95% CI 0.459–0.815, $p=0.002$). Sensitivity was negatively associated with adaptation, whereas material capacity was strongly positive. Gendered vulnerability showed no independent main effect, and the exposure-by-gendered-vulnerability interaction was statistically inconclusive. Qualitative evidence nevertheless showed that gender operated through sanitation, safety, care responsibilities, mobility, workload, information access, and resource constraints. The findings identify a clear vulnerability–adaptation gap and show that effective adaptation policy must strengthen material capacity, gender-responsive infrastructure, and institutional support so that highly vulnerable households can convert climate-risk awareness into action. Under the top-40% vulnerability threshold, 119 of 153 highly vulnerable households reported no substantive adaptation. Robustness checks across alternative PCA specifications and outcome definitions further confirmed the stability of the principal vulnerability–adaptation relationship.

Keywords: climate vulnerability; household adaptation; principal component analysis; Feminist Political Ecology; coastal Bangladesh

1. Introduction

Bangladesh's coast is a densely settled deltaic region in which climatic hazards interact with tidal rivers, land-use change, embankment systems and livelihood dependence. Brammer (2014) emphasizes the physical heterogeneity of Bangladesh's coastal processes, while the Intergovernmental Panel on Climate Change (IPCC, 2022) identifies low-lying deltas as settings where sea-level rise, extreme events, water insecurity and livelihood disruption can compound existing social vulnerability. The Bangladesh Country Climate and Development Report similarly places coastal resilience, water management and climate-resilient livelihoods at the center of national climate-development priorities (World Bank, 2022). These conditions make the southwest coast an important setting for examining why households exposed to similar environmental pressures can differ sharply in their capacity to adapt.

The coastal hazard environment is multidimensional. Cyclones and storm surges are intertwined with salinity intrusion, flooding, waterlogging, erosion and long-duration livelihood disruption rather than occurring as isolated shocks. Saha (2017) shows that cyclone impacts and salinity shape local coping in coastal Bangladesh, while Chen and Mueller (2018) demonstrate that soil salinity can influence longer-term migration decisions. Water insecurity is especially consequential because it connects environmental exposure to health, household labor and livelihood reproduction. Abedin et al. (2019) document climate-related freshwater scarcity and

health adaptation in southwestern coastal Bangladesh, and Khan et al. (2014) demonstrate important maternal-health consequences associated with saline drinking water. More recent work has drawn attention to reproductive-health and menstrual-hygiene burdens in saline coastal environments (Hossain & Pal, 2025; Sinha et al., 2024). Livelihood structure further mediates how environmental pressures are experienced. Among coastal smallholders, adaptation choices are shaped by land, assets, training and prior hazard experience rather than exposure alone (Aryal et al., 2020). Farmers' perceptions of salinity influence crop-management responses, but implementation depends on access to inputs, information and water-management options (Islam et al., 2020). Hoque, Quinn, and Sallu (2018) show that adaptation pathways are differentiated by wealth and social-ecological position, and recent evidence from nearby Dacope Upazila highlights the importance of credit, training, institutional support and livelihood diversification (Hasan et al., 2025). These studies suggest that climate risk generates a need to adapt, but does not guarantee the capacity to implement adaptation.

Vulnerability is also gendered. Early climate scholarship emphasized that access to assets, information, institutions and decision-making is socially differentiated, so climatic impacts cannot be understood as gender-neutral (Denton, 2002; Terry, 2009). MacGregor (2009) argued that climate research must examine social relations rather than treating gender as a secondary variable. Yet gender-sensitive analysis should not equate women with vulnerability. Arora-Jonsson (2011) demonstrates how universalized narratives of female vulnerability can obscure structural power, while Evertsen (2023) shows how women in coastal Bangladesh may be constructed as fixed 'subjects of risk' in adaptation discourse. A stronger approach therefore asks how household authority, care work, safety, mobility, information and resource access produce differentiated vulnerability.

Empirical research in Bangladesh supports such a relational approach. Bari et al. (2024) demonstrate intersectional differences in gender-based vulnerability and adaptive capacity in disaster-prone coastal areas. Fatema et al. (2023) identify shelter access, privacy, sanitation and safety as central features of women's disaster experiences. Esha (2024) shows that water infrastructure is experienced through gendered labor and local power relations, while Alam and Khalil (2022) demonstrate that gender, migration and immobility reshape vulnerability after coastal hazards. Khalil et al. (2021) further show that women's linking social capital with NGOs can create adaptation opportunities after cyclones. Together, these findings indicate that gender is more meaningfully measured through social relations and burdens than through respondent sex or household-head sex alone. Moreover, existing coastal Bangladesh studies have generated important evidence on vulnerability, gender and adaptation, but these strands remain insufficiently integrated. Vulnerability assessments often stop at ranking households or places, while adaptation studies examine strategies or determinants without directly asking whether the most vulnerable households are able to translate climatic pressure into action. Khan, Hasan, and Kabir (2022) identify socioeconomic and institutional determinants of livelihood vulnerability in southwest Bangladesh, whereas Kabir et al. (2021) examine adaptation determinants across the coastal zone. Recent studies further show that formal adaptation programs can reproduce gender inequities or fail to translate policy commitments into substantive authority (Ahmed, Eklund, & Kiester, 2023; Chowdhury, Hossain, & Ibn Farid, 2026; Islam & Islam, 2026). What remains less clear is how multidimensional and gendered household vulnerability is associated with observed adaptation, and which households combine high vulnerability with little or no substantive adaptation.

Against this background, the study asks: How are multidimensional climate vulnerability and gendered household relations associated with the adoption and intensity of household adaptation measures in coastal communities of Bangladesh? The study has two objectives: (1) to assess multidimensional and gender-sensitive household vulnerability among coastal households in Koyra Upazila using a PCA-weighted household vulnerability index; and (2) to examine the association between household vulnerability and the

adoption and intensity of adaptation measures, with particular attention to gendered, socioeconomic and institutional factors. The study contributes by integrating IPCC climate-risk framing with Feminist Political Ecology (FPE), deriving transparent PCA-based weights for a large indicator set, testing alternative component-retention and correlation assumptions, assessing index and outcome sensitivity, and integrating quantitative patterns with qualitative explanations of adaptation constraints.

Based on the preceding theoretical and empirical arguments, the study tests two hypotheses:

H1: Higher multidimensional household vulnerability, incorporating household sensitivity, gendered vulnerability, and material-capacity constraints, is associated with a lower likelihood of adopting substantive climate adaptation measures and a lower intensity of household adaptation.

H2: Greater gendered household vulnerability is associated with a lower likelihood of adopting substantive climate adaptation measures.

2. Literature Review

2.1 Climate vulnerability and household adaptation

Vulnerability is not a directly observable trait but a relational condition produced through environmental pressures, socioeconomic circumstances and response capacity. Adger (2006) synthesizes vulnerability around susceptibility to harm and limited capacity to respond, whereas O'Brien et al. (2007) distinguish outcome-oriented interpretations from contextual approaches that emphasize the social conditions producing harm. Füssel (2007) similarly argues that vulnerability assessments must specify the system, attribute of concern, hazard and temporal reference. These distinctions are particularly important in coastal Bangladesh because households experiencing the same cyclone, flood or salinity event can face different consequences depending on housing, health, livelihood dependence, savings, gender relations and institutional reach.

Adaptation is analytically distinct from vulnerability. Smit and Wandel (2006) distinguish implemented adjustments from adaptive capacity, while Engle (2011) emphasizes governance, institutions and management as components of the capacity to adapt. Adger et al. (2003) similarly frame adaptation as a development process embedded in social and economic conditions. This distinction matters empirically: a raised house plinth or salt-tolerant crop is an observed adaptation, whereas savings, education, access to institutions or livelihood diversification are conditions that may enable such an adaptation. Treating an implemented adaptation simultaneously as a vulnerability indicator and an outcome risks creating mechanical circularity.

Bangladesh evidence reinforces this separation. Alam, Alam, and Mushtaq (2017) show that hazard-prone rural households perceive climatic changes and adopt both farm and non-farm strategies, but financial and informational constraints shape their choices. Alam, Alam, and Mushtaq (2016) demonstrate that institutional access and social capital influence adaptation decisions, while Aryal et al. (2020) identify assets and training as important determinants among coastal smallholders. Kabir et al. (2021) and Hasan et al. (2025) similarly show that household resources, credit and institutional support matter for adaptation. Adaptation therefore reflects an interaction between need and feasible action rather than a simple response to hazard intensity.

2.2 Gendered vulnerability and climate adaptation

Gendered climate vulnerability emerges through differences in resource control, labor obligations, mobility, safety, information and authority. Denton (2002) and Terry (2009) argue that climate vulnerability is shaped by development inequalities rather than biological difference. Kaijser and Kronsell (2014) extend this reasoning through intersectionality, showing that gender interacts with class, age, location and other social positions. Djoudi et al. (2016) caution against binary male-female comparisons that obscure intersecting inequalities. Kabeer's (1999) resources-agency-achievements framework is useful here because participation in

a household decision does not necessarily imply control over resources or the ability to implement the decision.

Coastal Bangladesh provides concrete examples of these relations. Water collection and water management can intensify women's time and health burdens under salinity and freshwater scarcity (Esha, 2024; Abedin et al., 2019). Shelter conditions can create privacy, sanitation and harassment concerns that shape evacuation decisions (Fatema et al., 2023). Saline water can create reproductive and menstrual-hygiene challenges that are simultaneously environmental, embodied and gendered (Khan et al., 2011; Hossain & Pal, 2025; Sinha et al., 2024). Hossain, Khan, and Ibn Farid (2025) show that women's agency under climatic pressure depends on combinations of enabling conditions, while Bari et al. (2024) demonstrate that gendered vulnerability varies with broader socioeconomic position. These findings justify an index that measures gendered mechanisms directly instead of assigning vulnerability on the basis of respondent sex.

2.3 Feminist Political Ecology

Feminist Political Ecology provides the principal lens for interpreting the gender dimension. Rocheleau, Thomas-Slayter, and Wangari (1996) place gendered knowledge, resource rights and environmental responsibilities at the center of political ecology. Elmhirst (2011) argues that feminist political ecologies examine how environmental subjectivities and inequalities are produced through power, while Nightingale (2011) demonstrates that gender is materially constituted through intersecting relations of class, caste and place. This perspective shifts analysis from the claim that women are inherently vulnerable to the institutional and material processes that distribute environmental burdens and adaptive opportunities.

FPE is especially relevant to adaptation because response strategies are political as well as technical. Eriksen, Nightingale, and Eakin (2015) show that adaptation is embedded in authority, knowledge and contested social relations. Gonda (2019) calls for gender-and-climate research to engage directly with power in adaptation policy and practice, and Sultana (2011) demonstrates how water insecurity is experienced through embodied and emotional geographies of access and control. In coastal Bangladesh, such a lens directs attention to who collects water, who can travel safely, who manages care dependants, who controls adaptation expenditure, whose information is considered actionable, and whose priorities enter local disaster institutions. This relational approach also helps avoid stereotypes. Arora-Jonsson (2011) critiques the repeated association of women with vulnerability and virtue, while Evertsen (2023) shows how coastal adaptation discourse in Bangladesh can construct women as risk subjects. The present study therefore conceptualizes gendered vulnerability as a formative set of safety, health, care, information, workload and decision-making constraints. It does not assume that a female respondent or a female-headed household is intrinsically more vulnerable.

2.4 IPCC climate-risk framework and multidimensional measurement

The study combines FPE with the contemporary IPCC climate-risk framework. The IPCC (2022) conceptualizes climate risk through interactions among hazard, exposure and vulnerability, with vulnerability referring to propensity or predisposition to be adversely affected. This distinction is important for empirical modeling: exposure may generate pressure or incentives to adapt, while sensitivity and limited capacity can constrain the ability to respond. Combining exposure indiscriminately into a vulnerability score can obscure these pathways when the research question concerns adaptation behavior.

Composite indices remain useful because household vulnerability is multidimensional, but their construction must be transparent. Hahn et al. (2009) demonstrate the practical value of normalized household indicators, while Hinkel (2011) warns that an index should be tailored to its analytical purpose. OECD/JRC guidance recommends explicit decisions on theoretical structure, normalization, weighting, aggregation and robustness (OECD & European Commission, Joint Research Centre, 2008). In Bangladesh, Uddin et al. (2019) use PCA to map coastal climate vulnerability, illustrating the value of empirically derived weights when many

indicators are correlated. PCA is also well established for multidimensional household indices in development research (Filmer & Pritchett, 2001; Vyas & Kumaranayake, 2006).

2.5 Vulnerability-adaptation relationship

The relationship between vulnerability and adaptation is theoretically ambiguous. Greater exposure or experienced loss may increase perceived need, but sensitivity can simultaneously erode the assets, health and labor required for investment. Alam (2017) shows that vulnerability changes across livelihood cycles, while Hoque et al. (2019) demonstrate that agricultural vulnerability in coastal Bangladesh reflects interacting livelihood and environmental conditions. Hoque, Quinn, and Sallu (2018) further show that adaptation opportunities and constraints differ across social-ecological and wealth positions. These studies imply that the households with the greatest adaptation need may not be those with the greatest capacity to act.

Institutions can mediate this conversion of need into action. Alam, Alam, and Mushtaq (2016) find that institutional access and social capital shape household adaptation, and Haque, Khan, and Choudhury (2024) show that multi-level institutions can facilitate early warning and adaptation technologies when coordination works effectively. Khan, Hasan, and Kabir (2022) identify local-government services and community-organization membership as important for adaptive capacity in southwest Bangladesh. Yet institutional presence is not equivalent to equitable access: Islam and Islam (2026) show that NGO-led adaptation governance can reproduce intersectional exclusion, and Chowdhury, Hossain, and Ibn Farid (2026) identify a policy-practice gap in gender-responsive community adaptation.

2.6 Conceptual framework

The conceptual framework separates climate-related exposure from household vulnerability, consistent with IPCC climate-risk framing, while using FPE to explain how vulnerability is socially produced through gendered labor, safety, mobility, agency and resource access. The PCA-weighted GSHVI combines household sensitivity, gendered vulnerability and material-capacity deficit. Institutional access is retained separately as a potentially enabling condition, and substantive household adaptation is represented by both adoption of at least one measure and the number of measures adopted. Exposure is also modeled separately, allowing the analysis to examine whether environmental pressure has an independent association with adaptation after household vulnerability is considered. The framework provides an analytical map linking the two research objectives to measurement, statistical modeling and qualitative interpretation.

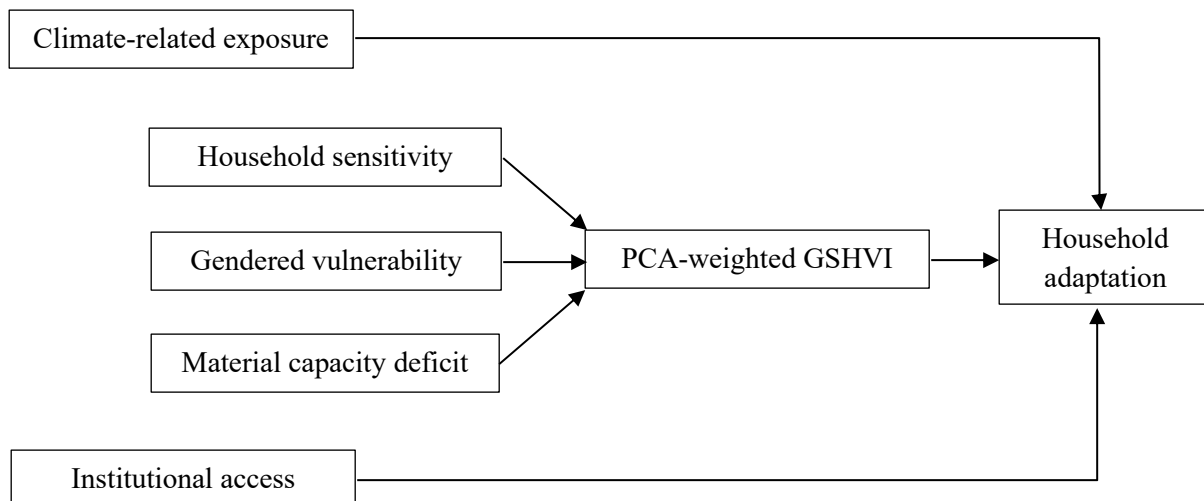


Figure 1: Conceptual framework

Theoretical basis: IPCC (2022) and Feminist Political Ecology (Rocheleau et al., 1996; Elmhirst, 2011; Gonda, 2019)

3. Materials and Methods

3.1 Study area

The study was conducted in Koyra Upazila of Khulna District in southwest coastal Bangladesh, focusing on Dakshin Bedkashi, Koyra Sader and Uttar Bedkashi unions. Koyra is characterized by tidal rivers, embankment-dependent settlements, climate-sensitive agriculture and fisheries, recurrent cyclones, salinity intrusion and freshwater constraints. These features are consistent with wider descriptions of the southwest coast (Brammer, 2014; Saha, 2017) and with recent empirical vulnerability research in Koyra and neighboring coastal upazilas (Khan et al., 2022; Hasan et al., 2025). The three unions also provide substantial internal variation in hazard exposure, infrastructure, material resources and institutional access, making them analytically useful for examining within-upazila differences.

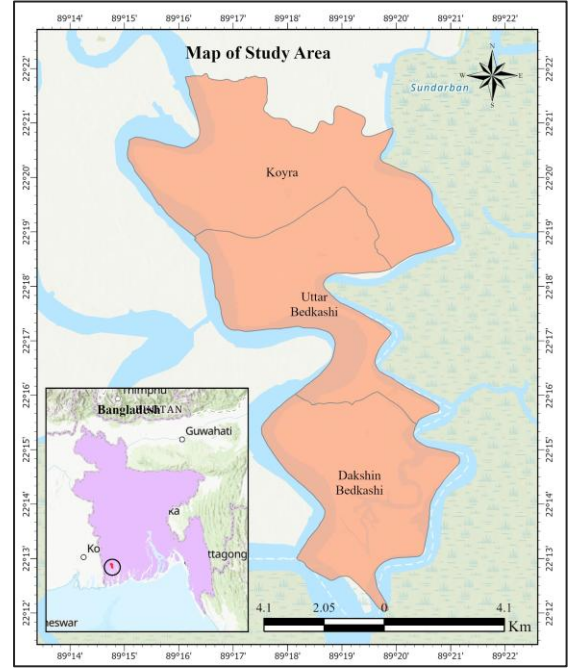


Figure 2: Study area

3.2 Research design and data sources

A quantitatively dominant convergent mixed-methods design was used. The quantitative strand comprised a household survey and supplied the principal inferential analysis, while the qualitative focus-group discussion (FGD) was used to explain, qualify and contextualize statistical patterns. The two strands were analyzed separately and integrated at interpretation through a joint display and narrative triangulation, following the convergent logic described by Creswell and Plano Clark (2018). Survey data was collected by using KoBoCollect mobile application. The instrument covered household composition, hazards, housing, water and sanitation, gender-specific safety and health, livelihoods, savings and debt, environmental change, institutions, coping, preparedness and adaptation.

The analytical qualitative data contained 15 structured FGD records, five from each study union. Participant categories were vulnerable households; adolescent girls; men engaged in farming, fishing, day labor and related livelihoods; elderly people and persons with disabilities; and members of local disaster-management structures.

3.3 Sampling strategy and sample-size determination

The household survey used a random sampling design. The sampling frame contained 8,661 households: 3,398 in Dakshin Bedkashi, 2,600 in Koyra Sader and 2,663 in Uttar Bedkashi. The required sample size was determined with the finite-population Yamane (1967) equation using a 5% margin of error.

$$n = \frac{N}{1 + Ne^2} \quad (1)$$

where n is the required sample size, N is the finite household population and e is the acceptable sampling error. Substituting $N=8,661$ and $e=0.05$ gives $n=382.34$, which was rounded to 383 households.

$$n_h = \frac{N_h}{N} n \quad (2)$$

Proportional allocation was then used to distribute the target sample among unions, where N_h is the number of households in stratum h and n_h is its allocated sample. The planned allocation was 150 households in Dakshin

Bedkashi, 115 in Koyra Sader and 118 in Uttar Bedkashi. The final valid analytical dataset retained the same overall N=383 but contained 149, 116 and 118 households respectively. Table 1 reports the target and achieved samples rather than treating the field allocation as perfectly realized.

Table 1: Sampling design

Union	Sampling-frame households	Share (%)	Calculated allocation	Target n	Achieved n
Dakshin Bedkashi	3,398	39.23	150.26	150	149
Koyra Sader	2,600	30.02	114.98	115	116
Uttar Bedkashi	2,663	30.75	117.76	118	118
Total	8,661	100.00	383.00	383	383

3.4 Analytical variables and data preparation

The primary analytical unit was the household. Respondent sex was retained as a control variable but was not used as a proxy for household-head gender because most female respondents were spouses rather than household heads. Climate-sensitive livelihood dependence was coded for households whose primary livelihood was agriculture, aquaculture/fishing, livestock or daily wage labor. Continuous household controls were respondent age and household size. Union fixed effects were included in regression models to account for systematic contextual differences among Dakshin Bedkashi, Koyra Sader and Uttar Bedkashi.

Index indicators were selected by combining the survey's original multidimensional risk structure with the conceptual requirements of IPCC vulnerability framing, FPE and prior household-index research. Indicators were oriented to a 0-1 scale before weighting. For vulnerability-positive indicators, larger values indicate greater exposure, sensitivity or gendered vulnerability; for capacity-positive dimensions, larger values indicate stronger material or institutional capacity. Binary items were coded 0/1, ordinal items were mapped to ordered 0-1 scores, and continuous items were rescaled where necessary. For water depth and self-sufficiency duration, extreme values were capped at the 99th percentile before min-max scaling to reduce leverage from a small number of observations.

3.5 PCA-based index construction

PCA was used as a weighting device rather than as a claim that all indicators reflect a single latent trait. This distinction is important because vulnerability is a formative construct: housing, WASH, health, gender relations, savings and institutional access can jointly produce vulnerability even when they are not interchangeable manifestations of one underlying variable. PCA nevertheless provides an empirical basis for weighting correlated indicators and has been used extensively for multidimensional household indices (Filmer & Pritchett, 2001; Vyas & Kumaranayake, 2006) and coastal vulnerability assessment in Bangladesh (Uddin et al., 2019). The general procedure followed Jolliffe and Cadima (2016), complemented by composite-index robustness guidance from OECD/JRC (2008) and Tate (2012, 2013).

PCA was conducted separately for five theoretically defined dimensions: climate-related exposure, household sensitivity, gendered vulnerability, material adaptive capacity and institutional access. Performing dimension-specific PCA preserved the conceptual structure rather than allowing statistically correlated but theoretically distinct indicators to collapse into a single undifferentiated component. Indicators were standardized before PCA:

$$Z_{ij} = \frac{x_{ij} - \bar{x}_j}{s_j} \quad (3)$$

where x_{ij} is household i 's value on indicator j , $\bar{x}_j$ is the sample mean and s_j is the sample standard deviation. Principal component scores are linear combinations of the standardized indicators:

$$PC_{ik} = \sum_{j=1}^p a_{jk} Z_{ij} \quad (4)$$

where a_{jk} is the coefficient for indicator j on component k . Sampling adequacy was assessed using the Kaiser-Meyer-Olkin (KMO) statistic and Bartlett's test of sphericity.

A KMO of at least 0.50 and a significant Bartlett test were treated as minimum evidence that PCA was usable, with higher KMO values indicating stronger adequacy (Kaiser, 1974; Bartlett, 1954). Horn's parallel analysis was used as the primary retention rule: observed eigenvalues were compared with the 95th-percentile eigenvalues from 1,000 random-data replications, and components were retained only when the observed eigenvalue exceeded the corresponding simulated threshold. The Kaiser eigenvalue-greater-than-one rule and scree plots were retained as complementary diagnostics and sensitivity checks.

Indicator weights were derived from squared loadings across all components retained within a dimension, weighted by each component's share of variance. Let l_{jk} denote the loading of indicator j on retained component k and v_k the proportion of variance explained by component k . Indicator contribution and normalized weight were calculated as:

$$C_j = \sum_{k=1}^m v_k l_{jk}^2 \quad (5)$$

$$w_j = \frac{C_j}{\sum_{r=1}^p C_r} \quad (6)$$

The PCA-weighted score for household i in dimension d was then calculated from the original oriented 0-1 indicators so that the final domain scores retained an intuitive scale:

$$D_{id} = \sum_{j=1}^{p_d} w_{jd} X_{ijd} \quad (7)$$

Material capacity was coded positively, so a material-capacity deficit was created as:

$$MCD_i = 1 - MC_i \quad (8)$$

A second-stage PCA of sensitivity, gendered vulnerability and material-capacity deficit was examined for domain weighting, but the three-domain matrix had KMO=0.455 and was therefore not considered adequate for PCA. Domain weights were consequently based on the relative proportion of variance retained by the primary parallel-analysis solution within the three constituent domains. This information-retention rule produced weights of 0.3621 for sensitivity, 0.3561 for gendered vulnerability and 0.2819 for material-capacity deficit. The PCA-weighted Gender-Sensitive Household Vulnerability Index (GSHVI) was therefore:

$$GSHVI_i = 0.3621S_i + 0.3561GV_i + 0.2819MCD_i \quad (9)$$

Exposure was deliberately excluded from the GSHVI and entered separately in regression models, consistent with IPCC (2022). Institutional access was likewise retained separately because institutions can mediate the conversion of household resources and risk awareness into action (Engle, 2011; Alam et al., 2016; Haque et al., 2024). This architecture makes the GSHVI an explanatory household-vulnerability measure rather than an all-purpose risk index.

3.6 Indicator specification, correlations and PCA weights

Table 2 reports every indicator used in the five PCA dimensions. Each indicator occupies a separate row, with its Pearson correlation with its corresponding PCA-weighted dimension score, PCA weight, and literature basis. Weights are dimension-specific and sum to one within each dimension.

Table 2: Indicator–dimension Pearson correlations, PCA-derived weights, and supporting literature

Dimension	Indicator	Pearson r	PCA weight	Sources
Exposure	Cyclone/storm surge	0.720	0.1431	IPCC, 2022; Saha, 2017; Uddin et al., 2019
	Flooding	0.499	0.0770	Brammer, 2014; Uddin et al., 2019
	Salinity intrusion	0.224	0.0518	Saha, 2017; Abedin et al., 2019; Islam et al., 2020
	Waterlogging	0.570	0.0928	Brammer, 2014; Khan et al., 2022
	River erosion/embankment collapse	0.762	0.0967	Brammer, 2014; Khan et al., 2022
	Heat stress	0.079	0.0846	IPCC, 2022; Ahmed et al., 2026
	Thunderstorms	-0.372	0.1328	IPCC, 2022; Uddin et al., 2019
	Peak physical impact severity	0.594	0.1068	Hahn et al., 2009; Khan et al., 2022
	Duration of negative effects	0.548	0.1309	Füssel, 2007; Uddin et al., 2019
	Perceived worsening of hazard frequency/intensity	0.536	0.0834	Alam et al., 2017; Aryal et al., 2020
Sensitivity	Wall material fragility	0.112	0.0325	Cutter et al., 2003; Hahn et al., 2009
	Roof material fragility	0.002	0.0812	Hahn et al., 2009; Khan et al., 2022
	Floor material fragility	0.085	0.0066	Hahn et al., 2009; Uddin et al., 2019
	Disaster-related house damage severity	0.477	0.0602	Cutter et al., 2003; Uddin et al., 2019
	Frequency of house damage/flooding	0.387	0.0650	Hahn et al., 2009; Khan et al., 2022
	Water depth inside house	-0.001	0.0554	Uddin et al., 2019; Hoque et al., 2019
	Travel time/inaccessibility to cyclone shelter	0.138	0.0267	Fatema et al., 2023; Khan et al., 2022
	Shelter access path unusable during disaster	0.270	0.0549	Fatema et al., 2023; Haque et al., 2024
	Unsafe drinking-water quality	0.320	0.0286	Abedin et al., 2019; Hossain & Pal, 2025
	Post-disaster water salinity/contamination	0.663	0.0568	Abedin et al., 2019; Saha, 2017
	Drinking-water source damaged/flooded	0.636	0.0590	Abedin et al., 2019; Uddin et al., 2019
	Toilet facility vulnerability	0.167	0.0668	Fatema et al., 2023; Sinha et al., 2024
	Toilet unusability	0.004	0.0249	Fatema et al., 2023; Esha, 2024
	Protective embankment condition	0.464	0.0564	Brammer, 2014; Khan et al., 2022
	History of embankment failure	0.123	0.0148	Brammer, 2014; Uddin et al., 2019
	Nearby embankment weakness	0.494	0.0443	Khan et al., 2022; Hasan et al., 2025
	Post-disaster road impassability	0.618	0.0529	Haque et al., 2024; Khan et al., 2022
	Primary livelihood disruption	0.527	0.0465	Aryal et al., 2020; Hoque et al., 2019
	Productive/household asset-loss breadth	0.127	0.0073	Cutter et al., 2003; Alam, 2017
	Chronic illness/disability constraining evacuation	0.207	0.0582	IPCC, 2022; Djoudi et al., 2016
	Decline in agricultural/fishing productivity	0.499	0.0508	Islam et al., 2020; Hoque et al., 2019
	Increase in water-borne disease burden	0.450	0.0441	Abedin et al., 2019; Hossain & Pal, 2025
	Household dependency ratio	0.043	0.0061	Cutter et al., 2003; Hahn et al., 2009
Gendered vulnerability	Unsafe/inaccessible water for women and girls	0.442	0.0423	Esha, 2024; Sultana, 2011
	Sanitation: lack of privacy	0.429	0.0530	Fatema et al., 2023; Sinha et al., 2024
	Sanitation: distance at night	0.079	0.0293	Fatema et al., 2023; Djoudi et al., 2016

Dimension	Indicator	Pearson r	PCA weight	Sources
	Sanitation: fear of harassment/safety	0.010	0.0509	Fatema et al., 2023; Terry, 2009
	Sanitation: facility flooded/unusable	0.251	0.0491	Fatema et al., 2023; Esha, 2024
	Sanitation: restricted timing	0.183	0.0294	Fatema et al., 2023; Sultana, 2011
	Sanitation: travel far for open defecation	0.170	0.0122	Fatema et al., 2023; Sinha et al., 2024
	Sanitation: lack of water	0.695	0.0741	Esha, 2024; Sinha et al., 2024
	Perceived safety risk in cyclone shelters	0.227	0.0296	Fatema et al., 2023; Bari et al., 2024
	Lack of separate lockable sanitation in shelter	0.249	0.0392	Fatema et al., 2023; Roy et al., 2022
	Evacuation: safety/harassment concern	0.034	0.0403	Fatema et al., 2023; Bari et al., 2024
	Evacuation: carrying dependants	0.233	0.0313	Djouidi et al., 2016; MacGregor, 2009
	Evacuation: managing belongings	0.331	0.0425	Denton, 2002; Hossain et al., 2025
	Evacuation: appropriate clothing constraint	-0.111	0.0255	Fatema et al., 2023; Terry, 2009
	Evacuation: menstrual-product access	0.104	0.0395	Sinha et al., 2024; Fatema et al., 2023
	Evacuation: mobility/disability constraint	0.085	0.0132	Djouidi et al., 2016; Kaijser & Kronsell, 2014
	Evacuation: lack of information	0.614	0.0637	Denton, 2002; Haque et al., 2024
	Menstrual-hygiene difficulty during disasters	0.093	0.0042	Sinha et al., 2024; Hossain & Pal, 2025
	Post-disaster prenatal/postnatal care constraint	-0.008	0.0166	Khan et al., 2011, 2014; Hossain & Pal, 2025
	Male-only evacuation/preparedness decision-making	-0.194	0.0458	Kabeer, 1999; Bari et al., 2024
	Early-warning inequity within household	0.330	0.0635	Denton, 2002; Haque et al., 2024
	Women's income disproportionately affected	-0.213	0.0665	Bari et al., 2024; Hossain et al., 2025
	Environmental burden: increased water-collection time/distance	0.085	0.0197	Esha, 2024; Sultana, 2011
	Environmental burden: health problems	0.201	0.0236	Khan et al., 2011; Hossain & Pal, 2025
	Environmental burden: increased domestic workload	0.128	0.0351	MacGregor, 2009; Esha, 2024
	Environmental burden: reduced homestead/poultry income	0.413	0.0404	Bari et al., 2024; Aryal et al., 2020
	Environmental burden: hygiene/sanitation difficulty	0.295	0.0196	Sinha et al., 2024; Fatema et al., 2023
Material capacity	Household savings	0.919	0.3360	Filmer & Pritchett, 2001; Aryal et al., 2020
	Income-source diversification	0.794	0.3536	Alam et al., 2017; Hasan et al., 2025
	Post-disaster self-sufficiency duration	0.556	0.2430	Hahn et al., 2009; Alam, 2017
	Household educational capital	0.054	0.0036	Vyas & Kumaranayake, 2006; Khan et al., 2022
	Debt-free disaster recovery	-0.052	0.0638	Alam et al., 2016; Hasan et al., 2025
Local access	Needs of women/vulnerable groups considered in local planning	0.529	0.0844	Roy et al., 2022; Chowdhury et al., 2026
	Disaster/climate adaptation training	0.679	0.0974	Aryal et al., 2020; Hasan et al., 2025

Dimension	Indicator	Pearson r	PCA weight	Sources
	UDMC awareness/participation	0.715	0.1197	Khan et al., 2022; Haque et al., 2024
	Early-warning channel diversity	0.021	0.0279	Haque et al., 2024; Engle, 2011
	Early-warning timeliness and clarity	-0.110	0.0352	Haque et al., 2024; Khan et al., 2022
	Perceived UDMC inclusiveness	0.064	0.0396	Chowdhury et al., 2026; Islam & Islam, 2026
	Perceived fairness/transparency of relief	0.173	0.0301	Alam et al., 2016; Islam & Islam, 2026
	Formal safety-net access	0.583	0.0677	Engle, 2011; Khan et al., 2022
	Safety-net continuity after disaster	-0.409	0.0744	Engle, 2011; Chowdhury et al., 2026
	Female/community-group membership	0.712	0.0937	Khalil et al., 2021; Khan et al., 2022
	Community-group support during/after disaster	0.813	0.1401	Khalil et al., 2021; Alam et al., 2016
	Direct contact pathway to UDMC/Union Parishad	0.321	0.0619	Haque et al., 2024; Islam & Islam, 2026
	Institutional grievance responsiveness	0.784	0.1279	Chowdhury et al., 2026; Islam & Islam, 2026

(Note: Pearson r represents the descriptive correlation between each oriented indicator and its corresponding PCA-weighted dimension score)

3.7 Index sensitivity and robustness analysis

Sensitivity analysis was treated as part of index validation rather than as a post hoc exercise. Four alternatives were compared with the primary parallel-analysis GSHVI: (i) Kaiser-retention PCA; (ii) an equal-weight benchmark using the same indicator set; (iii) a categorical-aware heterogeneous-correlation PCA; and (iv) an exposure-inclusive PCA risk index. For the heterogeneous-correlation specification, polychoric correlations were estimated for binary/ordinal indicator pairs and Spearman rank correlations for pairs involving continuous indicators; the resulting matrix was projected to the nearest positive-semidefinite correlation matrix before PCA, and the primary retained-component counts were held fixed to isolate the effect of correlation choice (Holgado-Tello et al., 2010). Robustness was assessed using Pearson and Spearman correlations, same-quintile agreement, top-20% and top-40% overlap, and the stability of the vulnerability-adaptation regression coefficient.

Additional checks examined both measurement and outcome robustness. Leave-one-indicator-out analysis recalculated the GSHVI after sequentially excluding each sensitivity, gendered-vulnerability or material-capacity indicator while preserving the primary retained-component count in the affected domain. PCA-weight stability was assessed with 300 nonparametric household bootstrap resamples. Vulnerability thresholds were varied across the top 20%, top 33% and top 40% of the GSHVI distribution. To test whether the binary adaptation outcome was driven by one measure, AdaptAny was reconstructed four times after excluding each substantive adaptation in turn and the primary logistic model was re-estimated.

3.8 Measurement of household adaptation

The outcome measure distinguishes substantive material or livelihood adaptation from short-term preparedness. Four survey responses were treated as substantive adaptations: raising the house plinth, homestead gardening as a food or livelihood backup, use of salt-tolerant crops and storm-resistant housing features. These practices correspond to structural and agricultural adaptations documented in coastal Bangladesh (Aryal et al., 2020; Islam et al., 2020; Hasan et al., 2025). Keeping documents in a safe place was treated as preparedness rather than substantive adaptation because it protects recovery capability without

materially modifying housing or livelihood exposure. Raised plinth was therefore excluded from all vulnerability-index inputs to avoid predictor-outcome circularity.

Two dependent variables were constructed. AdaptAny equals 1 when the household reported at least one of the four substantive adaptations and 0 otherwise. AdaptCount is the number of substantive measures adopted, ranging from 0 to 4. These outcomes capture adoption and intensity respectively; they do not imply that every adaptation is equally effective or sustainable.

3.9 Statistical models and diagnostics

Descriptive statistics summarized household characteristics, hazards, PCA dimensions and adaptation. Multivariable models used standardized continuous indices, so odds ratios (ORs) and incidence-rate ratios (IRRs) represent a one-standard-deviation difference. Standard errors were clustered across 27 union-by-ward clusters. To reduce reliance on large-cluster asymptotics, the cluster sandwich covariance used the finite-sample correction and statistical inference was referenced to a t distribution with $G-1=26$ degrees of freedom, consistent with the small-cluster considerations discussed by Cameron and Miller (2015). Cluster-pairs bootstrap checks were also conducted for the principal total-index and component coefficients. All models controlled for respondent age, household size, respondent sex, climate-sensitive livelihood dependence and union fixed effects.

The primary binary logistic model estimated the association between overall household vulnerability and adoption:

$$\ln \left[\frac{P(A_i = 1)}{1 - P(A_i = 1)} \right] = \beta_0 + \beta_1 \text{GSHVI}_i + \beta_2 E_i + \beta_3 \text{IA}_i + \gamma' X_i + \delta_u \quad (10)$$

where E_i is exposure, IA_i institutional access, X_i the vector of household controls and δ_u the union fixed effects. A decomposed model replaced the composite GSHVI with its major dimensions:

$$\text{logit}(P_i) = \beta_0 + \beta_1 E_i + \beta_2 S_i + \beta_3 \text{GV}_i + \beta_4 \text{MC}_i + \beta_5 \text{IA}_i + \gamma' X_i + \delta_u \quad (11)$$

A third model examined whether the association between exposure and adaptation varied with gendered vulnerability, without simultaneously including a composite that already contains the gender component:

$$\text{logit}(P_i) = \beta_0 + \beta_1 E_i + \beta_2 \text{GV}_i + \beta_3 (E_i \times \text{GV}_i) + \beta_4 S_i + \beta_5 \text{MC}_i + \beta_6 \text{IA}_i + \gamma' X_i + \delta_u \quad (12)$$

Adaptation intensity was modeled with a Poisson generalized linear model:

$$\ln[E(Y_i | X_i)] = \beta_0 + \beta_1 \text{GSHVI}_i + \beta_2 E_i + \beta_3 \text{IA}_i + \gamma' X_i + \delta_u \quad (13)$$

Multicollinearity was assessed with variance inflation factors (VIFs). Logistic-model performance was evaluated with Akaike and Bayesian information criteria (AIC/BIC), area under the receiver-operating-characteristic curve (AUC), McFadden and Nagelkerke pseudo- R^2 , and the Hosmer-Lemeshow calibration test. Poisson adequacy was assessed using Pearson dispersion and comparison with a negative-binomial specification, following Cameron and Trivedi (2013). Small-cluster robustness was evaluated with cluster-pairs bootstrap confidence intervals for the principal coefficients. Because the data are cross-sectional, coefficients are interpreted as associations rather than causal effects.

3.10 Qualitative analysis and mixed-method integration

FGD records were analyzed thematically using the broad stages of familiarization, coding, theme development and interpretation described by Braun and Clarke (2006). Coding proceeded in two analytic passes. The first used deductive categories from FPE and the quantitative framework—resource access, agency, care and labor, mobility, safety, health, information and institutional power. The second recoded the records for locally recurring themes including embankment weakness, distance to shelters, saline water, debt-financed recovery

and inadequate rescue resources. A structured matrix compared themes by union and participant category, and a consistency pass returned to the original archived records before interpretation.

4. Results

4.1 Household characteristics and hazard profile

The final sample comprised 383 households: 149 in Dakshin Bedkashi, 116 in Koyra Sader and 118 in Uttar Bedkashi. Respondents had a mean age of 38.3 years (SD=10.9) and a mean household size of 4.36 persons (SD=1.65). Women constituted 315 respondents (82.2%), but respondent sex should not be interpreted as household-head sex: 246 respondents were spouses, 87 were male heads, 35 were female heads and 15 were other family members. Daily wage labor was the most common primary livelihood (49.3%), followed by agriculture (21.1%) and aquaculture/fishing (11.7%); 85.4% of households were classified as dependent on a climate-sensitive primary livelihood.

Exposure to multiple hazards was widespread. Salinity intrusion was reported by 84.9% of households, cyclone or storm surge by 74.7%, river erosion or embankment collapse by 55.1%, flooding by 53.0%, waterlogging by 52.7%, heat stress by 44.1% and thunderstorms by 24.3%. Material and institutional buffers were limited: 64.8% of households reported no savings, only 14.1% had received disaster-preparedness or climate-adaptation training and 75.7% were unaware of the Union Disaster Management Committee (UDMC).

Table 3: Characteristics of surveyed households (N=383)

Characteristic	Value
Dakshin Bedkashi	149 (38.9%)
Koyra Sader	116 (30.3%)
Uttar Bedkashi	118 (30.8%)
Female respondents	315 (82.2%)
Mean age	38.3 (SD 10.9)
Mean household size	4.36 (SD 1.65)
Climate-sensitive primary livelihood	327 (85.4%)
No household savings	248 (64.8%)
Received disaster/adaptation training	54 (14.1%)
Unaware of UDMC	290 (75.7%)

4.2 Household adaptation profile

Overall, 235 households (61.4%) reported at least one substantive adaptation, and the mean adaptation count was 0.95 (SD=0.92). The distribution was concentrated at low counts: 148 households adopted none, 126 adopted one, 89 adopted two, 19 adopted three and one household reported all four measures. Raised house plinths were the most common substantive adaptation (38.1%), followed by salt-tolerant crops (26.4%), homestead gardening (25.1%) and storm-resistant housing features (5.7%). Keeping documents safe was reported by 37.3% of households but remained classified as preparedness.

Table 4: Household adaptation measures by union

Adaptation measure	Dakshin Bedkashi	Koyra Sader	Uttar Bedkashi	Overall
Raised house plinth	49.7	39.7	22.0	38.1
Homestead gardening	43.0	13.8	13.6	25.1
Salt-tolerant crops	40.9	11.2	22.9	26.4
Storm-resistant housing	8.7	6.9	0.8	5.7
At least one substantive adaptation	91.3	44.0	40.7	61.4
Mean adaptation count	1.42	0.72	0.59	0.95

4.3 PCA suitability and component retention

PCA diagnostics supported dimension-specific component extraction, although adequacy varied. KMO values were 0.797 for exposure, 0.780 for sensitivity, 0.717 for gendered vulnerability and 0.774 for institutional access, indicating acceptable to good sampling adequacy. Material capacity had a lower KMO of 0.570, above the minimum threshold but indicative of a weaker shared-correlation structure. Bartlett's tests were significant for all five dimensions ($p < 0.001$), rejecting identity correlation matrices. Under the primary Horn parallel-analysis criterion, three components were retained for exposure, four for sensitivity, five for gendered vulnerability, one for material capacity and three for institutional access, explaining 75.8%, 48.6%, 47.7%, 37.8% and 52.2% of variance respectively. The Kaiser rule retained more components in four dimensions and was therefore treated as a robustness specification rather than the principal retention rule.

Table 5: PCA suitability, component retention and explained variance

Dimension	Indicators	KMO	Bartlett χ^2	df	p	Parallel PCs	Kaiser PCs	Primary retained variance %
Exposure	10	0.797	2153.8	45	<0.001	3	3	75.8
Sensitivity	23	0.780	2773.0	253	<0.001	4	7	48.6
Gendered vulnerability	27	0.717	3140.0	351	<0.001	5	9	47.7
Material capacity	5	0.570	253.7	10	<0.001	1	2	37.8
Institutional access	13	0.774	1353.4	78	<0.001	3	4	52.2

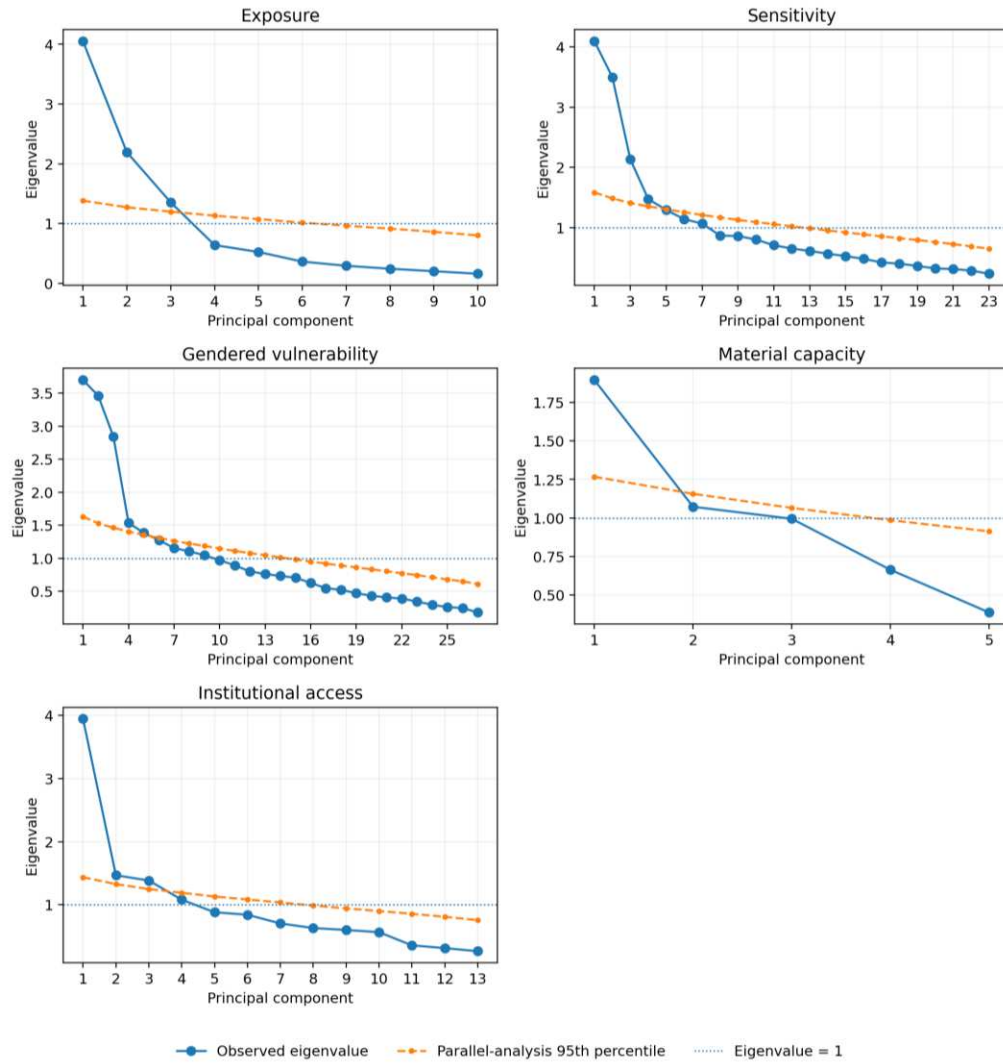


Figure 3: Scree and parallel-analysis diagnostics for different PCA dimensions

Table 6: Eigenvalues and variance explained by principal components retained by parallel analysis

Dimension	PC	Eigenvalue	Variance %	Cumulative %
Exposure	1	4.049	40.38	40.38
	2	2.193	21.87	62.25
	3	1.355	13.51	75.76
Sensitivity	1	4.093	17.75	17.75
	2	3.499	15.17	32.92
	3	2.133	9.25	42.17
	4	1.472	6.39	48.56
Gendered vulnerability	1	3.699	13.66	13.66
	2	3.463	12.79	26.46
	3	2.843	10.50	36.96
	4	1.536	5.67	42.64
	5	1.384	5.11	47.75
Material capacity	1	1.895	37.80	37.80
Institutional access	1	3.946	30.27	30.27
	2	1.467	11.26	41.53
	3	1.384	10.62	52.15

4.4 Component structure and PCA-derived weights

The retained components did not reduce to one simple latent dimension, which is consistent with the formative character of the index. Exposure PC1 was dominated by cyclone/storm surge, impact duration, thunderstorms and peak impact, whereas PC2 emphasized flooding, waterlogging and salinity. The four sensitivity components separated housing fragility, WASH/infrastructure, shelter/health constraints and residual water/toilet conditions. The five gendered-vulnerability components distinguished information and warning inequity, sanitation and safety, household-belonging and workload burdens, water collection/care constraints and sanitation distance. Material capacity retained one dominant component centered on diversification, savings and post-disaster self-sufficiency. Institutional access retained three components representing organizational connection, inclusiveness/warning systems and direct institutional contact.

Table 7: Interpretation of retained principal components based on dominant loadings

Dimension	Component	Largest absolute loadings
Exposure	PC1	Cyclone/storm surge (.866); duration (.842); thunderstorms (−.837); peak impact (.720)
	PC2	Waterlogging (.824); flooding (.807); salinity (.614)
	PC3	Heat stress (.654); erosion (.590); perceived worsening (.403)
Sensitivity	PC1	Roof fragility (.784); damage frequency (−.698); toilet vulnerability (.673); damage severity (−.612)
	PC2	Water-source damage (.761); embankment condition (.730); salinity (.728); road impassability (.725)
	PC3	Shelter travel (.566); chronic illness/disability (.459); productivity decline (.456)
	PC4	Unsafe drinking water (.559); toilet unusability (−.553); embankment failure (−.419)
Gendered vulnerability	PC1	Lack of information (.713); sanitation water (.710); women's income (−.704); warning inequity (.632)
	PC2	Sanitation flooded (.695); harassment (−.559); male-only decision (−.557); evacuation safety (−.554)
	PC3	Managing belongings (.597); restricted sanitation timing (.595); domestic workload (.547)
	PC4	Water-collection burden (.540); evacuation safety (.443); carrying dependants (−.345)
	PC5	Sanitation distance at night (.758); travel for open defecation (.459)
Material capacity	PC1	Income diversification (.819); savings (.798); self-sufficiency (.679)
Institutional access	PC1	Group support (.829); grievance responsiveness (.790); UDMC awareness (.770); training (.695)
	PC2	UDMC inclusiveness (.706); warning-channel diversity (−.581); relief fairness (.494)
	PC3	Direct contact pathway (.743); needs consideration (−.576); warning clarity (.521)

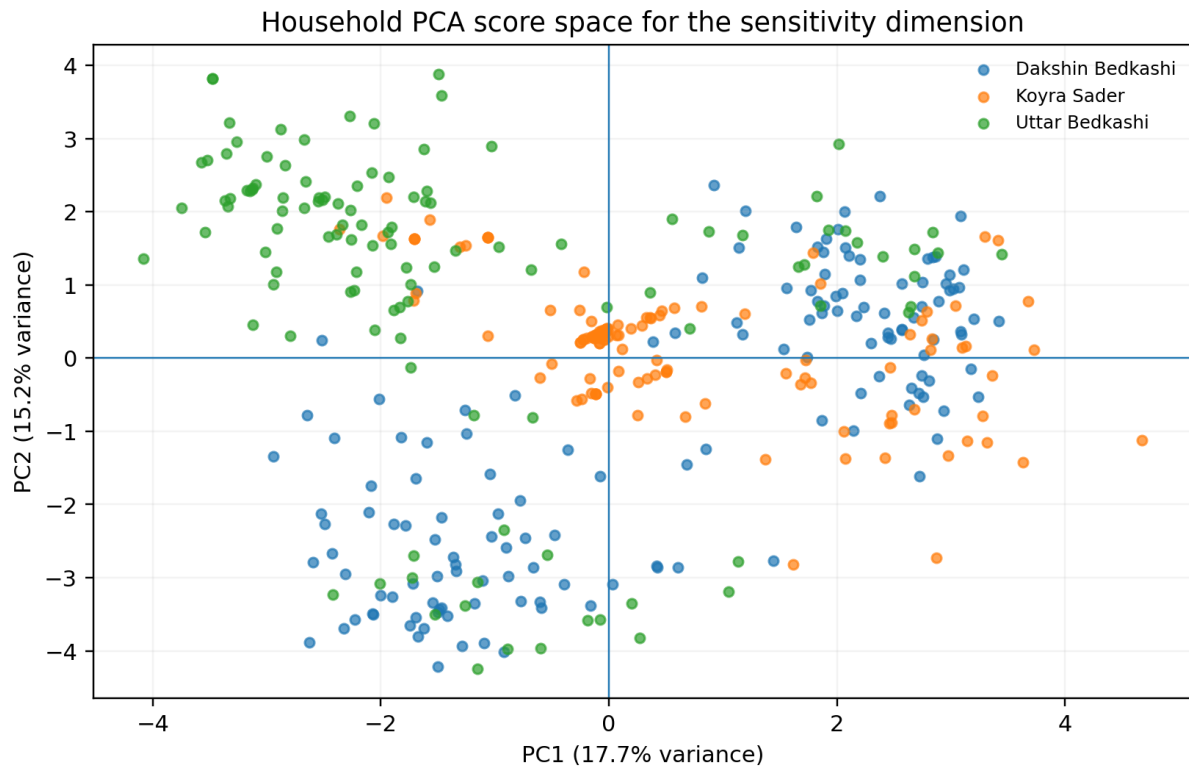


Figure 4: Household PCA score space for the first two sensitivity components, by union.

4.5 PCA-weighted household vulnerability and spatial differences

The primary parallel-analysis GSHVI had a mean of 0.518 (SD=0.104) and ranged from 0.296 to 0.726. Mean vulnerability was highest in Uttar Bedkashi (0.594), followed by Koyra Sader (0.533) and Dakshin Bedkashi (0.447). The decomposition shows why vulnerability cannot be inferred from exposure alone. Dakshin Bedkashi had high exposure (0.616) but stronger material capacity (0.470) and lower gendered vulnerability (0.351). Uttar Bedkashi combined high exposure (0.600), the highest sensitivity (0.586), the highest gendered vulnerability (0.462) and weak material capacity (0.230). Koyra Sader had the lowest exposure (0.372), but very low material capacity (0.200) raised its overall household-vulnerability score.

Table 8: PCA-weighted analytical dimensions and adaptation by union

Union	Exposure	Sensitivity	Gendered vuln.	Material capacity	Institutional access	GSHVI	Any adapt. %	Mean count
Dakshin Bedkashi	0.616	0.477	0.351	0.470	0.358	0.447	91.3	1.42
Koyra Sader	0.372	0.460	0.396	0.200	0.211	0.533	44.0	0.72
Uttar Bedkashi	0.600	0.586	0.462	0.230	0.332	0.594	40.7	0.59
Overall	0.537	0.505	0.399	0.314	0.305	0.518	61.4	0.95

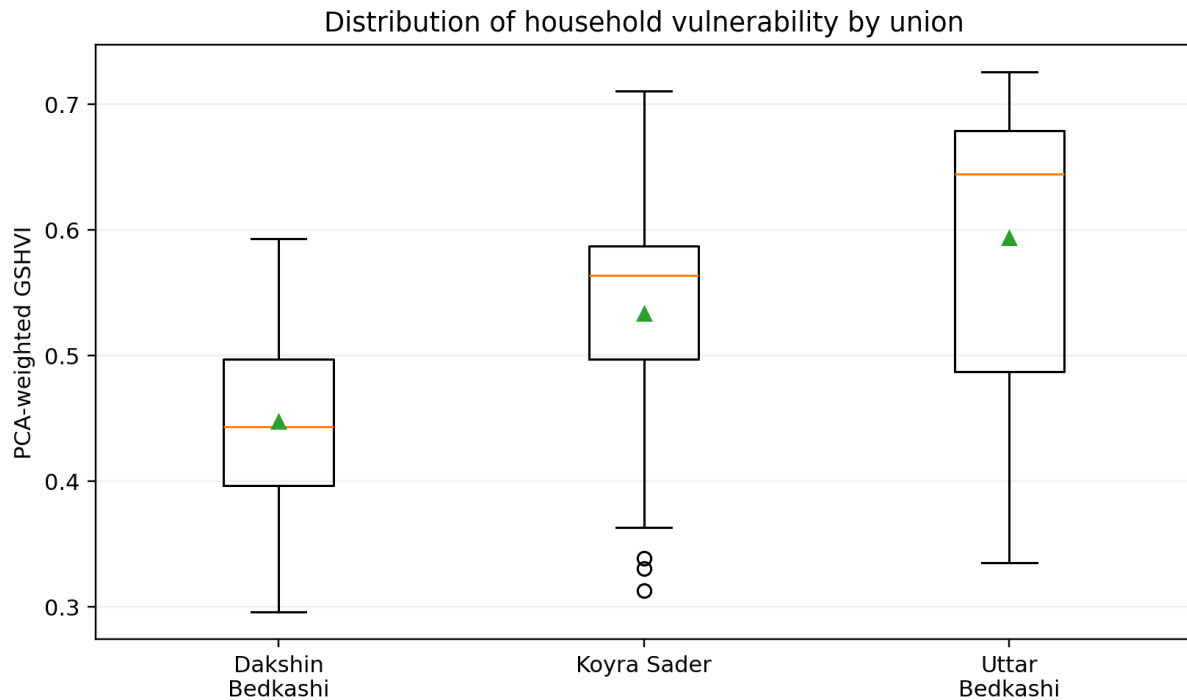


Figure 5: Distribution of the PCA-weighted GSHVI by union (*triangles indicate union means*)

4.6 Index sensitivity and robustness

Household vulnerability rankings were highly stable across alternative component-retention, weighting and correlation assumptions. The Kaiser-retention index correlated 0.991 (Spearman) with the primary parallel-analysis GSHVI and placed 87.5% of households in the same vulnerability quintile. The categorical-aware heterogeneous-correlation specification correlated 0.995 and retained 90.1% in the same quintile, indicating that the primary ranking was not dependent on treating ordinal responses as interval-scaled Pearson variables. The equal-weight benchmark was somewhat less concordant but still strongly correlated ($\rho=0.962$). In contrast, reincorporating exposure into an overall risk index reduced the rank correlation to 0.709 and same-quintile agreement to 44.4%, showing that the conceptual treatment of exposure matters more than the weighting rule itself.

Table 9: Sensitivity of household vulnerability rankings to index specification

Index specification	Spearman ρ	Pearson r	Same quintile %	Top-20 overlap %	Top-40 overlap %
Parallel-analysis PCA (primary)	1.000	1.000	100.0	100.0	100.0
Kaiser-retention PCA	0.991	0.987	87.5	94.8	94.8
Categorical-aware heterogeneous PCA	0.995	0.996	90.1	98.7	96.7
Equal-weight benchmark	0.962	0.955	72.6	79.2	88.9
Exposure-inclusive PCA risk	0.709	0.717	44.4	80.5	63.4

Leave-one-indicator-out analysis showed that most individual sensitivity and gendered-vulnerability indicators had very little influence on household rankings, generally preserving Spearman correlations above 0.994. Material-capacity indicators were more influential: removing household savings reduced the correlation with the primary GSHVI to 0.906, while removing income diversification reduced it to 0.957. Bootstrap weight analysis showed that the primary material-capacity weights for diversification (0.354), savings (0.336) and

self-sufficiency (0.243) were comparatively stable; educational capital carried a very small primary weight (0.004) and showed the greatest proportional uncertainty. These diagnostics identify material capacity as the part of the index most sensitive to indicator specification without overturning the overall ranking pattern.

Table 10: Sensitivity of the vulnerability-adaptation association to alternative index specifications

Specification	Vulnerability OR	95% t(26) CI	p	AIC	AUC
Parallel-analysis PCA (primary)	0.134	0.052–0.344	<0.001	284.7	0.924
Kaiser-retention PCA	0.161	0.054–0.487	0.002	296.1	0.919
Categorical-aware heterogeneous PCA	0.137	0.055–0.344	<0.001	282.8	0.924
Equal-weight benchmark	0.216	0.078–0.601	0.005	310.6	0.908
Exposure-inclusive PCA risk	0.180	0.051–0.634	0.010	319.8	0.898

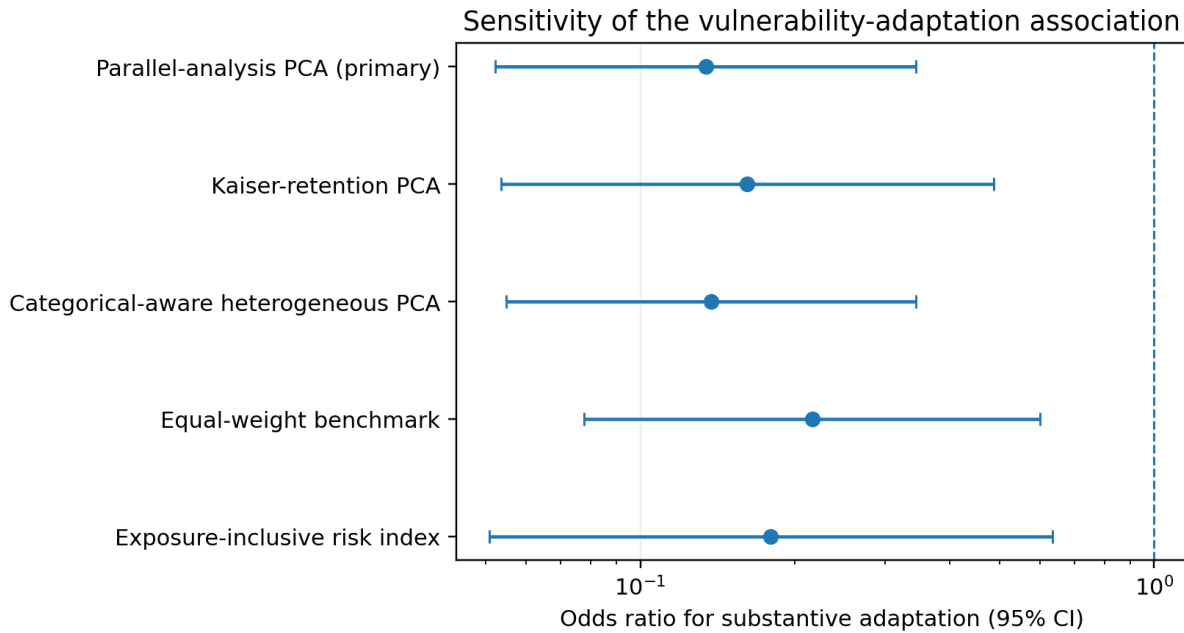


Figure 6: Robustness of the vulnerability–adaptation odds ratio across alternative index specifications.

The adaptation outcome was also robust to the composition of the four-measure endpoint. Excluding raised plinth produced OR=0.344 (95% CI 0.191–0.621), excluding homestead gardening OR=0.261 (0.134–0.512), excluding salt-tolerant crops OR=0.261 (0.139–0.491), and excluding storm-resistant housing OR=0.136 (0.053–0.351); all $p \leq 0.001$ under the t(26)-referenced cluster correction. The negative vulnerability-adaptation association therefore was not generated by any single adaptation measure.

4.7 Multivariable determinants of adaptation

The primary parallel-analysis logistic model showed a strong negative association between household vulnerability and substantive adaptation. After adjustment for exposure, institutional access, respondent age, household size, respondent sex, climate-sensitive livelihood dependence and union fixed effects, a one-standard-deviation increase in GSHVI was associated with OR=0.134 (95% t(26) CI 0.052–0.344, $p < 0.001$), equivalent to approximately 86.6% lower odds of reporting at least one substantive adaptation. Exposure was not independently associated with adaptation (OR=0.886, $p = 0.773$), whereas institutional access was positively associated in the total-index model (OR=1.950, 95% CI 1.070–3.554, $p = 0.031$).

The decomposed model identified sensitivity and material capacity as the clearest household mechanisms. Sensitivity was negatively associated with adaptation (OR=0.315, 95% CI 0.139–0.715, $p = 0.008$), whereas

material capacity was strongly positive (OR=5.861, 95% CI 2.170–15.829, $p=0.001$). Institutional access was also positive (OR=1.662), although the $t(26)$ -referenced p value was 0.079 and the 95% CI included one (0.939–2.941), so its independent association is less stable than that of sensitivity or material capacity. Gendered vulnerability showed no independent main effect (OR=0.937, $p=0.883$), and neither exposure nor the household controls was statistically significant.

Table 11: Cluster-robust logistic regression models of substantive adaptation

Predictor	Primary GSHVI model OR (95% t(26) CI); p	Component model OR (95% t(26) CI); p
GSHVI (1 SD)	0.134 (0.052–0.344); $p<0.001$	—
Exposure (1 SD)	0.886 (0.378–2.077); $p=0.773$	0.905 (0.421–1.946); $p=0.790$
Sensitivity (1 SD)	—	0.315 (0.139–0.715); $p=0.008$
Gendered vulnerability (1 SD)	—	0.937 (0.379–2.316); $p=0.883$
Material capacity (1 SD)	—	5.861 (2.170–15.829); $p=0.001$
Institutional access (1 SD)	1.950 (1.070–3.554); $p=0.031$	1.662 (0.939–2.941); $p=0.079$
Respondent age (1 SD)	0.992 (0.710–1.386); $p=0.962$	1.054 (0.721–1.542); $p=0.778$
Household size (1 SD)	0.936 (0.674–1.299); $p=0.680$	0.854 (0.578–1.264); $p=0.416$
Female respondent	0.896 (0.341–2.350); $p=0.816$	0.880 (0.314–2.467); $p=0.801$
Climate-sensitive livelihood	0.758 (0.307–1.868); $p=0.533$	0.865 (0.358–2.089); $p=0.738$
Koyra Sader (vs Dakshin)	0.207 (0.021–2.000); $p=0.165$	0.164 (0.020–1.344); $p=0.089$
Uttar Bedkashi (vs Dakshin)	0.445 (0.081–2.451); $p=0.338$	0.419 (0.067–2.608); $p=0.337$

Model diagnostics supported the total-index specification. The primary GSHVI model had AIC=284.7, BIC=324.2, AUC=0.924, McFadden pseudo- $R^2=0.482$ and Nagelkerke $R^2=0.644$; the Hosmer-Lemeshow test was not significant ($\chi^2=9.07$, $df=8$, $p=0.337$), indicating acceptable calibration across risk deciles. The component model had slightly higher discrimination (AUC=0.930) and lower AIC (277.6) but showed weaker calibration (Hosmer-Lemeshow $p=0.016$), so its coefficients are interpreted primarily as mechanism-specific associations rather than as a superior predictive model. All VIFs were below 2.62. A 499-resample cluster-pairs bootstrap for the GSHVI coefficient yielded an odds-ratio interval of 0.038–0.420, consistent with the cluster-corrected result. In the component bootstrap (299 resamples), sensitivity and material capacity remained clearly associated with adaptation, whereas institutional access remained positive but inference was more method-sensitive.

4.8 Exposure and gendered vulnerability

The exposure-by-gendered-vulnerability interaction remained negative in direction but statistically inconclusive. The interaction OR was 0.583 (95% $t(26)$ CI 0.304–1.119, $p=0.101$). Neither the exposure main effect (OR=0.801, $p=0.594$) nor the gendered-vulnerability main effect (OR=0.836, $p=0.619$) was significant. Sensitivity remained negatively associated with adaptation (OR=0.368, $p=0.007$), while material capacity remained strongly positive (OR=6.497, $p=0.001$). Institutional access was positive but did not reach the 0.05 threshold under $t(26)$ -referenced inference (OR=1.631, $p=0.094$). The results therefore do not establish statistical moderation, although the direction is compatible with the possibility that gendered burdens become more constraining as exposure increases.

Table 12: Exposure $\times$ gendered-vulnerability interaction model

Predictor	OR	95% t(26) CI	p
Exposure	0.801	0.343–1.868	0.594
Gendered vulnerability	0.836	0.401–1.741	0.619
Exposure $\times$ gendered vulnerability	0.583	0.304–1.119	0.101
Sensitivity	0.368	0.183–0.741	0.007

Material capacity	6.497	2.275–18.555	0.001
Institutional access	1.631	0.915–2.906	0.094

4.9 Adaptation intensity and count-model diagnostics

The adaptation-count analysis was consistent with the binary outcome. In the cluster-corrected Poisson model, a one-standard-deviation increase in GSHVI was associated with IRR=0.611 (95% t(26) CI 0.459–0.815, p=0.002), corresponding to an expected adaptation count approximately 38.9% lower at one standard deviation higher vulnerability, holding other model variables constant. Exposure (IRR=0.988, p=0.867) and institutional access (IRR=1.049, p=0.490) were not significant in this total-index count specification.

The Pearson dispersion statistic was 0.849, providing no evidence of overdispersion. A negative-binomial specification estimated a near-zero alpha and had a higher AIC (863.8) than the Poisson model (861.8), indicating that the additional dispersion parameter did not improve fit. The Poisson specification was therefore retained.

Table 13: Cluster-robust Poisson model of adaptation intensity

Predictor	IRR	95% t(26) CI	p
GSHVI (1 SD)	0.611	0.459–0.815	0.002
Exposure (1 SD)	0.988	0.854–1.143	0.867
Institutional access (1 SD)	1.049	0.912–1.206	0.490
Age (1 SD)	0.940	0.840–1.052	0.268
Household size (1 SD)	0.982	0.919–1.050	0.586
Female respondent	1.142	0.850–1.536	0.364
Climate-sensitive livelihood	0.875	0.726–1.056	0.157

4.10 Adaptation-gap households and threshold sensitivity

The adaptation-gap analysis identified households that combined high PCA-weighted vulnerability with no substantive adaptation. Under the primary top-40% definition, the threshold was GSHVI=0.552 and 153 households were classified as highly vulnerable. Of these, 119 households (77.8%) had adopted none of the four substantive measures, equivalent to 31.1% of the total sample. The gap was concentrated in Uttar Bedkashi and Koyra Sader: 67 of 78 highly vulnerable households in Uttar Bedkashi and 51 of 67 in Koyra Sader had no substantive adaptation, compared with 1 of 8 in Dakshin Bedkashi.

Table 14: Sensitivity of adaptation-gap estimates to the vulnerability threshold

High-vulnerability definition	GSHVI threshold	High-vulnerability N	Gap N	Gap within high (%)	Gap in sample (%)
Top 20%	0.614	77	67	87.0	17.5
Top 33%	0.572	128	106	82.8	27.7
Top 40%	0.552	153	119	77.8	31.1

The substantive conclusion was stable across alternative thresholds. Among the top 20% most vulnerable households, 67 of 77 (87.0%) had no substantive adaptation; among the top 33%, 106 of 128 (82.8%) had none; and among the top 40%, 119 of 153 (77.8%) had none. The absolute size of the target group changes with the threshold, but the concentration of non-adoption among the most vulnerable households remains pronounced.

4.11 Qualitative integration

The qualitative evidence clarifies why high vulnerability can coexist with low adaptation. Across FGDs, residents described weak embankments, damaged roads, distant or insufficient shelters and recurrent livelihood losses. A men's group in Dakshin Bedkashi summarized the infrastructural constraint directly: “We

have very risky embankments here and there are no major roads.” Vulnerable households also described borrowing to restart farming or repair fishing gear. One Dakshin Bedkashi group stated, *“We don't have the money we need, but we have to borrow money or spend what we have.”* These accounts are consistent with the strong quantitative role of material capacity and with the persistence of the vulnerability-adaptation gap.

Gendered burdens appeared most clearly in water, sanitation, evacuation and recovery. Adolescent girls in Uttar Bedkashi described cyclone shelters as places where *“Men and women [are] living together. Toilet facilities are not good. The shelters are overcrowded.”* Women described participating in household decisions while also undertaking additional post-disaster labor and facing limited financial room to act. Elderly and disabled participants emphasized mobility dependence; one Uttar Bedkashi group stated, *“We can't go ourselves, we need the help of others.”* These accounts support a relational interpretation of gendered vulnerability: voice may exist in some decisions while safety, care responsibilities, mobility and resource access remain constrained.

FGD participants from disaster-management structures described active communication among committees, volunteers and local authorities but also emphasized limited operational capacity. A committee group reported that *“The weakness is that we do not have the necessary funds,”* alongside shortages of rescue equipment, safe water and transport infrastructure. This qualitative distinction between institutional presence and operational capability helps explain why institutional access is positive in the quantitative models but less stable than material capacity under alternative inference procedures.

Table 15: Mixed-method joint display of principal quantitative and qualitative findings

Quantitative result	Qualitative evidence	Integrated interpretation
Higher GSHVI strongly associated with lower adaptation	Debt-financed recovery, asset loss and difficult post-disaster labor	High adaptation need can coexist with insufficient financial and labor capacity to invest in longer-term measures
Sensitivity negatively associated with adaptation	Weak embankments, impassable roads, saline water and inadequate shelters	Structural sensitivity includes constraints that individual households cannot readily overcome
Material capacity strongly positive	Low savings, borrowing and disrupted livelihoods shaped recovery choices	Liquidity, diversification and self-sufficiency are central to converting risk awareness into action
Gender main effect non-significant; interaction inconclusive	Women and girls reported sanitation, care, safety, mobility and recovery burdens alongside some decision voice	Gender operates relationally and contextually rather than as a simple female-versus-male coefficient
Institutional access positive but inference-sensitive	Committees reported active coordination but insufficient funds, equipment and infrastructure	Connection to institutions can enable adaptation, but operational capability and last-mile reach determine whether access becomes effective support

5. Discussion

5.1 A vulnerability–adaptation gap rather than an automatic adaptation response

The central finding is that greater multidimensional household vulnerability is associated with less, not more, substantive adaptation. The primary parallel-analysis GSHVI had a strong negative association with adoption, and the direction remained stable under Kaiser retention, categorical-aware heterogeneous-correlation PCA, equal weighting and an exposure-inclusive alternative. The leave-one-adaptation-out analysis likewise showed

that the association was not driven by a single outcome component. This pattern reinforces the conceptual distinction between vulnerability, adaptive capacity and observed adaptation emphasized by Smit and Wandel (2006) and Engle (2011): climate pressure can increase the need to act while sensitivity and resource scarcity simultaneously reduce the ability to do so.

The result is consistent with adaptation research showing that households require material and institutional opportunity structures. Aryal et al. (2020) demonstrate that assets and training influence coastal farmers' adaptation choices, while Kabir et al. (2021) identify socioeconomic determinants of adaptation across coastal Bangladesh. Alam, Alam, and Mushtaq (2016) show that institutions and social capital shape adaptation decisions, and Hasan et al. (2025) identify credit, training and diversification as enabling conditions in southwest Bangladesh. The present study extends these findings by directly linking a multidimensional vulnerability index to observed adaptation and identifying a large high-vulnerability, low-adaptation group.

Spatial patterns reinforce this argument. Dakshin Bedkashi had high climate exposure but stronger material capacity and much higher observed adaptation. Uttar Bedkashi combined high exposure with the highest sensitivity and highest overall household vulnerability, while Koyra Sader had lower exposure but very weak material capacity. These contrasts demonstrate why exposure alone is not an adequate proxy for the household constraints that shape action. They also support Hinkel's (2011) argument that an index must be judged by its analytical purpose: an exposure-inclusive risk measure may be useful for hazard planning, but an exposure-separated vulnerability measure is more informative when the aim is to explain adaptation behavior.

5.2 Sensitivity and material capacity as the strongest household mechanisms

The decomposed regression identifies household sensitivity and material capacity as the clearest mechanisms. Sensitivity was negatively associated with adaptation even after exposure and union context were controlled, and its cluster-bootstrap interval remained below one. This is plausible because climate shocks can damage housing, water systems, roads, livelihoods and productive assets simultaneously, creating competing demands for scarce resources. Alam (2017) treats vulnerability as dynamic across livelihood cycles, and Hoque, Quinn, and Sallu (2018) show that adaptation opportunities are stratified by socioeconomic position. The FGD evidence on embankment failure, road constraints and debt-financed recovery illustrates how post-disaster costs can crowd out preventive investment.

Material capacity had the largest positive association with adaptation. Under the primary parallel-analysis weights, the domain was dominated by income diversification, household savings and post-disaster self-sufficiency, while educational capital contributed very little. Diversified livelihoods can reduce dependence on a single climate-sensitive income stream (Hasan et al., 2025), while savings and assets expand the feasible set of adaptation options (Aryal et al., 2020). Leave-one-out analysis showed that household rankings were most sensitive to the removal of savings and diversification, and bootstrap weights confirmed their importance. This concentration is substantively informative but also indicates that future longitudinal work should measure liquidity, debt, land and productive assets in greater detail.

Salinity illustrates the multidimensional constraint particularly well. Farmers may recognize salinity and adjust crop practices, but implementation requires appropriate varieties, irrigation, land access and finance (Islam et al., 2020). Water scarcity similarly creates simultaneous health and adaptation demands (Abedin et al., 2019). A household may therefore need to improve water storage, housing, crops and income diversification at the same time, making adaptation prioritization a function of economic room to maneuver rather than awareness alone.

5.3 Gendered vulnerability as a relational mechanism

The gender results require careful interpretation. Neither respondent sex nor the PCA-weighted gendered-vulnerability score had a statistically significant independent main effect once household sensitivity, material capacity, institutional access and place were considered. The exposure-by-gender interaction was also statistically inconclusive at the conventional 0.05 level ($p=0.101$). These results do not support a simple claim that women adapt less. Such a claim would reproduce the universalizing problem identified by Arora-Jonsson (2011) and Evertsen (2023), and it would be especially inappropriate because respondent sex is not equivalent to household headship in this dataset.

The value of the gender analysis lies instead in construct specification and qualitative mechanism. The PCA gender domain incorporates safety, sanitation, care burdens, warning inequity, workload, mobility and household decision-making. Bari et al. (2024) similarly demonstrate the usefulness of intersectional approaches to gendered coastal vulnerability, while Fatema et al. (2023) document shelter, sanitation and safety burdens. The qualitative evidence showed women exercising voice in some household decisions while still facing additional labor, limited financial room and embodied safety constraints. The categorical-aware PCA sensitivity produced nearly identical household rankings, strengthening confidence that these conclusions are not artifacts of treating ordinal responses as interval-scaled data.

FPE provides a stronger interpretation than a binary sex coefficient. Rocheleau et al. (1996), Elmhirst (2011) and Nightingale (2011) argue that gender is produced through material and institutional relations. In Koyra, safe shelter access, sanitation, water collection, care responsibilities and control over adaptation resources are therefore not peripheral 'women's issues'; they are mechanisms that shape what adaptation is feasible and acceptable. The negative direction of the exposure-by-gender interaction is consistent with this logic, but the $p=0.101$ result means that the present cross-sectional sample does not establish statistical moderation. Future work should test this mechanism with larger samples and paired intra-household measures of bargaining and resource control.

5.4 Institutional access and the last mile of adaptation

Institutional access showed a positive relationship with adaptation, but its independent statistical evidence was less stable than that for material capacity. It was significant in the total-index model under the $t(26)$ -referenced cluster correction, positive but not conventionally significant in the component model, and its cluster-pairs bootstrap interval was above one. Rather than treating these results as contradictory, they suggest an enabling role whose magnitude is sensitive to model specification and correlated household conditions. This interpretation aligns with evidence that adaptation depends on information, organizations, credit and public services (Alam et al., 2016; Haque et al., 2024), while avoiding an overly categorical significance-based conclusion.

The qualitative evidence nevertheless shows that institutional presence is not sufficient. Disaster-management participants described active coordination but inadequate funds, equipment, roads and water systems. Islam and Islam (2026) similarly caution that NGO adaptation governance does not automatically produce equitable access, while Chowdhury, Hossain, and Ibn Farid (2026) identify a policy-practice gap in gender-responsive adaptation. Low community awareness of the UDMC and low training coverage in the survey point to a last-mile governance problem: formal structures exist, but many households remain weakly connected to them and local organizations may lack the resources needed to translate connection into effective adaptation support.

This result has implications for social protection as well as disaster governance. Households without savings or predictable safety-net support may use debt to finance immediate recovery, consuming resources that could otherwise support adaptation. Accessible training, transparent beneficiary selection, predictable relief and

direct contact with local institutions can reduce information and transaction costs, but these measures need to be paired with sufficient operational capacity.

5.5 Methodological contribution of PCA weighting and sensitivity analysis

The methodological contribution lies in combining theory-led dimensions, indicator-level transparency and explicit robustness testing rather than in PCA alone. The primary index used Horn's parallel analysis to reduce the risk of over-retaining components, while Kaiser retention was treated as an alternative. Because the indicator set mixes binary, ordinal and continuous measures, a categorical-aware heterogeneous-correlation PCA was also estimated; its near-identical ranking and regression result provide direct evidence that the primary findings are not dependent on Pearson correlation assumptions. This combination of theory-constrained PCA and sensitivity analysis preserves the IPCC/FPE structure while allowing empirical covariance to determine indicator importance.

The results also demonstrate why PCA diagnostics and weighting choices must be reported explicitly. KMO values were acceptable for four dimensions but only marginal for material capacity, and a second-stage PCA of the three GSHVI domains was rejected because KMO was 0.455. Domain weights were therefore based on the relative variance retained in the primary parallel-analysis solutions, while equal-domain weighting was examined through the broader equal-weight benchmark. The robustness results show that household rankings are highly stable to component-retention and correlation assumptions but more sensitive to how material capacity is represented. This prevents the GSHVI from being presented as a mechanically precise score and identifies where measurement improvement is most valuable.

Sensitivity results strengthen the substantive conclusion while locating the main sources of uncertainty. Kaiser, heterogeneous-correlation and equal-weight specifications all retained a strong negative vulnerability-adaptation association. Reincorporating exposure changed household ranks more substantially because it changes the construct being measured rather than merely the statistical weighting. Leave-one-indicator-out and bootstrap analyses identified savings and income diversification as influential within material capacity, while leave-one-adaptation-out models showed that no single adaptation measure generated the main regression result. Small-cluster bootstrap checks also preserved the direction of the principal coefficients.

5.6 Policy implications

First, adaptation targeting should combine household vulnerability with observed response rather than rely on hazard exposure alone. Under the primary top-40% threshold, 119 highly vulnerable households reported no substantive adaptation. These households constitute a concrete priority group for grants, concessional finance, technical assistance, climate-resilient housing, WASH investment and livelihood support. This approach is consistent with the socially inclusive orientation of Bangladesh's National Adaptation Plan (Ministry of Environment, Forest and Climate Change, 2022) and the long-term resilience objectives of Bangladesh Delta Plan 2100 (General Economics Division, 2018).

Second, programs should address material constraints directly. Information campaigns are unlikely to generate substantial adaptation where households lack savings, diversified income or the ability to recover without debt. The strong material-capacity association suggests combining awareness with financial and technical instruments, including support for raised housing, salt-tolerant agriculture, water security and livelihood diversification. Such measures align with evidence from coastal farming and fishing communities (Aryal et al., 2020; Hasan et al., 2025).

Third, gender-responsive adaptation should address infrastructure and authority together. Separate, lockable and well-lit sanitation, safe water points, accessible shelter space, menstrual-hygiene provision, maternal-health continuity and support for care-dependent evacuation are practical requirements. Yet infrastructure

alone cannot resolve unequal control over household resources or institutional decisions. Roy, Tandukar, and Bhattarai (2022) argue for integrating gender and cultural sustainability into adaptation practice, while Ahmed, Eklund, and Kiester (2023) show that poorly designed adaptation can reproduce gender inequities. Programming should therefore assess substantive decision authority rather than participation counts alone.

Fourth, local institutions need greater visibility, predictability and operational capacity. Routine ward-level outreach, clear UDMC contact pathways, repeated training, inclusive drills, transparent relief criteria and coordination among Union Parishads, CPP volunteers, NGOs and sector agencies can strengthen last-mile adaptation. These priorities are compatible with the Bangladesh Climate Change Strategy and Action Plan (Government of Bangladesh, 2009) and the country's broader climate-development agenda (World Bank, 2022).

6. Conclusion

This study examined the relationship between multidimensional, gender-sensitive household vulnerability and adaptation in three unions of Koyra Upazila using a quantitatively dominant convergent mixed-methods design. A PCA-weighted GSHVI was developed from household sensitivity, gendered vulnerability and material-capacity deficit, while climate-related exposure and institutional access were retained as separate dimensions. Indicator weights were derived from dimension-specific PCA with parallel analysis as the primary retention rule, and the index was subjected to Kaiser-retention, equal-weight, categorical-aware heterogeneous-correlation, leave-one-out, bootstrap and threshold sensitivity checks.

The empirical results point to a clear vulnerability-adaptation gap. Higher PCA-weighted vulnerability was strongly associated with lower adaptation adoption and lower adaptation intensity. Sensitivity constrained adaptation, while material capacity was the strongest enabling household factor. Institutional access was positive but less stable across model and inference specifications. Exposure by itself did not explain adaptation after household conditions and place were considered. The gendered-vulnerability main effect and exposure interaction were statistically inconclusive, which argues against simplistic claims that women uniformly adapt less; qualitative evidence instead shows gender operating through safety, care, sanitation, workload, mobility, information and negotiated access to resources.

The study's practical implication is that climate policy should not assume that the most exposed or most vulnerable households will adapt autonomously. Under the primary definition, more than three-quarters of households in the high-vulnerability group had adopted none of the four substantive measures, with the gap concentrated in Uttar Bedkashi and Koyra Sader. Targeting these households requires material support, gender-responsive WASH and shelter design, livelihood and finance interventions, and institutions that are visible and operationally capable at the last mile.

Several limitations should guide interpretation. The cross-sectional design does not establish causality. Adaptation is measured with four material or livelihood responses available in the survey and therefore does not capture migration, informal social-network strategies or adaptation quality. The respondent pool is predominantly female and lacks paired adult interviews within households, limiting direct measurement of intra-household bargaining. PCA weights are sample-dependent, and the material-capacity dimension showed only marginal KMO adequacy. Although parallel-analysis, categorical-aware, leave-one-out, bootstrap and outcome-composition checks indicated broad robustness, future work should collect richer asset, debt and liquidity measures and validate the index longitudinally.

Overall, the evidence supports a simple but consequential conclusion: vulnerability creates adaptation need, but it can simultaneously narrow the space for adaptation. Effective resilience policy in coastal Bangladesh must therefore do more than communicate climate risk; it must expand the material, social and institutional conditions that make adaptation possible.

Declaration of generative AI

During the preparation of this manuscript, the authors used ChatGPT 5.6 to assist with language editing, grammatical correction, improvement of clarity and organization, and refinement of the presentation and interpretation of the analyses. All AI-generated suggestions were critically reviewed, verified, and edited by the authors. The authors take full responsibility for the accuracy, integrity, interpretation, and final content of the manuscript.

Declaration of competing interest

The author declares that they have no financial interests or personal affiliations that could have affected the conduct, interpretation, or reporting of this research.

Source of Funding

This research received no specific funding from any funding agency.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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