Abstract

Climate change has emerged as one of the most defining challenges of the 21st century, marked by an increasing frequency, severity, and unpredictability of hydroclimatic extremes. Events such as prolonged droughts, intense rainfall, deadly heatwaves, and their compound occurrences are no longer rare; they have become persistent realities reshaping global ecosystems and threatening socio-economic stability. These impacts are particularly acute in ecologically sensitive and socio-politically complex transboundary regions where fragmented governance, rapid land-use change, and population pressures converge with evolving climate risks.

A particularly critical region is Northeast India (NEI) and West Bengal, due to its substantial hydrological and geopolitical continuity with Bangladesh. This tri-jurisdictional zone is connected by major shared rivers such as the Barak, Brahmaputra, and Ganga, and experiences common hydroclimatic challenges, monsoon variability, frequent floods, seasonal droughts, and rising temperatures. Despite these deep ecological and hydrological linkages, most previous studies have treated NEI and Bangladesh as separate entities due to political boundaries, thereby fragmenting the assessment of shared risks and undermining the formulation of effective cross-border strategies. This division overlooks the climatic and geographical reality that both regions are climatologically similar and hydrologically integrated. The lack of a joint climate assessment limits the scope for unified early warning systems, transboundary flood control, and coordinated adaptation planning. To overcome these challenges, this thesis adopts a unified, transboundary approach that treats NEI, Bangladesh, and bordering West Bengal as a single climatic system, henceforth referred to as NEIB.

This thesis unfolds through several interconnected modules. It begins by analyzing long-term historical trends (1981-2014) in temperature and precipitation extremes using Expert Team on Climate Change Detection and Indices (ETCCDI). It also assesses future climate projections from 14 CMIP6 Global Climate Models (GCMs) under four Shared Socioeconomic Pathways (SSPs). The study evaluates projected changes in temperature and rainfall extremes across various temporal scales up to the year 2100. Key findings indicate consistent warming, and a trend toward more intense but less frequent rainfall events, conditions that collectively increase the risk of floods, droughts, and heatwaves throughout the NEIB region.

The thesis then turns to local-scale hydrological concerns, presenting a scenario-based framework to assess future water scarcity in seven river catchments of NEI. This is achieved by integrating projected LULC dynamics (modelled using Cellular Automata-Markov Chain (CA-MC) techniques) and future climate data into process-based hydrological simulations via HEC-HMS. Water stress is quantified using the Falkenmark Water Stress Index. The results reveal that rapid urban expansion and deforestation, particularly in the Gomati and Haora basins are expected to intensify runoff while diminishing natural groundwater recharge. Building upon these analyses, the thesis next introduces a robust methodology for watershed vulnerability assessment, particularly well-suited for data-scarce and climate-sensitive environments. By integrating the Analytic Hierarchy Process (AHP) with the Group Method of Data Handling (GMDH), the framework combines the transparency and interpretability of expert-based decision-making with the non-linear modelling strength of data-driven learning. Dual-case vulnerability maps are developed for watersheds by incorporating climatic, hydrological, and socio-economic indicators. Importantly, this framework is not only tailored to the specific conditions of the NEIB region but

is also broadly applicable to other regions of the world that share similar climatological characteristics, making it a valuable tool for global climate adaptation planning.

In the subsequent section, a newly integrated Multi-Criteria Decision-Making (MCDM) framework is proposed to map spatial drought vulnerability across the NEIB region using a Combined Drought Vulnerability Index (CDVI). The approach incorporates 16 parameters across meteorological, hydrological, agricultural, and socio-economic categories, applying the Weighted Aggregated Sum Product Assessment (WASPAS) method with Criteria Importance through Intercriteria Correlation (CRITIC) weights. Compared to the AHP, the WASPAS-based model shows greater sensitivity while consistently identifying high-risk zones such as Tripura, Mizoram, Manipur, West Bengal, and Southern Bangladesh.

Further, the study explores the emerging threat of compound extremes by examining Drought–Heatwave Composite Events (DHCEs), whose joint impacts on climate and populations can be more severe than either event alone. These events are identified using threshold-based criteria involving maximum temperature and 3-month SPEI values. To assess societal impacts, the analysis employs population exposure metrics, including the Population Exposure Index (PExI), to quantify the extent of population exposure to DHCEs. The results indicate a pronounced increase in the frequency, duration, and severity of DHCEs under high-emission scenarios, with NEI emerging as a prominent hotspot.

Methodologically, the thesis underscores the value of integrated modelling by employing tools such as GMDH, MLP neural networks, CA-MC simulation, and high-resolution datasets (Sentinel-2, IMD & BMD, ERA5, NEX-GDDP) to enhance spatial precision and predictive reliability. Collectively, this research offers a scientifically rigorous, spatially detailed, and policy-relevant framework for hydroclimatic vulnerability assessment in transboundary, data-deficient, and climate-sensitive regions like NEIB. By synthesizing future climate projections, the thesis contributes to the development of robust adaptation strategies that are region-specific, equity-centered, and future-oriented. The outcomes including CDVI maps, DHCE metrics, and vulnerability indices serve as vital decision-support tools for disaster planners, climate policymakers, regional institutions, and transboundary water managers. These insights are designed to inform early warning systems, cross-border resource sharing protocols, climate-resilient infrastructure planning, and integrated water governance, thereby advancing sustainable development in one of the world’s most vulnerable yet under-researched regions.

Additionally, this thesis highlights the unique climatic and hydrological behaviour of NEI compared to other parts of the country. While most regions of India show a steady decline in both total rainfall and rainy days, NEI experiences nearly stable annual rainfall but a sharp reduction in wet days, resulting in fewer yet more intense rainfall events. Combined with steep terrain, fragile ecosystems, and Transboundary River systems, these factors amplify the occurrence of compound drought-flood and hot-dry spell events. Together, these characteristics establish NEI as a critical climate hotspot within South Asia that requires region-specific adaptation and management strategies.

Keywords: Hydroclimatic Extremes, Transboundary Vulnerability, Water Scarcity; Vulnerability Mapping; Population Exposure; Climate Hotspot.