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Brototi Biswas
Bhagwan Balasaheb Ghute *Editors*

Flood Risk Management

Assessment and Strategy

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Dedicated to
Those from whom we learn something

Foreword

Flood risk management is a comprehensive and multidisciplinary process that involves identifying, assessing, and mitigating potential flood hazards in a given area. This process requires a deep understanding of various factors that contribute to flooding, including weather patterns, geography, hydrology, and land use. It also involves the identification of flood-prone areas and the development of effective management strategies to mitigate the potential risks associated with flooding. These management strategies may include structural measures such as building flood barriers and levees, as well as non-structural measures such as land use planning and early warning systems. The goal of flood risk management is to ensure the safety and security of communities during natural disasters and to minimize the potential damage to property and loss of life.

Flood assessment and strategy are integral components of flood risk management that involve a detailed and comprehensive analysis of various factors contributing to flooding. Flood assessment encompasses the identification of flood-prone areas, evaluating the likelihood and potential severity of flooding, and estimating the potential damage to property and loss of life. Flood strategy involves developing practical and effective management strategies to mitigate the potential risks associated with flooding, which may include measures such as building flood barriers and levees, along with non-structural measures such as land use planning and early warning systems. The ultimate goal of flood assessment and strategy is to ensure the safety and security of communities during natural disasters and to minimize the potential damage to property and loss of life, by providing an in-depth analysis of flood risk management and developing practical solutions to mitigate the risks associated with floods.

The book titled *Flood Risk Management—Assessment and Strategy* consists of 21 chapters written by different contributing authors. I have high regard for the esteemed editors, Dr. Brototi Biswas from the Department of Geography & Resource Management at Mizoram (Central) University, India, and Dr. Bhagwan Balasaheb Ghute from the Department of Geology at Toshniwal Arts, Commerce, and Science College, Sengaon, Hingoli, Maharashtra, India. They have dedicated their time and expertise to editing this comprehensive guide on various techniques for flood management and assessment strategy. This highly informative book will be invaluable to planners, scientists, and researchers, providing them with the necessary tools and knowledge to tackle the ongoing challenges in this critical field. The primary targets of the book are academics, researchers, students (both undergraduate and postgraduate), policymakers and program planners, managers, and practitioners in the field of disaster, DRR and governance, climate change, CCA, and environment to provide a better and comprehensive understanding of the disaster where disaster is an event of everyday life. I extend my sincerest wishes for the resounding success of this significant contribution to the scientific community.

February 2024

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Preface

Floods are among the most significant and recurring natural hazards that affect millions of people worldwide. The increasing frequency and intensity of floods due to climate change, population growth, and urbanization have made flood risk management a crucial issue in society. This book, entitled *Flood Risk Management—Assessment Strategy*, aims to provide readers with an in-depth understanding of the assessment strategy for flood risk management. The book covers a range of topics related to flood risk assessment, including the identification of hazards, vulnerability assessment, risk assessment, and risk management strategies. The book is intended for policymakers, flood risk managers, researchers, and students interested in understanding the assessment strategy for flood risk management. It provides a comprehensive overview of the subject and is structured to enable readers to easily navigate and access the information they need.

The first chapter entitled "Spatiotemporal Dynamics of Flood Exposure in Bangladesh: A GIS and Remote Sensing Based Approach" by Rezwan Ahmed et al. confidently establishes a strong foundation for future assessments of flood exposure and risk in Bangladesh. This has been achieved by replicating a geospatial modeling approach that ensures an accurate and comprehensive analysis of the spatiotemporal dynamics of flood exposure in the region.

The second chapter "Analyzing Spatiotemporal Changes in Flood Risk Zones to Mitigate Flood Hazards in a Floodplain Area Using a GIS-Based AHP Technique," was contributed by Subaran Chandra Sarker. The study found that all the components that influence flood risk had a somewhat beneficial impact on the danger of flooding, with altitude and drainage density having the most significant effects. This finding can help local governments and researchers develop flood control plans. It suggests that increasing the carrying capacity of the existing drainage system, improving science and technology, and enhancing the accuracy of weather forecasts can mitigate flood hazards.

In the third chapter "Mapping of Glacial Lakes and Glacial Lake Outburst Flood in Lahul and Spiti District Using Remote Sensing and GIS", of their study, Rongali et al. conducted an extensive mapping exercise of glacial lakes and glacial lake outburst floods in the Lahul and Spiti district. The study utilized remote sensing and GIS to provide detailed and accurate data on the region's glacial lakes and the potential risks of glacial lake outburst floods.

In the fourth chapter "Mapping Flood Susceptibility and Risk in the Ganges Tidal Floodplain Utilizing a Weighted Factor Analysis Model" of the book, Tithi and Kazi Md. explore the Ganges Tidal Floodplain's flood susceptibility and risk. They employ a Weighted Factor Analysis Model to map the flood-prone areas and evaluate the potential risks. Their study aims to provide insights into the region's flood hazards and to assist policymakers in developing effective flood management strategies.

In the fifth chapter titled "Assessment of Flood Vulnerability in Vedganga River Basin Spread Over Maharashtra–Karnataka States in India Using Geospatial Techniques", Gurav et al. employed geospatial technologies to evaluate the susceptibility of the Vedganga river basin to flooding. The study covered the region that extends across the states of Maharashtra and Karnataka in India, and aimed to identify the factors that contribute to flood vulnerability in the area. The authors utilized geospatial data analysis and mapping to analyze the topography, land use, and other relevant factors, and present their findings in the chapter.

The sixth chapter entitled "A Geospatial Approach to Water Spread Prediction Across Selected Rhino-Bearing Protected Areas of Assam, India", presents the findings of a study conducted by Sarkar et al. The study aimed to develop a model that could predict water spread across selected Rhino-bearing protected areas in Assam, India, using geospatial technology. The chapter provides an in-depth analysis of the methodology used, the results obtained, and their implications for Rhino habitat conservation in the region.

The seventh chapter "Changing Population Dynamics, Losses and Adaptation to Recurring Floods in Bongaigaon" by Girimallika Borah explores the impacts of changing population dynamics, losses, and adaptation to recurring floods in Bongaigaon. This chapter delves into the various challenges faced by the population of Bongaigaon, a city in Assam, India, due to the recurring floods and how they have adapted to cope with the situation.

In the eighth chapter "Sub-watershed Prioritization of Ajay River Basin for Flood Susceptibility Analysis, West Bengal, India", the authors Ghosh and Prakasam present a detailed analysis of the flood susceptibility of the Ajay River basin in West Bengal, India. The study involved sub-watershed prioritization to identify areas that are most vulnerable to flooding. The chapter provides valuable insights into the factors that contribute to flood susceptibility and proposes strategies to mitigate the impact of floods in the region.

In the ninth chapter "Flood Impact on Mangrove Health Dynamics in Sagar Island of West Bengal: A Geoinformatics Based Approach", Goswami presents a fascinating study on the impacts of flooding on mangrove health dynamics in Sagar Island, located in the West Bengal region of India. The study employs a cutting-edge geoinformatics-based approach, providing valuable insights into the complex and ever-changing nature of these vital ecosystems. By analyzing the spatial and temporal patterns of mangrove health, Goswami sheds light on the crucial role these environments play in the face of environmental threats such as flooding.

In the tenth chapter "Flood Susceptibility Zonation of Paschim Medinipur and Hooghly District in West Bengal, India Using EDAS Model", Sanjib Majumder, who studies natural disasters, created a flood susceptibility map of the Paschim Medinipur and Hooghly districts in West Bengal, India. The goal of the study was to identify areas that were most at risk of flooding and provide valuable information for disaster management and mitigation efforts in the region. The map was developed using the EDAS model (Exponential Distribution, Analytic Hierarchy Process, and Simple Additive Weighting).

In the eleventh chapter "Flood Vulnerability Mapping and Resilience in Urban Setting: A Review of Conceptual Frameworks and Assessment Methods", authors Panigrahi and Sharma delve into the topic of flood vulnerability mapping and urban resilience. The chapter provides an in-depth review of various conceptual frameworks and assessment methods that are used for analyzing flood vulnerability and developing strategies for building resilience in urban settings. By exploring these frameworks and methods, the authors aim to shed light on the key factors that contribute to flood vulnerability and the measures that can be taken to enhance urban resilience against floods.

In the twelfth chapter "ANN Model Based Optimization Along with Statistical Monitoring of Flow Forecasting: An Analysis on Longitudinal Data of Mayurakshi River, India", Suprakash Pan presents a comprehensive analysis of the longitudinal data of the Mayurakshi River in India. In order to forecast the flow of the river, Pan utilizes an ANN model-based optimization approach, which is paired with statistical monitoring techniques. The study provides valuable insights into the dynamics of the river and offers a reliable framework for predicting its flow patterns.

The thirteenth chapter "Application of Geographic Information System and Remote Sensing on Flood Hazard Assessment and its Impact on Agriculture: A Review" by Nandy and Kumar provides a detailed analysis of how GIS and Remote Sensing techniques assess flood hazards and their impact on agriculture. It reviews the literature, highlights methods and techniques, and discusses potential flood management strategies.

The fourteenth chapter "Flood Observation and Impact Assessment on Agriculture and Built-Up Area in Selected Districts of Haryana by Adopting Random Forest LULC Classifier" provides a comprehensive report on a study conducted by Majumder. The study aimed to assess the impact of floods in selected districts of Haryana on agriculture and built-up areas using the Random Forest LULC classifier. The chapter elaborates on the methodology employed by the researcher, along with the data collection techniques and analysis procedures used in the study.

The fifteenth chapter "Assessment of the Jiadhal River Channel Shifting and Its Impact on the Land Use Land Cover" by Manisha Pathak is a comprehensive study that utilizes remote sensing and GIS techniques to assess the shifting of the Jiadhal river channel in Assam. The chapter provides a detailed analysis of the shifting patterns of the river channel and how it has affected the surrounding land use and cover. This study sheds light on the importance of understanding the relationship between natural phenomena and human activity, and how they interact to shape the environment.

The sixteenth chapter "Bhutiabasti Underwater: An In-Depth Analysis of Flooding's Effects on Lives and Livelihood in the Himalaya Foothills, India" discusses the impact of environmental degradation, climate change, and economic policies on people's lives and their means of earning a livelihood. Through this piece, Sarkar aims to shed light on the challenges faced by the people living in this region and the urgent need for sustainable development to ensure a better future for them.

In the seventeenth chapter "Flood Zonation Using Geospatial Technology: A Case Study on Kopili River Basin, Assam", the authors Kramsapi and Rongpi delve into a comprehensive case study centered on the implementation of geospatial technology to establish flood zonation in the Kopili River basin located in Assam. Additionally, the chapter presents insights into the application of remote sensing and GIS techniques that can help to prevent flooding and mitigate its impact on the area's communities.

The eighteenth chapter "Flood Hazard Mapping and Monitoring in the Kamrup District of the Lower Brahmaputra Valley, Assam: A Geospatial Appraisal," by Biswajit Bordoloi, focuses on geospatial analysis to evaluate the hazards and monitoring systems in the Kamrup district. It provides valuable insights that can improve hazard mapping and monitoring in other regions.

The nineteenth chapter "Geomorphometry Based Flood Susceptibility Prioritization: A Case Study of Chalakudy River Basin, Kerala, India" discusses a research study by Artha et al. It applies geomorphometry techniques to prioritize flood susceptibility in the region, providing valuable insights for flood management and planning.

The twentieth chapter "Regional Planning Framework for Addressing Flood Vulnerability: A Comprehensive Case Study of South 24 Parganas, West Bengal, India" explores a thorough case study conducted by Suprakash Pan. The study investigates the regional planning framework for managing flood vulnerability in the Sundarbans, a large deltaic region situated in South 24 Parganas, West Bengal, India. The chapter provides a detailed analysis and insights into the study, which can be useful for policymakers and researchers interested in flood management.

The twenty-first chapter "The Sundarbans and the Coastal Flooding in Bangladesh" is by Md. Mujibor Rahman. The Sundarbans mangroves play a crucial role in reducing the impact of cyclones by lowering surge height, velocity, and flooded area. However, their degradation poses a significant threat to the region.

Aizawl, India — Brototi Biswas
Sengaon, India — Bhagwan Balasaheb Ghute

Contents

Editors and Contributors

About the Editors

Dr. Brototi Biswas is a Professor at the Department of Geography & Resource Management, Mizoram (Central) University, India. Her areas of research interest cover Physical Geography, Climate Change, Urban Planning, Applied Climatology, Hazards & Disasters, Oceanography, Social Geography, Natural Resource Management, RS & GIS, and Environmental Issues. She has delivered invited lectures in University Grants Commissions (UGC) sponsored national seminars and academic departments of different colleges in India. She was awarded the "Best Teacher award" in 2013 by Maharashtra Dalit Sahitya Academy. She has successfully guided 02 Ph.D. students while at present supervising 06 Ph.D. students. She has guided 12 dissertations for postgraduate students. She has conducted (Organizing Secretary) 04 conferences and 01 three-day workshop. The various conferences and workshops were sponsored by UP Higher Education Department, Rajiv Gandhi National Institute of Youth Development (RGNIYD), and Mizoram University. She has also conducted 04 Indian Institute of Remote Sensing (IIRS) outreach programmes. She has completed 04 research projects as Principal Investigator and 01 research project as Principal Investigator is undergoing. The funding agencies for the various research projects are UGC, SRTM University (Maharashtra), ICSSR, and DST.

She has been serving as a reviewer for many International journals. She has to her credit more than 45 research papers and 1 authored books.

Dr. Bhagwan Balasaheb Ghute is an Assistant Professor at the Department of Geology, Toshniwal Arts, Commerce, and Science College, Sengaon, District Hingoli (Maharashtra), India. He has been working there since 2011. Dr. Ghute completed his B.Sc. and M.Sc. in Geology from Swami Ramanand Teerth Marathwada University in Nanded in 2006 and 2008, respectively, with first-class. He was awarded the Dr. Bhimrao Pingale first merit award during his M.Sc. geology. In December 2010, he secured the first rank from Maharashtra for the State Eligibility Test for the Earth, Atmospheric, Ocean, and Planetary Sciences for the lectureship. Swami Ramanand Teerth Marathwada University, Nanded, recognized him as a Post Graduate (PG) teacher and Ph.D. Research supervisor. Dr. Ghute has completed two MRPs funded by Swami Ramanand Teerth Marathwada University, Nanded, and Rajiv Gandhi Science and Technology Commission, Mumbai. He is a life member of various societies and journals and was nominated as a Member of the Board of Studies in Geology at SRTM University for 2023–2027. His primary research areas include quaternary geology, groundwater, remote sensing, and GIS. Dr. Ghute has published more than 25 research papers in national and international journals.

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Spatiotemporal Dynamics of Flood Exposure in Bangladesh: A GIS and Remote Sensing Based Approach

Rezwan Ahmed, Nusrat Zahan Jarin, and Obaidur Rahman

Abstract The need for flood risk evaluation in Bangladesh is underscored by its unique geographic location, dense population, and regular encounters with severe hydro-meteorological phenomena. Previous literature has brought broad attention to flood extent mapping and simulation modeling; however, a gap remains in understanding the spatial and temporal dynamics of flood exposure in Bangladesh. This study attempts to fill that gap and introduces a state-of-the-art flood risk assessment methodology, focusing particularly on the population being exposed. The methodology leverages the processing and visualization capabilities of Google Earth Engine and ArcGIS Pro to conduct a weighted linear modeling (WLM) approach using Sentinel 1 SAR and Gridded Population of the World (GPW) as input features. This method identifies the recurrent zone of flood impact and quantifies the population directly exposed to those recurrent flood events. The results of this study deduced that around 15,649,130 individuals in the country were directly susceptible to flood risk in 2023 during monsoon season, with the northeastern zone being especially hard-hit. Approximately 33.46% of the population in Sylhet division was directly affected by the flood. Our findings, derived from a seamless integration of high spatial resolution multispectral remote sensing and a linear overlay model, provide a granular perspective on flood exposure dynamics in Bangladesh that is necessary to fortify the flood preparedness mechanism. Overall, this paper creates a space for future flood exposure and risk assessments in Bangladesh by replicating the geospatial modeling approach initiated in this research.

Keywords Sentinel 1 SAR · Flood extent · Flood exposure · Google earth engine · Weighted linear model (WLM)

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1 Introduction

Bangladesh, a low-lying South Asian country, is not only known for its overburdening population; it's also an extremely flood-prone country. The geographical location coupled with human exposure to flood events makes it a place of risk, compounded by the human, social, and climatic factors facilitating substantial property and agricultural damage every year. The flood occurrence in 2017, along with previous floods in 1954, 1955, 1974, 1987, 1988, 1995, 1998, 2004, 2007, and 2014, resulted in extensive property destruction and significant loss of life (Rahman et al. 2019). Approximately 80% of the country's land area is occupied by the floodplains of the Ganges, Brahmaputra, Meghna, and other minor rivers (Brammer 1990). The Bangladesh Water Development Board (BWDB) claimed that the cumulative discharge in the Brahmaputra and Jamuna rivers inside the nation is growing due to heavy rainfall in China, Nepal, and India. Consequently, the extra water cannot be effectively drained into the Bay of Bengal (Rahman et al. 2019).

1.1 Flood Exposure

According to FEMA, Exposure refers to the estimated monetary value of structures, population (in terms of both individuals and their economic worth), or crops that might be affected by a natural disaster. More specifically, Population exposure refers to the quantification of individuals who are found to be subjected to a hazard based on a methodology particular to that hazard. Understanding the concept of Population exposure of flood is important as it directly connects the net loss possibility and vulnerability of human resource of a country like Bangladesh.

Previous literature focused primarily on delineating the flooded and non-flooded areas using a number of threshold methods. For example, Tiwari et al. (2020) looked at the efficiency of the threshold techniques for determining rainfall induced inundated and non-inundated pixels using Sentinel 1 SAR scenes in India. Vanama et al. (2020) attempted to look at OTSU threshold method to find a temporal histogram of rapid floods in India. DeVries et al. (2020), on the other hand, attempted to determine the unexpected floods focusing on multitemporal SAR statistics using global surface inundation algorithm. Some previous literature examined the landsat multispectral imageries instead of sentinel to assess seasonal and permanent water bodies. For example, Mehmood et al. (2021) devised a flood monitoring algorithm (FMA) using a combination of Landsat 5, 7 and 8 putting a special focus on landuse and elevation data. In addition to looking at multi-temporal and the occurrence patterns of floods, some literature considered more human based approaches such as inundated settlements and agricultural damage analysis. A good example of that is the paper from Pandey et al. (2022) where the authors detected the inundated settlement and agricultural lands of Ganges–Brahmaputra basin using SAR GRD datasets. Nghia et al. (2022) also based their study on damage assessment and assessed the shifting flooding pattern in Mekong River using Sentinel-1 SAR imageries.

Plenty of literature also discussed extensively about the flood occurrence types and patterns of Bangladesh. According to Singha et al. (2020), flood is a frequent occurrence in northeastern Bangladesh along with the three major rivers, The Ganges, Brahmaputra and Meghna. They also assessed the extent of paddy field inundation and reported 1.61–18.17% paddy field to be affected between 2014 and 2018 (Singha et al. 2020). Another research by Uddin and Matin (2021) conducted GIS based shelter suitability analysis and flood assessments in Bangladesh. Considering factors like travel time, distance to road, distance to settlements and flood occurrence (Uddin and Matin 2021) adopted the analytical hierarchy process (AHP) to assess the shelter suitability.

Again, a significant number of publications discussed composite flood susceptibility and risk analysis. Ghosh and Kar in 2018 discussed hazard and vulnerability factors such as landform, slope, distance from river, literacy etc. to build a composite risk index value for a Malda district of West Bengal (Ghosh and Kar 2018). Again, Radwan et al. (2019) emphasized on five return periods (REP) corresponding to flood hazards to show the multicriteria based flood vulnerability. In addition to this, the machine learning approach ANN (artificial neural network) had previously been employed with multi-criteria decision analysis to create flood inventory maps of Bangladesh (Rahman et al. 2019). This paper added logistic regression, Mike-11 hydrological model and causative factors with Analytical Hierarchy Process (AHP) to generate flood hazard layer (Rahman et al. 2019).

Although a substantial amount of research evaluated flood hazard and susceptibility in different countries (Danumah et al. 2016; Khosravi et al. 2018) with the lens of both multiple attributes and decision tree-based approach, there is a considerable gap in the assessment of the directly impacted population in Bangladesh. While there has been much discussion about composite risk and vulnerabilities, the topic of a primary element exposure has not received as much attention. A similar literature discussed the rapid assessment of flood affected population with MODIS (MODerate resolution Imaging Spectro-radiometer) daily images in Islamabad, Pakistan (Raza et al. 2017). However, the coarse spatial resolution of MODIS data will limit the quantification of flood affected population, as Bangladesh is a small country. Implementing finer spatial resolution data is needed for accurate estimation of affected population. This paper attempts to address these gaps by answering three research questions:

1. Is there any major change in yearly flood inundation pattern in the past 10 years?
2. Which zones of Bangladesh are the most pronounced for composite flood exposure?
3. Is there any considerable shift in population being affected by floods throughout these years?

Gaining a comprehensive understanding of the geographical and temporal changes in population that are directly affected by floods is essential for upgrading the comprehensive flood mitigation framework. This research aims to quantify the population impacted by floods in Bangladesh from 2014 to 2023 using multispectral satellite images from the Sentinel 1 SAR. The analysis will include all districts in Bangladesh and their yearwise extent of composite flooding pattern. The outcome will serve as a guide for policymakers to allocate possible adaptation resources in an equitable way.

1.2 Study Area

Situated at the confluence of the Ganges, Brahmaputra, and Meghna rivers, Bangladesh (Fig. 1) is characterized by its extensive deltaic topography, which covers approximately 80% of the country's land area (Rahman and Di 2017). This geographical positioning renders it one of the most flood-prone countries in the world, with nearly a quarter of its land area susceptible to flooding annually (Hofer and Messerli 2006). The country's topography is predominantly flat, with more than 90% of its territory consisting of fertile floodplains which, while advantageous for agriculture, significantly heightens its vulnerability to flood events (Brammer 2014). The low-lying nature of the terrain, with the majority of the land being less than 10 m above sea level, further exacerbates this susceptibility, particularly in the face of rising sea levels due to climate change (Mirza 2003).

Bangladesh's climate is categorized as a subtropical monsoon, marked by heavy monsoon rains from June to October. This period often results in widespread flooding, impacting both rural and urban areas across the country (Auerbach et al. 2015). The annual monsoons, coupled with snow melt water from the Himalayas, contribute to the swelling of rivers, leading to regular seasonal flooding (Syvitski et al. 2009).

Urban areas in Bangladesh, particularly Dhaka, Chittagong, Bogra, Rajshahi, etc., face increasing flood risks due to rapid urbanization, which has led to a substantial reduction in natural drainage areas and an increase in impervious surfaces (Dewan 2013). This urban expansion, often unplanned and haphazard, compounds the flood risk in these areas, rendering them particularly vulnerable during the monsoon season (Alam and Rabbani 2007). In recent years, the impacts of climate change have become increasingly evident in Bangladesh, with changes in rainfall patterns and the intensity of cyclonic storms leading to more severe and unpredictable flooding (Kabir et al. 2016). The country's reliance on agriculture, combined with its high population density, makes the societal and economic impacts of these flooding events particularly acute (Rahman et al. 2013).

1.3 Population

Bangladesh is one of the most densely populated countries in the world, with a population exceeding 160 million as of 2021 (BBS 2021). The distribution of this population is not uniform across the country, a factor that significantly influences the impact and management of flood events. Hence, understanding the population

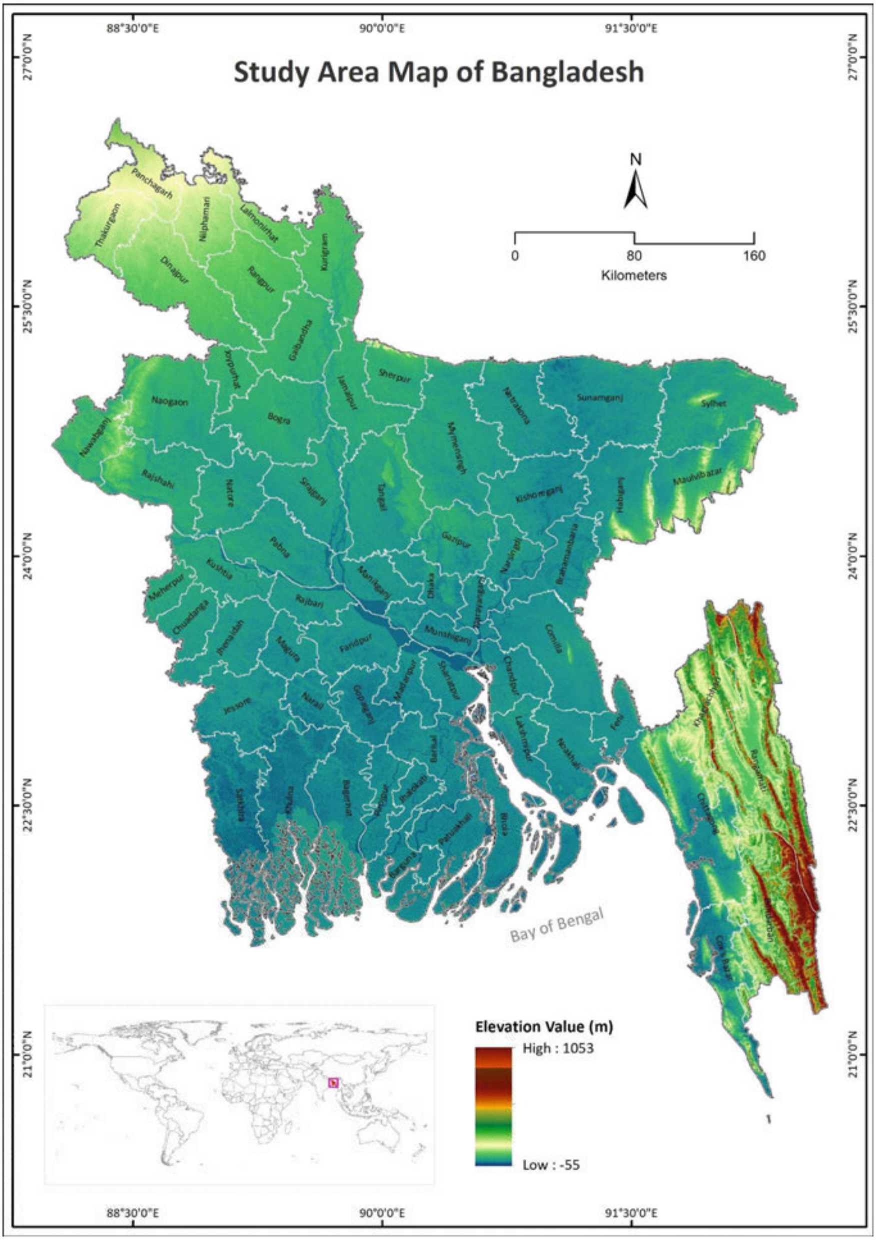

Fig. 1 Map of the study area (*Data source* Shuttle Radar Topography Mission (SRTM) Global)

and its distribution in Bangladesh is crucial for the spatiotemporal dynamics of flood exposure.

The majority of Bangladesh's population is concentrated in rural areas, with approximately 63% of the populace residing in these regions as of 2020 (BBS 2020). These rural populations primarily depend on agriculture for their livelihoods, making them particularly vulnerable to the impacts of flooding. The density and distribution of the rural population, often located in low-lying flood-prone areas, exacerbate the risks and consequences of flooding events, affecting both livelihoods and food security (Faisal and Parveen 2004). Urban population distribution in Bangladesh has been characterized by rapid and often unplanned urbanization, particularly in cities like Dhaka and Chittagong. Dhaka, the capital and the largest city, is among the world's most densely populated cities, with a density of over 23,000 people per km^2 (UN DESA 2018). This high density, coupled with inadequate urban planning, exacerbates the vulnerability of these urban populations to flooding. The lack of adequate infrastructure, such as drainage and flood defenses, further compounds this vulnerability (Rahman et al. 2012).

Figure 2 shows the population density maps in Bangladesh from 2014 to 2023 acquired from the LandScan data explorer. The population density layers for each year were divided into 5 classes, from very low to very high, depending on the number of people per km^2. The very low population density class contained a range of 0–2000 people per km^2. Similarly, the 2001–12,000, 12,001–36,000, 36,001–108,000, and 108,001–250,000 ranges were named as low, moderate, high, and very high population densities, respectively.

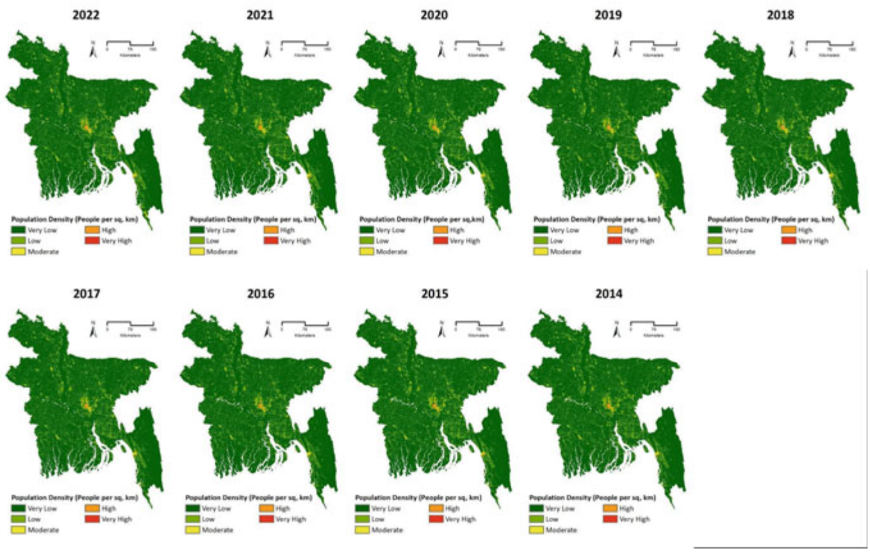

Fig. 2 Population density in Bangladesh from 2014 to 2022 (*Data source* Oak Ridge National Laboratory's LandScan Population Data Explorer)

The geographic distribution of the population in Bangladesh is also influenced by factors such as elevation and proximity to rivers. Populations in low-lying areas, particularly in the delta regions of the Ganges, Brahmaputra, and Meghna rivers, are more prone to annual monsoon floods and cyclonic storm surges. In contrast, populations in higher-elevation areas, such as the Chittagong Hill Tracts, are relatively less affected by such events (Paul and Routray 2011). The demographic trends in Bangladesh also play a role in shaping the population distribution. The country has experienced a significant demographic transition, with declining fertility rates and an increasing trend towards urbanization. This demographic shift is likely to influence future patterns of population distribution and, consequently, the dynamics of flood exposure and vulnerability (Haque and Zaman 1993).

1.4 Permanent Water Bodies

Bangladesh is a riverine country where small to large rivers flow from north to south and eventually merge into the Bay of Bengal. These rivers undergo significant flooding during the monsoon seasons. During the monsoon season, a significant amount of precipitation occurs, resulting in the inundation of low-lying areas with rainwater (Alam and Ahamed 2022). Bangladesh primarily comprises riverine and deltaic sediments deposited by three major and very active rivers that flow into the country: the Brahmaputra, Ganges, and Meghna rivers (Sarker et al. 2003) as represented in Fig. 3.

The deposited sediments provide a suitable environment for agricultural and residential land use decisions. During monsoon and pre-monsoon, when the storm surge and heavy rainfall-induced floods take place, the river and wetland adjacent settlement areas become highly exposed to multidimensional damage.

2 Materials and Methods

Data from multiple sources was integrated into this methodology for the analysis of the spatiotemporal dynamics of flood exposure in Bangladesh. Mainly, four types of data, including satellite imagery, population data, administrative boundaries, and permanent water bodies, were used to determine the flood exposure of populations in Bangladesh. Details of the data are given in Table 1.

At first, advanced remote sensing techniques were employed using Google Earth Engine (GEE) to analyze environmental changes, specifically water detection in Bangladesh. The study was conducted over each year from 2014 to 2023, and a composite of flood events were identified. Sentinel-1 Ground Range Detected (GRD) imagery, available on GEE, was chosen for its ability to penetrate cloud cover and its sensitivity to moisture, making it suitable for water detection.

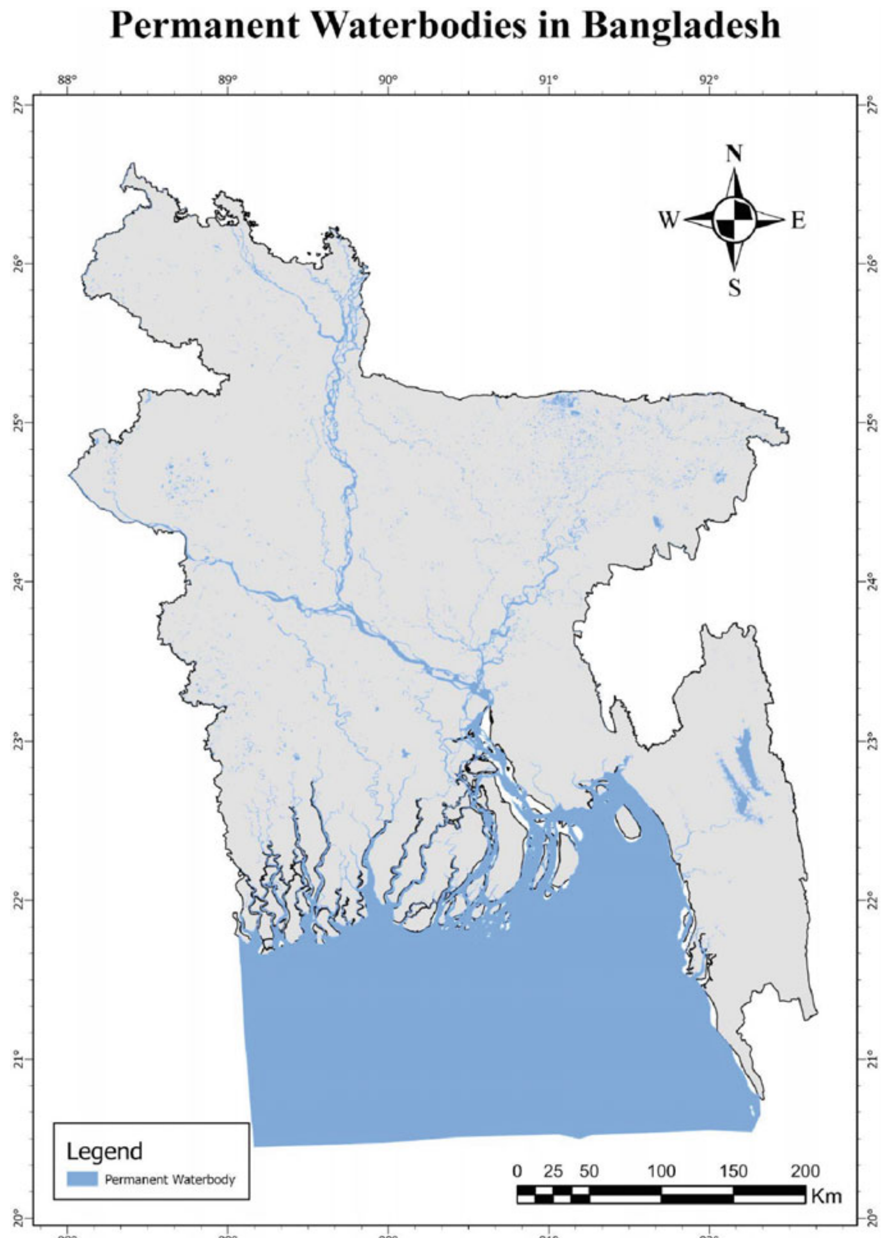

Fig. 3 Permanent water bodies in Bangladesh

Table 1 Data sources with description

Name of the dataset	Source	Description
Satellite Images	Sentinel-1 SAR	Sentinel-1 SAR data is used for flood mapping because it can penetrate through clouds and provide all-weather, high-resolution imagery of flooded areas (Attema et al. 2010)
Population Data	Oak Ridge National Laboratory's LandScan Population Data Explorer	Population Data Explorer provides high-resolution population data, which is valuable for various applications such as urban planning, disaster response, and resource allocation (Sims et al. 2023)
Administrative Boundaries	Bangladesh Bureau of Statistics	Used to define the area of Bangladesh
Permanent Water Bodies	Bangladesh Bureau of Statistics (BBS) and Bangladesh Water Development Board (BWDB)	This layer is used to exclude the areas that are not occupied by humans. Permanent river data was collected from BBS while the permanent wetland data was collected from BWDB and then both layers were merged into a single layer

The first step involved filtering the 'COPERNICUS/S1_GRD' image collection in GEE to select images that cover Bangladesh during the specified period. The selection was further refined to include only images with VV (vertical–vertical) polarization, known for its effectiveness in water body detection. To address the issue of speckle noise, a common challenge in SAR data, a focal median filter was applied. This process smoothed the VV polarization band by replacing each pixel's value with the median of neighboring pixel values within a 100-m radius. This technique helped enhance the clarity and usability of the SAR imagery. The process can be mathematically represented as follows:

$$Pi, j = median(\{Px, y|(x, y) \in N(i, j)\})$$

where P(i,j) is the pixel value at position (i, j) in the processed image, and N(i,j) denotes the neighborhood within the specified radius around the pixel (i, j) in the original image. In GEE, this was implemented as a focal median (radius = 100, units = meters'), effectively reducing the speckle noise and enhancing the quality of the SAR imagery. The application of the focal median filter significantly improved the clarity of the SAR imagery. By smoothing out speckle noise, distinct features, especially water bodies, became more discernible. This enhancement was critical for the subsequent stages of our analysis, such as accurate water detection and classification. The detailed methodology has been provided in Fig. 4.

Water detection was then performed using a threshold-based approach. A specific threshold value of −16 was set to classify pixels; those with values below this threshold were identified as water. This classification method, though approximate, was chosen based on its effectiveness in differentiating between water and non-water surfaces. The classified water pixels were then masked to exclude non-water pixels,

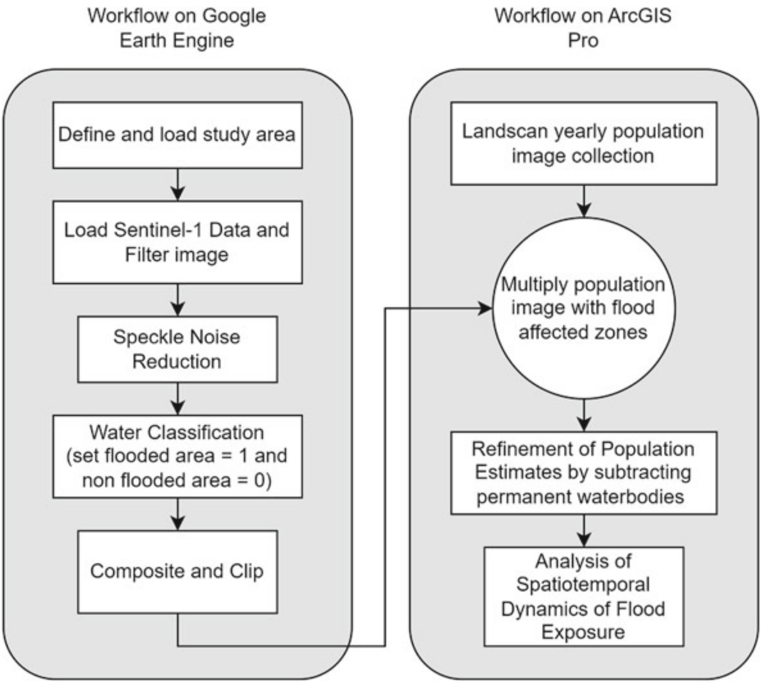

Fig. 4 Methodological workflow

ensuring that only water bodies were highlighted. These water pixels were added as a separate band to each image in the processed collection. Then a composite image was generated to represent the maximum extent of water coverage during the study period of each year. This was achieved by taking the maximum value of the water pixel across all images in the collection and then clipping this composite to Bangladesh. This step was crucial for capturing the fullest extent of water presence over the entire study period.

After generating flood extent maps using remote sensing data, the subsequent phase involved the integration of a population layer from the LandScan dataset, a globally recognized database known for its detailed and accurate population distribution (Mohanty and Simonovic 2021). This integration was crucial for estimating the number of people exposed to flooding. Each individual flood layer was overlaid with LandScan's population data, which is renowned for its high spatial resolution and the integration of various data sources like census data and satellite imagery (Rose and Bright 2014). This process involved multiplying the flood extent map with the population layer, providing a spatially distributed estimate of population exposure to flooding. To refine these estimates and obtain a more accurate count of the affected population, areas with permanent water bodies were identified and subtracted from the initial flood exposure calculations. This step was crucial to ensure that the population count did not erroneously include people living in areas that are