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Climate change and flood risk in the U.S.: A mini review of models future scenarios and adaptation strategies

Phyllis Ang-E-Mwin Gyang¹, Akomolafe Oluwabunmi², Marvin Lotsah³ and Lois Kumiwaa Opoku^{4,*}

¹ Department of Geography, Environment, and Spatial Sciences, Michigan State University, East Lansing, MI, USA.

² Department of Engineering, University of Notre Dame, Notre Dame, IN, U.S.A.

³ Department of Community and Regional Planning, Alabama Agricultural and Mechanical University, Huntsville, Alabama, USA.

⁴ Department of Crop and Soil Sciences, Kwame Nkrumah University of Science and Technology, Ghana.

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Abstract

This paper systematically reviews the interplay between climate change, flood risk, and the adaptation strategies employed in the U.S., focusing on models and future scenarios. As climate change accelerates, the frequency and intensity of flood events have increased, posing significant threats to communities, infrastructure, and ecosystems. Advanced modeling techniques, including hydrological and climate models, provide critical insights into future flood scenarios by simulating precipitation patterns, storm surges, and sea-level rise under varying climate projections. These models are instrumental in understanding regional vulnerabilities and shaping adaptive responses. This review examines how these predictive models contribute to flood risk assessment and explores innovative adaptation strategies such as resilient infrastructure design, ecosystem-based solutions, and community engagement initiatives. Key challenges, including uncertainties in climate projections, funding limitations, and policy gaps, are addressed, with an emphasis on the need for cross-sectoral collaboration and robust governance frameworks. The paper also evaluates current U.S. flood mitigation policies and highlights emerging technologies like nature-based solutions and early warning systems as critical tools for enhancing resilience. By synthesizing recent research, this review offers a comprehensive understanding of the dynamic relationship between climate change and flood risk while providing actionable recommendations for adaptive planning. The study concludes that proactive measures integrating cutting-edge modeling with sustainable adaptation strategies are essential for reducing flood impacts and fostering climate resilience in the U.S.

Keywords: Climate Change; Flood Risk; Hydrological Models; Adaptation Strategies; Resilience; U.S. Disaster Management; Sustainable Infrastructure

1. Introduction

Climate change has emerged as one of the most pressing global challenges, profoundly altering weather patterns and amplifying the frequency and intensity of extreme events, including floods [1]. In the United States, flooding ranks as the most common and costly natural disaster, causing significant economic damage, loss of life, and disruption to infrastructure and communities [2]. These events are exacerbated by climate change, which drives rising sea levels, shifting precipitation patterns, and increased storm intensity, making flood risks more severe and widespread [3]. Understanding and mitigating these risks require a multi-faceted approach that combines predictive modeling, scenario analysis, and adaptive strategies tailored to local vulnerabilities.

* Corresponding author: Lois Kumiwaa Opoku

Predictive models are instrumental in forecasting flood events and assessing future risks under various climate scenarios. Hydrological and climate models, often enhanced by Geographic Information Systems (GIS), Remote Sensing (RS), and machine learning algorithms, have significantly advanced flood risk mapping and forecasting capabilities. According to Kuo et al. [4], "integrating machine learning with GIS and remote sensing enhances the spatial and temporal resolution of flood prediction models, allowing for more accurate and actionable insights." These technologies enable the identification of flood-prone areas, the simulation of potential future flood scenarios, and the development of early warning systems, thereby improving preparedness and response strategies [5].

In parallel with technical advancements, adaptation strategies play a critical role in reducing flood impacts. Measures such as resilient infrastructure design, ecosystem restoration, and community-based initiatives have shown promise in mitigating flood risks and enhancing societal resilience. For example, nature-based solutions, including wetland restoration and the use of green infrastructure, provide effective and sustainable alternatives to traditional flood defenses [6]. However, barriers such as fragmented policies, inconsistent data quality, and insufficient funding continue to hinder widespread implementation [7]. This systematic review explores the intersection of climate change, flood risk, and adaptation strategies in the U.S., with a focus on evaluating predictive models and future scenarios. It synthesizes recent advancements in technology and policy while identifying key challenges and opportunities for enhancing flood resilience. By analyzing case studies and current practices, this paper provides insights for researchers, practitioners, and policymakers on fostering adaptive strategies and innovative approaches to mitigate the escalating flood risks posed by climate change.

2. Literature Review

2.1. Climate Change and Flood Risk Dynamics

Climate change significantly influences flood risks in the United States, altering the frequency, intensity, and distribution of flood events. Key drivers include rising temperatures, shifting precipitation patterns, and sea-level rise. Rising temperatures increase the atmosphere's capacity to hold moisture, leading to heavier and more prolonged rainfall events [8]. In addition, warmer temperatures accelerate snowmelt in mountainous regions, intensifying spring floods in riverine systems [9]. Climate change also disrupts precipitation cycles, resulting in more frequent and intense rainstorms. This trend is particularly evident in the Midwest and Northeast, where heavy downpours have become increasingly common [10]. Conversely, some regions experience prolonged droughts followed by extreme rainfall, which exacerbates flash flood risks [1]. Moreover, global sea levels, which have risen approximately 8 inches since 1880, are projected to rise an additional 1 to 4 feet by 2100 [11]. This rise amplifies coastal flooding risks, particularly during storm surges and high tides, threatening infrastructure and ecosystems in low-lying areas such as Miami and New Orleans [12].

Regional variations in flood risks across the U.S. highlight the diverse impacts of climate change. Coastal flooding, driven by sea-level rise and stronger hurricanes, poses significant challenges along the Atlantic and Gulf coasts. Cities like New York and Houston have faced increased tidal flooding and storm surges, as evidenced by events such as Hurricane Sandy in 2012 and Hurricane Harvey in 2017 [13]. Riverine flooding, on the other hand, primarily affects inland areas, particularly along major rivers like the Mississippi and Missouri. Record rainfall during the 2019 Mississippi River flooding caused extensive economic and environmental damage [14]. Urban flooding, another growing concern, is exacerbated by impermeable surfaces and aging infrastructure in cities. Heavy rainfall often overwhelms urban drainage systems, leading to flash floods. Chicago, for instance, has experienced recurrent urban flooding linked to climate-driven extreme rainfall [15].

Several landmark studies and meta-analyses have provided critical insights into these dynamics. Milly et al. [9] emphasized the global shift in flood frequency and magnitude due to anthropogenic climate change, underscoring the need for adaptive flood management strategies. The Fourth National Climate Assessment documented a 55% increase in the frequency of heavy rainfall events in the Northeast and Midwest between 1958 and 2016, linking these trends directly to climate change [10]. Sweet et al. [11] provided comprehensive projections of sea-level rise, illustrating its role in increasing tidal flooding risks in coastal U.S. cities. Additionally, Smith et al. [15] highlighted the interplay of climate factors and urbanization in their meta-analysis of urban flooding, calling for enhanced urban planning to mitigate future risks. These findings underscore the intricate relationship between climate change and flood risks in the U.S., emphasizing the need for region-specific adaptation strategies to manage the growing threats posed by rising temperatures, changing precipitation patterns, and sea-level rise.

3. Predictive Models for Flood Risk Assessment

Predictive models play a crucial role in assessing flood risks, particularly under the evolving conditions brought about by climate change. Among the commonly used approaches are hydrological models, statistical models, and machine learning algorithms. Hydrological models, such as the Hydrologic Engineering Center's River Analysis System (HEC-RAS) and the Soil and Water Assessment Tool (SWAT), simulate water movement through landscapes and river systems, accounting for precipitation, soil properties, and land use [16]. These models are particularly effective for understanding riverine flood dynamics and the impact of land-use changes. Statistical models, on the other hand, rely on historical data to establish relationships between climate variables and flood events. For example, extreme value theory (EVT) is often used to predict the frequency and magnitude of extreme flood events [17]. Machine learning (ML) models, such as support vector machines, random forests, and deep learning algorithms, have recently gained traction for their ability to process vast datasets and identify complex patterns in flood risk assessment [18].

Each model type has strengths and limitations. Hydrological models provide detailed, process-based simulations but often require extensive input data, calibration, and computational resources, which can limit their applicability in real-time scenarios [19]. Statistical models are relatively simple and computationally efficient but may struggle to account for non-linear interactions and unprecedented changes in climate variables [19]. Machine learning models excel at capturing complex relationships and adapting to diverse datasets, but they can be sensitive to data quality and may lack interpretability, making it difficult to explain predictions to stakeholders [18]. Under climate change scenarios, the reliability of all these models can be challenged by uncertainties in future climate projections, variability in spatial and temporal data resolution, and the difficulty of integrating socio-economic factors into predictions.

The integration of Geographic Information Systems (GIS) and Remote Sensing (RS) has significantly enhanced the predictive capabilities of flood risk assessment models. GIS allows for spatial analysis and visualization of flood-prone areas, aiding in risk mapping and urban planning [20]. RS provides valuable data on environmental conditions, such as land cover, soil moisture, and precipitation, through satellite imagery and aerial observations [21]. When combined, GIS and RS enable the creation of spatially explicit flood risk models that incorporate both real-time and historical data. For instance, GIS-based flood simulation models have been used to predict urban flooding scenarios, while RS data from satellites like Sentinel-1 and Landsat have improved the accuracy of hydrological models by providing high-resolution environmental inputs [5].

Incorporating machine learning into GIS and RS systems further advances flood prediction capabilities. ML algorithms can analyze RS data to classify land use, predict rainfall intensity, and model flood extents with high accuracy [22]. For example, deep learning techniques have been used to enhance flood extent mapping from RS imagery, significantly improving the precision of flood risk assessments [23]. Despite these advancements, challenges remain, including the need for high-quality, interoperable datasets and the integration of socio-economic and climate change variables into predictive models. As climate change exacerbates flood risks, the combination of hydrological, statistical, and machine learning models with GIS and RS offers a powerful approach to enhance flood risk assessments. Addressing challenges such as data heterogeneity and model uncertainties will be essential to leverage the full potential of these technologies for flood risk mitigation.

4. Integration of Models, Scenarios, and Strategies in Predicting and Adapting to Climate Change-Induced Flood Risks in the U.S.

The integration of predictive models, future scenarios, and adaptation strategies is essential for managing flood risks exacerbated by climate change in the United States. Predictive models, such as hydrological simulations and climate projections, play a pivotal role in informing adaptation strategies under various climate scenarios, allowing for proactive planning and mitigation.

The integration of predictive models, future scenarios, and adaptation strategies is a cornerstone of efforts to mitigate the impacts of climate change-induced flood risks in the United States. Predictive models, such as hydrological simulations and climate projections, provide essential tools for understanding potential flood scenarios and informing adaptation strategies. For example, models like the U.S. Geological Survey's (USGS) SPARROW model and FEMA's Risk Mapping, Assessment, and Planning (Risk MAP) framework analyze hydrological patterns, climate data, and land use to simulate flood risks under changing climatic conditions. By incorporating global climate models (GCMs) and regional downscaling, these tools translate large-scale climate trends into localized flood predictions, making them invaluable for decision-making. The Intergovernmental Panel on Climate Change (IPCC) highlights that integrating these models with socioeconomic scenarios improves their applicability and reliability for crafting informed strategies [1]. Scenario-

based analyses play a critical role in this integration. Frameworks like the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) allow researchers to evaluate potential futures based on greenhouse gas trajectories and socioeconomic trends. Under high-emission scenarios (e.g., RCP8.5), regions like the Midwest and Gulf Coast face heightened flood risks due to intensified storm activity and rising sea levels, as observed in studies by the National Oceanic and Atmospheric Administration [3]. The coupling of these scenarios with predictive models enables stakeholders to assess a range of possible outcomes, offering a robust foundation for proactive adaptation planning.

These models and scenarios directly inform the development of structural and non-structural adaptation strategies. Structural measures, such as levees, floodwalls, and improved drainage systems, are designed to withstand increased flood frequencies, while non-structural measures, like land-use planning, early warning systems, and public education campaigns, address long-term resilience. FEMA's National Flood Insurance Program (NFIP) exemplifies the application of predictive modeling by regularly updating flood maps based on evolving risks. Such efforts ensure that adaptation measures remain effective under shifting climate conditions. Additionally, tools like the National Climate Assessment's (NCA) Climate Explorer assist local governments in aligning urban planning and infrastructure investments with anticipated flood hazards, demonstrating the practical utility of these integrated systems [24, 25].

5. Challenges

The integration of predictive models, future scenarios, and adaptation strategies to address climate change-induced flood risks in the U.S. is a complex process challenged by scientific, technological, economic, and social factors. Predictive models often face significant uncertainties due to assumptions about future climate conditions, emissions, and socioeconomic developments. These uncertainties can lead to discrepancies in the outputs of global climate models (GCMs), further compounded when scaling down to local or regional levels. This issue is particularly critical for predicting localized events such as flash floods, which require high-resolution data that is often unavailable in underserved or rural areas. Despite advancements like NOAA's use of LiDAR technology, many regions still lack comprehensive datasets, hindering the accuracy and reliability of projections [1, 3]. Interdisciplinary challenges also emerge when integrating diverse models, such as hydrological, atmospheric, and socioeconomic frameworks, with adaptation strategies. These models often operate independently, limiting their ability to produce cohesive, system-wide applications. Tools like FEMA's Risk Mapping Assessment highlight the gaps in combining technical methodologies for holistic planning. Climate models like Coupled Model Intercomparison Project Phase 6 (CMIP6), are critical tools that also address climate change and flood risk; however, this model functions at coarse spatial resolution. This may not capture localized phenomena as urban flooding. CMIP6 greatly relies on assumptions about socioeconomic development, and future emission leading to uncertainty. Eyring, V., et al [26] Weather Research and Forecasting Model (WRF) is another predictive model with high-resolution numerical weather prediction that requires a significant level of computational resources for high resolution simulations [27].

The economic and political dimensions exacerbate these issues, as adaptation strategies often involve high costs for structural measures, such as levees or floodwalls, which are constrained by budget limitations at local, state, and federal levels. Additionally, the politicization of climate adaptation can delay or hinder the implementation of necessary measures due to competing interests and public resistance [2]. Data gaps, particularly in high-resolution projections, further constrain localized decision-making. Addressing these challenges requires interdisciplinary collaboration among climatologists, urban planners, policymakers, and technologists. Advances in machine learning and artificial intelligence offer promising avenues for improving model accuracy and scenario analysis, potentially revolutionizing the field.

6. Opportunities

The issue of climate change and flood risk in the U.S. presents significant opportunities for innovation, cross-sector collaboration, and policy advancements that can enhance national resilience to flooding. Emerging technologies, such as AI-powered tools and satellite-based remote sensing, offer the potential to improve the accuracy of flood predictions and provide localized risk assessments, paving the way for data-driven adaptation strategies [1, 28]. Nature-based solutions, like wetland restoration and green infrastructure, not only mitigate flood risks but also support ecological and carbon sequestration goals [29]. Cross-sector collaboration is crucial for effective flood risk management, with partnerships between academia, private industry, government, and communities playing a vital role in developing and implementing inclusive solutions [30]. For example, integrating advanced modeling techniques into insurance and urban planning can promote equitable access to resources and reduce financial burdens on vulnerable populations. Additionally, policy enhancements, such as incorporating climate projections into zoning regulations and incentivizing

green infrastructure, can foster sustainable development while addressing flood risks [2]. To fully leverage these opportunities, future initiatives should prioritize interdisciplinary research, robust funding, and stakeholder engagement, ensuring that adaptation strategies are innovative, equitable, and forward-looking. These combined efforts will position the U.S. as a global leader in climate resilience and sustainable flood risk management [10].

7. Conclusion

In conclusion, this review highlights the critical role of integrating predictive models, scenario analysis, and adaptation strategies to mitigate the growing flood risks posed by climate change in the U.S. Predictive models provide essential insights into potential flood scenarios by simulating hydrological, meteorological, and socioeconomic factors under varying climate conditions. Scenario analysis complements these efforts by evaluating the impacts of different policy, development, and climate pathways, enabling planners to anticipate and prepare for a range of future outcomes. Adaptation strategies, informed by these models and scenarios, allow for targeted interventions that prioritize resilience, equity, and sustainability. However, the process faces challenges, including data limitations, model uncertainties, interdisciplinary gaps, economic constraints, and social inequities. The importance of addressing these challenges cannot be overstated. Effective integration of models and strategies will not only enhance the reliability of flood risk assessments but also ensure that adaptation measures are proactive, equitable, and grounded in scientific evidence. For policymakers, prioritizing investments in advanced technologies, such as machine learning for predictive modeling and LiDAR for precise data collection, is essential. Emphasizing social vulnerability metrics in flood risk analysis will help protect marginalized communities disproportionately affected by climate change impacts.

Future research should focus on improving model precision through advancements in high-resolution datasets and exploring the potential of machine learning and artificial intelligence to refine predictive capabilities. Additionally, interdisciplinary collaborations between scientists, policymakers, and local communities are vital for designing and implementing strategies that address the diverse dimensions of climate resilience. Policymakers must also create frameworks that encourage equitable resource allocation, facilitate public engagement, and support climate adaptation initiatives with consistent funding and bipartisan commitment. As climate change intensifies, the integration of predictive models, future scenarios, and adaptive strategies represents a pathway to safeguarding lives, infrastructure, and economies. Sustained efforts in research, policy, and practice are indispensable for fostering resilience and ensuring that the U.S. is equipped to meet the challenges of a changing climate.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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