



## Integrating Climate Change Projections into Flood Risk Mapping Using Remote Sensing and GIS: A Case Study of Northern India

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### Abstract

Floods are recurring and devastating natural hazards in Northern India, where climatic variations, rapid urbanisation, and environmental degradation exacerbate risks and impacts. Traditionally, flood risk assessments have relied on historical datasets; however, recent trends indicate that climate change is altering flood dynamics by intensifying rainfall patterns, accelerating glacier melt, and shifting flood-prone zones. This study integrates climate change projections into flood risk mapping using high-resolution remote sensing data, Digital Elevation Models (DEMs), and Geographic Information Systems (GIS) to develop a comprehensive risk assessment framework for the 2022 flood events. Using Sentinel-2 optical imagery, Sentinel-1 Synthetic Aperture Radar (SAR) data, and CartoDEM, flood extents were delineated and combined with downscaled climate model scenarios (RCP 4.5 and RCP 8.5) to forecast future flood scenarios. Socio-economic vulnerability indicators based on Census data and field surveys were integrated via a weighted overlay analysis to identify high-risk zones. Validation through ground control points (GCPs) and comparison with government reports yielded an overall accuracy of 87.4%. The findings indicate an increase in both the extent and frequency of flooding, with a significant shift of flood-prone areas toward peri-urban and semi-urban regions. Policy recommendations include the institutionalisation of remote sensing and GIS in disaster management, stricter floodplain zoning, and community-based resilience building. This study contributes to a deeper understanding of how climate change influences flood hazards and provides actionable insights to inform future urban planning and disaster risk reduction strategies in Northern India.

**Keywords:** Flood risk mapping, climate change projections, remote sensing, GIS, Northern India, Sentinel-2, Sentinel-1, CartoDEM, vulnerability assessment, disaster risk management

### Introduction

Flooding has long been a major natural hazard in India, particularly in the northern regions where the confluence of multiple river systems and intensive monsoon rains creates extensive floodplains and vulnerable settlements. With increasing urbanisation and ongoing climate change, the frequency and intensity of flood events have intensified, challenging traditional disaster management approaches. The historical reliance on statistical flood analysis has proven inadequate in the face of rapid climatic shifts and evolving land use patterns. Modern technological advancements, notably in remote sensing and Geographic Information Systems (GIS), offer unprecedented opportunities to understand and map flood risks by integrating multi-source data in near-real-time.

In recent years, satellite platforms such as Sentinel-2 and Sentinel-1 have become crucial tools in mapping flood extents due to their high spatial resolution, frequent revisit

times, and ability to capture data under adverse atmospheric conditions. Coupled with Digital Elevation Models (DEMs) like CartoDEM, these tools enable precise terrain analysis, allowing for the identification of low-lying areas that are especially prone to inundation. However, while conventional flood mapping provides a snapshot of the current situation, future flood hazards are likely to be significantly influenced by climate change. Changes in precipitation patterns, glacier dynamics, and sea-level rise are expected to modify the spatial distribution and severity of floods.

This study addresses the urgent need to incorporate climate change projections into flood risk mapping, with a focus on Northern India. By integrating climate model outputs, such as those generated under Representative Concentration Pathways (RCP) 4.5 and RCP 8.5, into remote sensing-based flood models, this research aims to produce dynamic flood risk maps that not only reflect current hazards but also

forecast future changes. Additionally, the study integrates socio-economic vulnerability data to provide a holistic risk assessment that can inform disaster management policies and urban planning initiatives. The objective is to create a robust framework capable of guiding flood mitigation strategies and resilience planning in a region where floods cause extensive human, economic, and environmental losses.

### Literature Review

Flood risk assessment has evolved significantly over the past decades, with remote sensing and GIS playing central roles. Early studies primarily focused on developing empirical models based on historical flood records (Yusuf & Francisco, 2009) [53]. The introduction of satellite imagery, particularly from programmes such as Landsat and MODIS, revolutionised flood mapping by providing consistent, multi-temporal data (Lillesand, Kiefer, & Chipman, 2015) [33]. With the advent of high-resolution data from Sentinel missions, researchers were able to produce more detailed and accurate flood extent maps (Drusch *et al.*, 2012) [55].

Recent literature has highlighted the necessity of incorporating climate change into flood risk assessments. Studies by Alfieri *et al.* (2017) [3] and IPCC (2021) [29] have demonstrated that climate change is leading to more frequent and intense flood events, necessitating the integration of downscaled climate projections into flood models. This integration allows for the anticipation of future trends and spatial shifts in flood hazards, rather than relying solely on historical data.

Furthermore, socio-economic vulnerability is recognised as a critical determinant in disaster risk assessments. Cutter *et al.* (2003) [16] introduced the concept of social vulnerability, which has since been expanded by subsequent studies (Birkmann *et al.*, 2016; Zhou *et al.*, 2020) [7, 47]. These studies underline that flood impacts are not uniformly distributed; instead, they are exacerbated in regions with high poverty, low literacy, poor housing quality, and inadequate access to emergency services. GIS-based multi-criteria decision analysis has been extensively employed in this domain to merge physical and socio-economic data, thereby enhancing the understanding of flood risks.

The current study builds on these strands of research by integrating high-resolution remote sensing data with climate change projections and socio-economic factors, aiming to generate dynamic, future-oriented flood risk maps for Northern India. Through this approach, the study addresses gaps in previous research that often overlooked the influence of future climatic conditions and socio-economic evolution on flood risk.

### Materials and Methods

The methodological approach in this study is designed to produce comprehensive flood risk maps that reflect both current and projected flood hazards. The study area, covering flood-prone districts of Northern India along the Ganga and its tributaries, was chosen based on historical flood records and socio-economic vulnerability indicators. Satellite data acquisition is a cornerstone of the methodology. Sentinel-2 Level-1C optical imagery was obtained from the Copernicus Open Access Hub, while Sentinel-1 SAR data was used to ensure mapping accuracy

during periods of cloud cover. These data sources were pre-processed using the Sentinel Application Platform (SNAP) to perform atmospheric correction, cloud masking, and radiometric calibration. CartoDEM, provided by ISRO, was employed for terrain analysis to derive DEM-based parameters such as elevation, slope, and drainage density, which are critical for identifying areas at risk of inundation.

To integrate climate change projections, the study utilised downscaled outputs from global climate models under RCP 4.5 and RCP 8.5 scenarios. These climate projections were integrated into hydrological models (such as HEC-RAS 2D) within a GIS framework to simulate future flood scenarios. The flood extent maps generated from these simulations were then overlaid with socio-economic data acquired from the Census of India (2011) [35], district statistical handbooks, and primary field surveys conducted in 2022. A composite vulnerability index was derived using a weighted overlay method, where physical vulnerability (derived from DEM analysis) and socio-economic vulnerability were combined with appropriate weightings.

The overall risk is computed using the common risk equation:  $\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability}$

This equation was operationalised using GIS software, with hazard data from satellite and climate models, exposure data from socio-economic mapping, and vulnerability scores from the weighted overlay analysis. Accuracy assessment of the flood maps was conducted using a confusion matrix derived from ground control points collected during field surveys. The resulting metrics demonstrated an overall accuracy of approximately 87.4% with a Kappa coefficient of 0.81, ensuring the reliability of the mapped outputs.

### Results and Analysis

The integration of remote sensing, GIS, and climate change projections provided several noteworthy results. Sentinel-2 imagery, processed using NDWI, revealed that during the 2022 flood event, approximately 6,500 square kilometres of land were inundated across the selected districts. The spatial distribution of flood extents showed a clear pattern where low-lying areas, particularly those under 60 metres in elevation, experienced prolonged inundation lasting more than ten days. Analysis using Sentinel-1 SAR data helped refine these maps in regions affected by persistent cloud cover, ensuring that areas such as rural floodplains along the Ganga, Ghaghara, and Kosi rivers were accurately identified.

The DEM analysis further corroborated these findings. Elevation and slope mapping demonstrated that regions with gentle slopes ( $<5^\circ$ ) and low elevation were highly susceptible to floodwater accumulation. The use of the Topographic Wetness Index (TWI) highlighted areas where water accumulation was likely, reinforcing the identification of high flood hazard zones. These terrain-based assessments were combined with socio-economic data to produce comprehensive vulnerability maps. The integrated vulnerability index revealed that communities in rural areas with poverty, poor housing quality, and low literacy levels were most at risk. Quantitatively, an estimated 3.2 million

people in the study area were directly affected, with agricultural losses exceeding 1,850 square kilometres.

Climate change projections added a dynamic dimension to the analysis. Under both RCP 4.5 and RCP 8.5 scenarios, the frequency and magnitude of flood events are projected to increase significantly in the coming decades. Simulation results indicate that in 2050, regions currently classified as moderate-risk could shift into the high-risk category, particularly in peri-urban and emerging informal settlement areas. The integration of future climate scenarios suggests that flood extents may expand both laterally and vertically, impacting more communities than historical data would suggest.

In addition to the spatial analysis, statistical evaluation of the mapping outputs showed robust performance. The confusion matrix analysis, based on 300 ground control points, yielded an overall accuracy of 87.4%, with a Kappa coefficient of 0.81. These figures are within the acceptable range for flood mapping studies and validate the efficacy of the methodology.

**Table 1:** Summary of Key Parameters and Projections

| Parameter                      | 2022 Flood Event | Future Projection (2050, RCP 8.5) | Implication                            |
|--------------------------------|------------------|-----------------------------------|--|
| Inundated Area (sq km)         | 6,500            | 8,200                             | Increased spatial extent of flooding   |
| Elevation (low-risk threshold) | < 60 m           | < 70 m                            | Shift in vulnerable zones              |
| Duration of Inundation         | > 10 days        | > 12 days                         | Longer duration under extreme events   |
| Affected Population            | 3.2 million      | 4.5 million                       | Increased exposure due to urbanisation |
| Agricultural Loss (sq km)      | 1,850            | 2,400                             | Greater impact on rural livelihoods    |

(Sources: Current Study; Alfieri *et al.*, 2017; IPCC, 2021) [3, 29].

### Findings Discussion

The results of the study reveal that integrating climate change projections into flood risk mapping using remote sensing and GIS dramatically enhances the understanding of future flood hazards. The 2022 baseline assessment shows significant inundation over a vast area, primarily affecting low-lying floodplains and rural settlements. The synthesis of high-resolution optical and SAR imagery ensured robust mapping of flood extents despite adverse weather conditions during the monsoon. DEM-based analyses further clarified the relationship between terrain characteristics and flood vulnerability, emphasizing that even slight increases in elevation thresholds under climate change scenarios can considerably expand flood-prone zones.

The inclusion of downscaled climate projections provides a forward-looking perspective, suggesting that current flood risk models, if based solely on historical data, are likely to underestimate future risks. Under both moderate (RCP 4.5) and high-emission (RCP 8.5) scenarios, the frequency and intensity of floods are projected to increase, particularly impacting peri-urban areas that are experiencing unplanned expansion. The socio-economic analysis corroborates that the communities most vulnerable to these changes are those already facing significant socio-economic challenges. These findings underscore the need for adaptive flood management strategies that are both proactive and dynamic.

An important outcome of the study is that it bridges the gap between purely physical hazard mapping and socio-economic vulnerability. By incorporating a composite vulnerability index into the flood risk model, the research demonstrates that flood impacts are a function of both the physical environment and the social structure of communities. The empirical evidence suggests that poorer, less educated communities with substandard housing are at disproportionately higher risk. This calls for targeted interventions that combine infrastructural improvements with socio-economic support measures, such as livelihood restoration and disaster insurance.

Furthermore, the high accuracy achieved through validation (87.4% overall accuracy and a Kappa coefficient of 0.81) indicates that the approach used in this study is robust and replicable. This validation is critical as it ensures that the integration of remote sensing, climate projections, and GIS offers a reliable basis for policy-making. The study's methodology and findings support the notion that modern, technology-driven approaches can and should play a central role in national and regional disaster management strategies.

### Conclusion

This study presents a comprehensive framework for integrating climate change projections into flood risk mapping using remote sensing and GIS techniques, focusing on a case study in Northern India. The results of the 2022 flood analysis, supplemented by DEM-based terrain assessments and downscaled climate projections, reveal that both the spatial extent and duration of flood events are likely to increase over the coming decades. The integration of socio-economic vulnerability data further refines the risk assessments, highlighting the critical need for targeted policy interventions in high-risk zones.

The research contributes significantly to the current understanding of flood dynamics by demonstrating that a combination of high-resolution satellite imagery, advanced hydrological modelling, and socio-economic analysis can produce reliable and actionable flood risk assessments. The findings have important implications for disaster risk management policy, land-use planning, and community resilience strategies in flood-prone regions. It is imperative that future flood management strategies incorporate these technological and methodological advancements to mitigate risks effectively and ensure the safety and well-being of vulnerable populations in the face of an increasingly volatile climate.

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