

Flood Risk and Spatial Adaptation Strategies in Riverine Settlements: A Case Study of the Middle Ganga Plain, Uttar Pradesh, India

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Abstract— Riverine settlements across the Indo-Gangetic plain face recurring monsoon flooding that threatens lives, livelihoods, and the built environment. This study examines flood risk patterns and spatial adaptation strategies adopted by households settled along a mid-sized tributary reach of the Ganga in eastern Uttar Pradesh. A structured household survey of 360 respondents drawn from twelve villages, stratified into three flood exposure zones (very high, high, and moderate), was combined with secondary hydrological and remote sensing data to construct a composite flood vulnerability index. Results indicate a strong negative correlation between distance from the river channel and vulnerability score ($r = -0.68$, $p < 0.01$), and a significant association between exposure zone and the type of adaptation strategy adopted (chi-square = 38.42, $df = 4$, $p < 0.001$). Households in the very high exposure zone relied predominantly on temporary structural measures such as plinth raising and stilted storage, while households in the moderate exposure zone favoured agricultural and livelihood diversification. The findings support an integrated spatial planning approach that combines structural protection near the active floodplain with land use zoning, early warning systems, and livelihood based adaptation further inland. The paper concludes with policy

recommendations for settlement planning in flood prone river corridors of South Asia.

Keywords: flood risk, riverine settlements, spatial adaptation, vulnerability index, flood zoning, Ganga plain

INTRODUCTION

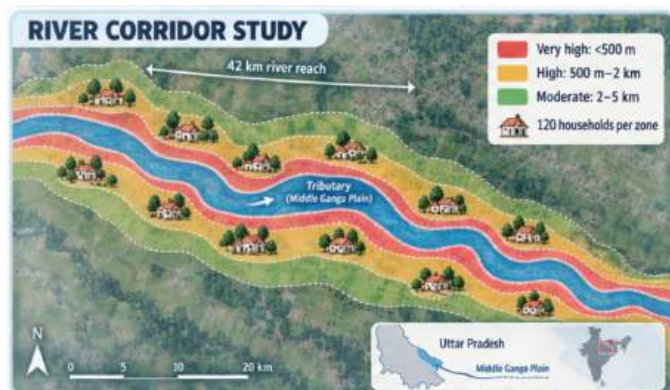
Riverine flooding remains one of the most persistent and geographically concentrated natural hazards affecting human settlements in South Asia. The Ganga, Brahmaputra, and their tributaries drain a densely populated alluvial plain where fertile soil, groundwater availability, and ease of transport have historically drawn settlement close to river channels, often within the active floodplain itself. This proximity, while economically rational at the household level, produces chronic exposure to seasonal inundation, bank erosion, and channel migration. Rivers of the Ganga plain are described as a lifeline for the region's population, yet the same rivers become a source of recurring damage when settlement and land development proceed without regard to fluvial dynamics.

Climate variability is intensifying this exposure. Modelling of riverine flood risk under warming scenarios projects substantial

increases in expected annual damages in the absence of adaptation, underscoring those floodproofing, elevation, and managed retreat can each be effective depending on local benefit-cost conditions. In deltaic and lower riparian tracts of the Ganga-Brahmaputra-Meghna system, the interaction of upstream discharge, sediment load, and low relief terrain produces some of the most extensive inundation extents recorded globally. At the same time, human settlement patterns on floodplains are not passive; households and communities actively negotiate flood exposure through informal and formal adaptation, ranging from house raising to seasonal migration.

Bhagirathi, Gandak, Kosi, lower Brahmaputra, and Ghaghara sub-basins as among the highest flood risk reaches in the country, with major flood events concentrated in the late monsoon months of August and September.

Sanyal and Lu conducted an early and widely cited assessment of flood vulnerability among human settlements in Gangetic West Bengal following the catastrophic floods of September 2000, defining settlement vulnerability as a function of floodwater depth and proximity to elevated ground suitable for temporary shelter. Their companion review of remote sensing applications in monsoon Asia flood management remains a reference point for hazard mapping methodology in the region. Building on this tradition, GIS based flood hazard mapping at varying administrative scales in West Bengal demonstrated that vulnerability assessments are highly sensitive to the spatial resolution at which settlement and hydrological data are integrated.



Despite an expanding body of flood hazard mapping research in India, comparatively fewer studies connect physical exposure with the spatial logic of household level adaptation within a single river corridor. This study addresses that gap by asking two questions. First, how does flood vulnerability vary spatially across zones of differing proximity to the river channel. Second, which adaptation strategies are associated with each exposure zone, and what does this imply for settlement and land use planning. The paper proceeds with a review of relevant literature, a description of the study area and methodology, presentation of results, and a discussion of spatial adaptation strategies before concluding with planning implications.

LITERATURE REVIEW

A substantial body of work has established the physical drivers of riverine flood hazard in the Indo-Gangetic basin. Flood hazard and susceptibility mapping using remote sensing and statistical approaches along the Ganga in Bihar has shown that slope, distance to river, drainage density, and land use jointly determine susceptibility zones, providing a basis for delineating high and low risk areas. Complementary basin scale analysis of Indian sub-continental river systems has identified the



Socio-economic vulnerability has received parallel attention. Rajesh, Jain, and Sharma applied categorical principal component analysis to rural households in the Kimsar region of Uttarakhand, showing that housing quality, asset ownership, and access to institutional credit are strong predictors of inherent vulnerability independent of physical hazard exposure. In Odisha, Mishra and Mishra examined vulnerability and adaptation in flood affected districts and found that landless and marginal farming households adapted primarily through livelihood diversification rather than structural protection, reflecting resource constraints. More recently, Mondal and colleagues applied the IPCC-AR5 vulnerability framework combined with DEMATEL methodology to the Indian Sundarban, confirming that exposure, sensitivity, and adaptive capacity interact non-linearly and that livelihood risk is highest where embankment maintenance is poor.

Comparable work in Bangladesh by Rakib, Islam, and Islam mapped flood vulnerability along the old Brahmaputra River and found that settlement age, house foundation type, and distance from the active channel jointly explained a large share of variance in reported flood damage. At a broader scale, global hydrological modelling of riverine flood risk under climate change scenarios for the United States has shown that without further adaptation, nationwide damages could rise by twenty to thirty percent under high emission pathways, a finding echoed in reviews of design considerations for riverine flood infrastructure under non-stationary climate conditions. Compound flood risk research in Europe has further shown that the co-occurrence of extreme precipitation and elevated river or coastal water levels is becoming more probable under continued warming, a dynamic increasingly relevant to lower Gangetic reaches during active monsoon depressions.

Delta scale studies have highlighted that coastal and deltaic populations bear a disproportionate share of global flood exposure because they combine riverine, tidal, and storm surge hazards within a single settlement system, and that improving the quality of global flood hazard datasets is essential for national scale risk management in data scarce river basins. Foundational vulnerability theory, notably Wisner, Blaikie, Cannon, and Davis' pressure and release model and Adger's synthesis of the vulnerability concept, provides the conceptual basis used in this study to treat vulnerability as the joint product of exposure, sensitivity, and adaptive capacity rather than physical hazard alone. Taken together, the literature supports an integrated approach in which spatial hazard mapping, socio-economic vulnerability assessment, and locally observed adaptation behaviour are analysed jointly, an approach adopted in the present study.

Study Area

The study was conducted along a forty two kilometre reach of a Ganga tributary in the Rapti-Ghaghara interfluvium of eastern Uttar Pradesh, an area characterised by low gradient alluvial terrain, high infiltration capacity, and a documented history of levee breaches and seasonal inundation. Twelve villages within a five kilometre buffer of the active channel were selected and stratified into three exposure zones on the basis of historical inundation frequency and elevation relative to the mean monsoon flood stage: very high exposure (within 500 metres of the channel, inundated in at least four of the last six monsoon seasons), high exposure (500 metres to 2 kilometres, inundated in two to three seasons), and moderate exposure (2 to 5 kilometres, inundated in zero to one season).

MATERIALS AND METHODS

A cross sectional household survey was administered between February and April 2024, covering 360 households selected through stratified random sampling, with 120 households drawn from each of the three exposure zones across the twelve study villages (30 households per village). The structured questionnaire recorded household demographic and socio-economic characteristics, flood exposure history over the preceding six monsoon seasons, reported property and crop damage, and adaptation measures adopted at the household and community level.

A composite Flood Vulnerability Index (FVI) was constructed for each household on a 0 to 1 scale using three equally weighted sub-indices following the IPCC exposure-sensitivity-adaptive capacity framework: an exposure sub-index based on distance from the channel and historical inundation frequency, a sensitivity sub-index based on housing construction type and asset value, and an inverted adaptive capacity sub-index based on income, savings, and access to early warning information. Secondary data on historical flood extent were derived from Sentinel-1 SAR imagery for the 2019 to 2024 monsoon seasons, cross validated against district disaster management records.

Statistical analysis included descriptive statistics of exposure and damage indicators by zone, Pearson correlation between distance from the river and FVI, one-way analysis of variance (ANOVA) to test differences in mean FVI across zones, and a chi-square test of independence to assess the association between exposure zone and the primary adaptation strategy reported by each household. All analyses were conducted using a five percent significance threshold.

RESULTS AND DISCUSSION

Table 1 summarises the socio-economic profile of the sample. Household size and primary occupation were broadly comparable across zones, while landholding size declined with proximity to the river, consistent with the historical settlement of land poor households on marginal floodplain land.

Table 1. Socio-economic profile of sampled households by exposure zone (N = 360)

Indicator	Very High Exposure (n=120)	High Exposure (n=120)	Moderate Exposure (n=120)
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Mean household size	5.4	5.2	5.1
Households below poverty line (%)	46.7	34.2	21.7
Mean landholding (acres)	0.8	1.4	2.3
Pucca (permanent) housing (%)	28.3	41.7	63.3
Access to institutional credit (%)	22.5	35.0	51.7

Mean reported property damage (INR)	68,400	41,200	14,600
Mean reported crop loss (%)	58.2	34.6	12.1
Households reporting displacement (%)	37.5	15.8	2.5

Table 2 reports flood exposure and damage indicators. The mean number of flood events experienced over six seasons declined sharply with distance from the channel, from 4.6 in the very high exposure zone to 0.7 in the moderate exposure zone. Mean reported crop and property damage followed the same gradient.

The composite Flood Vulnerability Index was highest in the very high exposure zone (mean FVI = 0.71, SD = 0.09), intermediate in the high exposure zone (mean FVI = 0.52, SD = 0.11), and lowest in the moderate exposure zone (mean FVI = 0.33, SD = 0.10). A one-way ANOVA confirmed that these differences were statistically significant ($F(2, 357) = 214.7, p < 0.001$), and a Pearson correlation between distance from the channel and FVI was strongly negative ($r = -0.68, p < 0.01$), indicating that proximity to the active channel remains the single strongest predictor of household vulnerability in this reach, consistent with the settlement-hazard proximity relationships reported in earlier Gangetic basin studies.

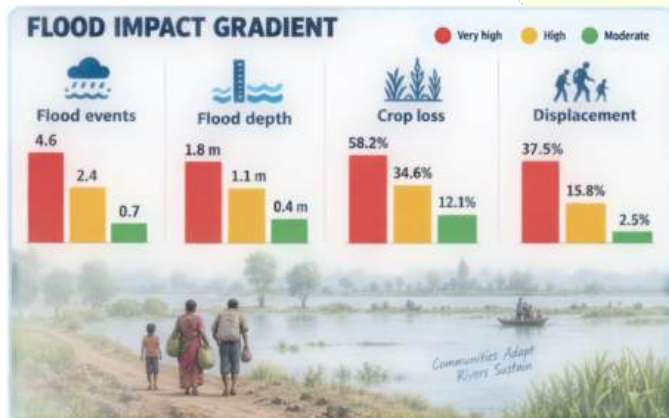


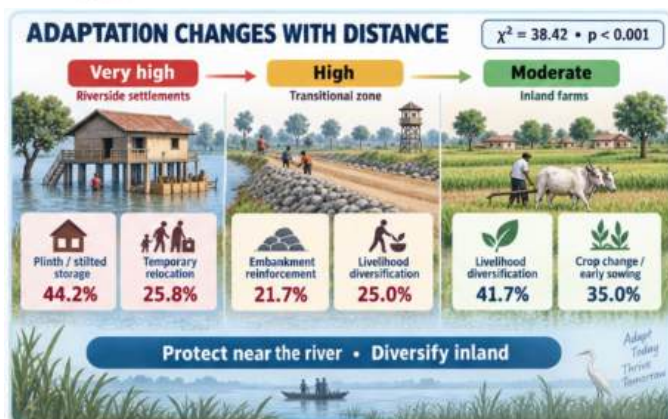
Table 3 presents the adaptation strategies reported as the primary response by households in each zone. A chi-square test of independence confirmed a significant association between exposure zone and adaptation type ($\chi^2 = 38.42, df = 4, p < 0.001$).

Table 3. Primary adaptation strategy reported, by exposure zone (percent of households)

Adaptation Strategy	Very High Exposure	High Exposure	Moderate Exposure
Plinth raising or stilted storage	44.2	27.5	9.2
Seasonal/temporary relocation	25.8	12.5	3.3
Embankment or bund reinforcement (community)	15.0	21.7	10.8
Livelihood diversification (non-farm income)	10.0	25.0	41.7
Crop pattern change / early sowing	5.0	13.3	35.0

Table 2. Flood exposure and reported damage by zone, 2019 to 2024 monsoon seasons

Indicator	Very High Exposure	High Exposure	Moderate Exposure
Mean flood events (of 6 seasons)	4.6	2.4	0.7
Mean maximum flood depth (metres)	1.8	1.1	0.4



The results indicate a clear spatial gradient in adaptation logic. Households closest to the channel invest in structural, house level measures aimed at short duration survival during inundation events, a pattern consistent with resource constrained households in similarly exposed reaches of West Bengal and the old Brahmaputra corridor. Households in the moderate exposure zone, facing lower and less frequent inundation, instead adapt through income and cropping pattern diversification, a strategy that requires less capital outlay and is feasible where flood events are episodic rather than annual. The high exposure zone occupies an intermediate position, combining household level structural measures with community embankment maintenance, suggesting that this zone is where collective action and local governance capacity most directly shape adaptation outcomes.

These patterns align closely with the vulnerability framework of Adger and the pressure and release model of Wisner and colleagues, in which adaptive capacity is shaped jointly by asset endowment and the severity of recurring exposure. They also reinforce the broader finding from national and delta scale hydrological studies that a purely structural or purely livelihood based approach to flood risk reduction is unlikely to be effective across an entire river corridor, since the appropriate strategy shifts systematically with distance from the channel.

Spatial Adaptation Strategies for Riverine Settlements

Based on the observed gradient, a zone differentiated planning approach is warranted. In the very high exposure zone, priorities should include enforceable setback regulations restricting new permanent construction within the active floodplain, community level early warning systems linked to upstream gauge data, and support for low cost house raising and elevated grain storage where relocation is not feasible. In the

high exposure zone, investment in maintained community embankments, combined with flood resilient infrastructure such as raised access roads and elevated common shelters, can reduce both physical damage and displacement. In the moderate exposure zone, planning should focus on protecting agricultural adaptive capacity through crop insurance, access to short duration and flood tolerant seed varieties, and diversification of rural non-farm employment, since this zone already demonstrates a self-organised shift toward livelihood based rather than structural adaptation.

Across all zones, land use zoning informed by SAR based inundation mapping, of the kind used in this study, offers a practical and updatable basis for demarcating exposure bands, particularly where historical revenue records under-represent recent channel migration. Aligning village level development planning with these zones, rather than with administrative boundaries alone, would improve the targeting of both structural and non-structural flood adaptation investment in riverine settlements of the Ganga plain.

CONCLUSION

This study demonstrates that flood vulnerability among riverine settlements in the middle Ganga plain follows a strong and statistically significant spatial gradient defined primarily by distance from the active river channel, and that households respond to this gradient with systematically different adaptation strategies. Structural, house level adaptation dominates in the immediate floodplain, while livelihood diversification becomes the primary strategy with increasing distance from the channel. These findings support a differentiated, zone based approach to flood risk management and settlement planning, integrating physical hazard mapping with socio-economic vulnerability assessment. Future research should extend this framework across multiple river reaches and monsoon seasons to test the stability of the observed adaptation gradient under changing climate and land use conditions.

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