ATTRIBUTION OF MAJOR FLOOD EVENTS IN BANGLADESH RIVERS TO HUMAN-INDUCED CLIMATE CHANGE: A LARGE-ENSEMBLE MODEL-BASED ANALYSIS

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ABSTRACT

Bangladesh, located at the convergence of the Ganges-Brahmaputra-Meghna (GBM) river system, faces frequent and intense flooding. With increasing climate variability, it is vital to assess the role of anthropogenic climate change in historical flood events to inform future mitigation efforts. This study investigates the influence of human-induced climate change on eight major floods in Bangladesh (1955–2007) using the d4PDF large-ensemble climate simulations combined with the CaMa-Flood hydrodynamic model. The Fraction of Attributable Risk (FAR) method is employed to compare flood probabilities under historical (HIS) and non-warming (NAT) scenarios. Findings indicate a notable rise in flood risk in recent decades, particularly during 1998, 2004, and 2007, with FAR values for the Ganges reaching up to 0.81, the Brahmaputra up to 0.80, and 0.67 for Meghna, highlighting a strong human-induced warning. In contrast, older events such as those in 1955 and 1987 show negligible human-caused impacts. The results underscore spatial and temporal variability in flood risks, with regions exposed to heavy monsoonal rainfall being most affected. This study emphasizes the need to integrate climate change projections into national flood management strategies. Policymakers should consider both human-induced and natural climate factors to develop resilient infrastructure and adaptive measures for vulnerable regions.

Keywords: *Flood Risk Attribution; GBM Basin; Fraction of Attributable Risk (FAR); d4PDF; CaMa-hydrodynamic model.*

1. INTRODUCTION

Bangladesh is highly vulnerable to natural hazards, and the climate disaster makes these threats worse by increasing their frequency and severity (Hossain et al., 2020). According to the Global Climate Hazard Index, Bangladesh ranked fifth among 170 nations for climate vulnerability (Kreft & Eckstein, 2014). Common disasters such as cyclones, storm surges, coastal erosion, floods, and droughts lead to significant loss of life and property, threatening the country's sustainable development (Dastagir, 2015). Outdoor flooding is one of the most frequent and destructive hazards. It contributes to the rise in both frequency and intensity of flooding events (Hirabayashi et al., 2021). Flooding in the region caused over USD 10 billion in economic losses between 2000 and 2013 (Uddin et al., 2023). The National Disaster Response Coordination Centre (NDRCC) reports that approximately 6.9 million people were affected, with 114 lives lost and over 297,000 people displaced. Around 593,250 homes were destroyed, forcing many families into temporary shelters during the floods of 2017 in Bangladesh (Philip et al., 2019). In 1987, significant damage occurred to about 2.06 million homes, representing 16.67 percent of the total number of dwellings in the country. In 1988, around 45 million people were displaced, with 12.8 million homes demolished, 5.4 million completely lost, and 7.4 million partially impacted (Ahmed et al., 2018). The flooding in 1998 affected roughly 30.92 million people across 52 out of 64 districts. It led to the complete destruction of about 916,660 homes and partial damage to another 1.3 million houses (Alauddin, 2010). Several factors contribute to the severe flooding in Bangladesh, linked to its geography and human activities (Ahmed et al., 2018; Philips et al., 2019). Geographically, Bangladesh lies at the junction of the Ganges, Brahmaputra, and Meghna River basin, which is the second-largest delta in the world by area (Brown & Nicholls, 2015). The dynamics of the GBM delta greatly influence flood patterns in Bangladesh, resulting in major upstream discharge and monsoonal overflow in low-lying areas. This increases both the extent and duration of flooding events.

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Prior research indicates that the melting of snow and ice in the Himalayas, along with monsoon precipitation in the extensive catchment areas of the GBM basins, leads to significant local rainfall (Hossain et al., 2020). However, there is a lack of consistent studies directly linking the floods in Bangladesh to climate change induced by human activities. Large-scale climate model simulations play an essential role in assessing the effects of internal variability and climate change on extreme weather events, particularly when detailed historical data is scarce (Utsumi & Kim, 2022). This research aims to explore the attribution of major flood events in Bangladesh rivers to human-induced climate change and examines how such anthropogenic influences have historically intensified flooding in these river systems.

2. STUDY AREA: THE GANGES-BRAHMAPUTRA-MEGHNA BASIN

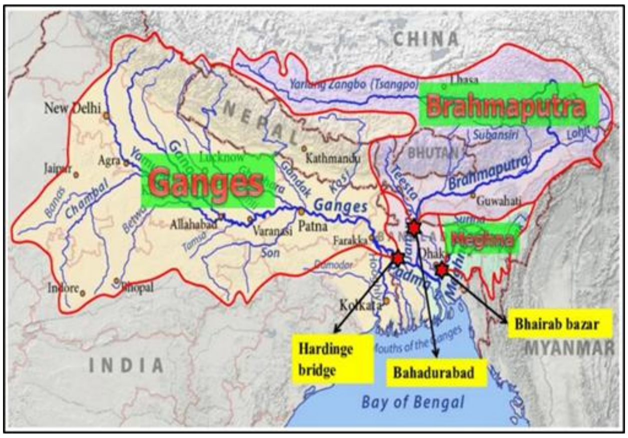

Figure 1: The Ganges–Brahmaputra–Meghna (GBM) River basin (Takeuchi & Masood, 2017)

This study focuses on the Ganges-Brahmaputra-Meghna (GBM) River basin, which is one of the world's largest and most complex transboundary river systems. It contributes enormously to local hydrology and flood patterns prior to discharging into the Bay of Bengal. Figure 1 depicts the three major rivers, such as the Ganges, Brahmaputra, and Meghna, as well as key monitoring stations, such as Hardinge Bridge, Bahadurabad, and Bhairab Bazar. Bangladesh is particularly vulnerable to large-scale floods due to its geographical location and river convergence. This study employs large-ensemble climate modeling to connect flood events to climate change caused by human activity.

3. DATA COLLECTION

This study employs runoff data from the large "Database for Policy Decision-Making for Future Climate Change" (d4PDF), which is intended to evaluate climate hazards, to assess major historical flooding incidents in Bangladesh between 1951 and 2010 (Alifu et al., 2022). The d4PDF dataset, featuring a high resolution of 0.25° × 0.25°, supplies runoff inputs every three hours for the CaMa-Flood model. This information is sourced from the MRI AGCM 3.2 and consists of 100-member ensembles for both Historical (HIS) and Non-global warming (NAT) experiments covering the years 1951 to 2010. The HIS trial incorporates human-induced factors (such as greenhouse gas emissions and recorded SST/SIC), while the NAT trial examines natural variability under pre-industrial conditions (Alifu et al., 2022; Uddin et al., 2023; Utsumi and Kim, 2022).

4. METHODOLOGY

The CaMa-Flood hydrodynamic model was developed to simulate river flow and floods on a wide scale. It is accessible through (CaMa-Flood:Global River Hydrodynamics Model). It aids in figuring out how floods are affected by climate change. By comparing the probability of flood events in Historical (HIS) and Non-global warming (NAT) simulations from the d4PDF ensemble, the Fraction of Attributable Risk (FAR) is a probabilistic method that quantifies human impact on climate. Furthermore, a comprehensive precipitation study examines flood patterns from nine major historical flood years (1955, 1963, 1974, 1987, 1988, 1998, 2004, 2007) using ERA-5 reanalysis data. Total monsoon rainfall, the number of days with heavy precipitation (≥10 mm), and days with exceptionally heavy precipitation (≥20 mm) are important metrices. Rainfall was assessed for both monsoon seasons and annual totals.

4.1 Flood Event Selection

Every year, Bangladesh experiences monsoon floods that cause significant economic and social challenges, such as disrupted livelihoods, infrastructure damage, and agricultural losses. Significant flooding incidents happened during the 19th and 20th centuries, according to historical records. Eight significant flood years have been selected for this study: 1955, 1963, 1974, 1987, 1988, 1998, 2004, and 2007. The severity of the flooding, the number of fatalities, and the ensuing economic and social consequences were taken into consideration when choosing these years (Ahmed et al., 2018).

4.2 Model Simulation and Analysis

The hydrodynamic CaMa-Flood model, which is applied here to the Ganges–Brahmaputra–Meghna (GBM) basin at 0.25°X0.25° resolution, reproduces the discharge of the Ganges and the interaction of the floods at a large spatial scale. Its sub-grid physics enables a computationally efficient floodplain representation in continental systems (Uddin et al., 2023; Yamazaki et al., 2011). The model was coerced with a three-hour overflow from a d4PDF ensemble dataset of HIS and NAT experiments, 1955–2007. Simulation over 6,000 ensemble eras under climate scenarios HIS/NAT. The analysis of annual maximum discharge outputs focused on assessing flood probabilities. A flood threshold, which corresponds to a 10-year return interval and is determined using Weibull's formula, defined exceedance events. The likelihood of flooding for both scenarios, P_{HIS} and P_{NAT}, was computed as the ratio of ensemble members that surpassed this threshold (Uddin et al., 2023). The Fraction of

Attributable Risk (FAR) indicated the extent of human influence on each flood occurrence. This method contrasts flood risk probabilities between historical climates and theoretical scenarios without warming. Additionally, ERA-5 reanalysis precipitation data, featuring a 0.1° resolution, were analyzed for overall precipitation during the monsoon season (June to September) and for occurrences of extreme precipitation (≥20 mm/day) during the specified flood years.

4.3 Attribution of Flood Events Using FAR

To evaluate the impact of human-induced climate change on historical flood events, this analysis utilizes the Fraction of Attributable Risk (FAR) method. FAR serves as a probabilistic metric that examines the likelihood of an event taking place in a historical context (P_{HIS}) and contrasts it with conditions that are unaffected by human activity (P_{NAT}) to assess the effect of anthropogenic warming on flooding. The equation for computing FAR is presented below.

$$\mathrm{FAR} = \frac{P_{HIS} - P_{NAT}}{P_{HIS}} \tag{1}$$

Where P_{HIS} is the probability of occurrence of flood events with human-induced activities, and P_{NAT} is the probability of occurrence of flood events without human-induced activities. FAR values range from -1 to 1; positive values indicate an increased flood risk due to climate change, while negative values suggest a reduced likelihood. Near-zero values imply negligible human influence.

5. RESULTS AND DISCUSSIONS

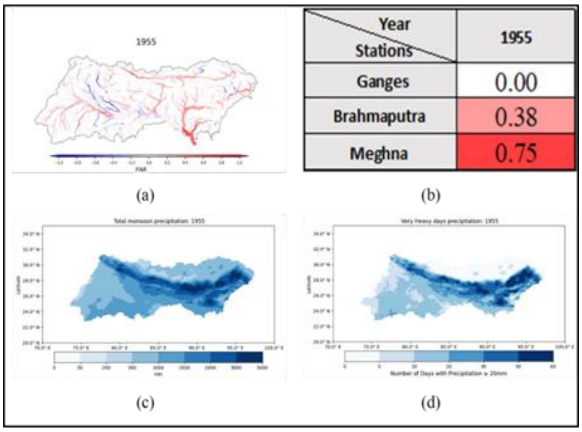

Figure 2. Hydro-metrological conditions of GMB basin,1955

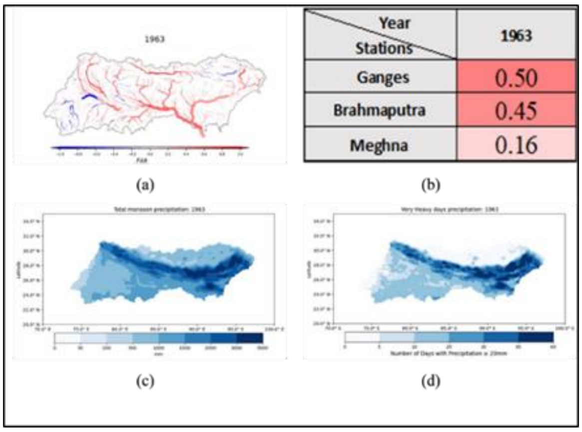

Figure 3: Hydro-metrological conditions of GMB basin,1963

The 1955 floods study revealed a considerable variance in climate change attribution across the GBM basin (Figure 2). The FAR value indicates a strong human-induced consequence of flooding in the Meghna (FAR = +0.75) and Brahmaputra (FAR = +0.38) rivers, while no such effect can be seen in the Ganges (FAR = 0.00). The present scenario is consistent with increased total monsoon rainfall and an increase in the number of extremely heavy rain days (≥ 20 mm) reported in the Meghna and Brahmaputra basins. In comparison with 60 days of exceptionally heavy rain, northeastern areas faced a higher risk of floods. The geographical FAR maps of the Brahmaputra-Meghna region reveal a positive FAR group with a high flood susceptibility due to climate change, whereas the Ganges basin appears unaffected during this year (1955). In 1963 (figure 3), the flood risks within the Ganges and Brahmaputra basin significantly escalated due to the human-induced climate crisis, as demonstrated by the elevated FAR values at Hardinge Bridge (+0.50) and Bahadurabad (+0.45). In contrast, the Meghna River exhibited only a slight anthropogenic influence (FAR=+0.16). This trend is linked to widespread heavy monsoon precipitation and an increase in the occurrence of extreme monsoon events, particularly in Assam and the upper Ganges basin (Samantray and Gouda, 2024). While some areas reflect neutral or even negative FAR values, the overall pattern indicates a pronounced increase in global warming effects in 1963 as compared to 1955. These findings emphasize the uneven distribution of flood risk across the basin in response to the climate crisis.

Figure 4 illustrates the geographical variety of anthropogenic climate change impacts on flood frequency across the GBM basin. The Ganges River experienced the largest increase in flood risk during the 1974 flood incident. The Ganges has a considerable increase in flood danger (about 71% at Hardinge Bridge), according to FAR analysis, whereas the Brahmaputra has little influence (near zero at Bahadurabad) and the Meghna has a tiny rise (~8% at Bhairab Bazar). This trend is consistent with the significant monsoon rainfall in 1974 (Figures 4.3 c & d), which was focused in the basin's eastern and central regions and increased the risk of flooding in the Ganges.

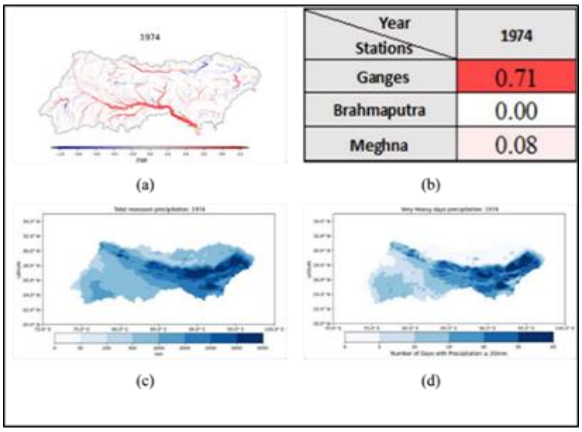

Figure 4: Hydro-metrological conditions of GMB basin,1974

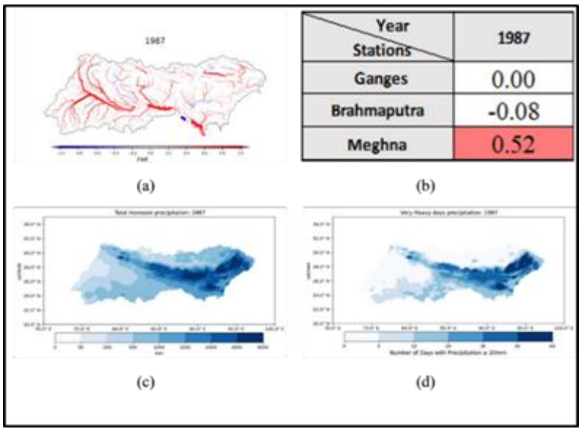

Figure 5:.Hydro-metrological conditions of GMB basin,1987

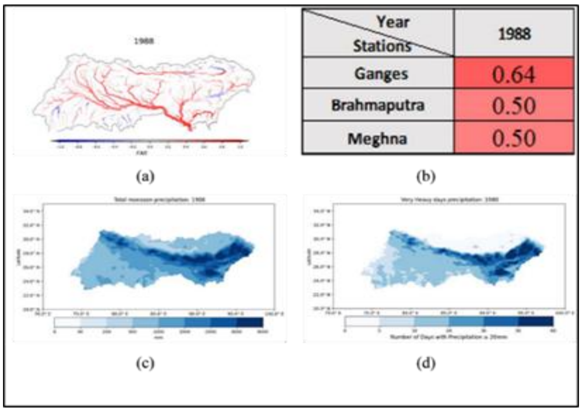

Figure 6: Hydro-metrological conditions of GMB basin,1988

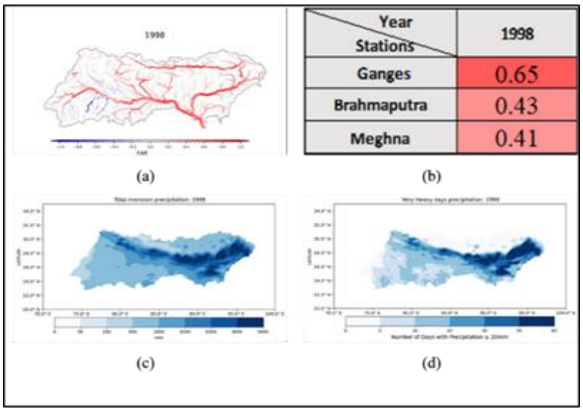

Figure 7: Hydro-metrological conditions of GMB basin,1998

In contrast, the flood event of 1987 (Figure 5) displays a distinctive regional distribution pattern. The FAR measurement reveals no significant anthropogenic impacts, aside from the flood event in the Ganges (FAR 0 near Hardinge Bridge), nor does it indicate a decrease in flood risk in the Brahmaputra (FAR = -0.08 near Bahadurabad). However, climate change has notably increased flood probabilities in the Meghna basin, where the FAR value is +0.52 in Bhairab Bazar. The present transition is characterized by similar types of precipitation (figure 5c and 5d), indicating a marked shift in climate sensitivity since 1974, with the Meghna basin becoming a notably affected area. These findings highlight the dynamic and regionally diverse character of climate change impacts on flooding within the GBM basin.

The analysis of attribution regarding the 1988 and 1998 floods in the Basin reveals a robust and significant human contribution to global warming. In the event of the 1988 flood, the deliberate fraction of Attributable Risk (FAR) represents a significant increase in the probability of a flood occurring in a given river: +0.64 for the Ganges near the Hardinge Bridge, +0.50 for the Brahmaputra near Bahadurabad, and +0.50 for the Meghna near Bhairab Bazar. In addition, the FAR standards, together with +0.65 for the Ganges, +0.43 for the Brahmaputra, and +0.41 for the Meghna, have also been observed in the case of the 1998 flood event. The precipitation model correlated with the above events (figure 6c-d, 7c-d) was comprehensive and severe, with a widespread effect on the entire area of the basin at the same time. The consistent high FAR values (all > 0.40) indicate that anthropogenetic influence occurs when major navigators promote flood threats throughout the GBM basin during such extreme, synchronous flood years. In 1998, the Brahmaputra and Meghna had a low but significant attribution, demonstrating substantial geographical variation throughout the basin. Unlike previous incidents with local consequences, the findings above emphasize the need for climate change to intensify simultaneous, high-magnitude flooding across the GBM basin.

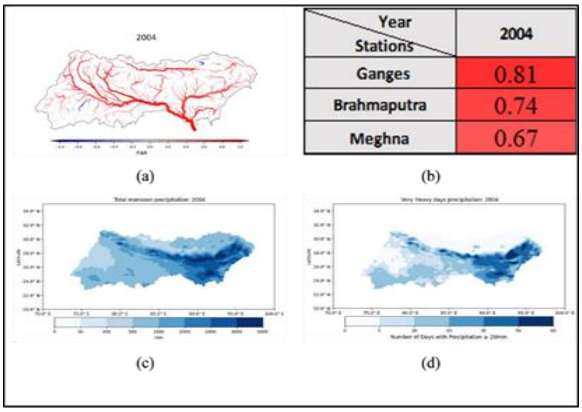

Figure 8: Hydro-metrological conditions of GMB basin,2004

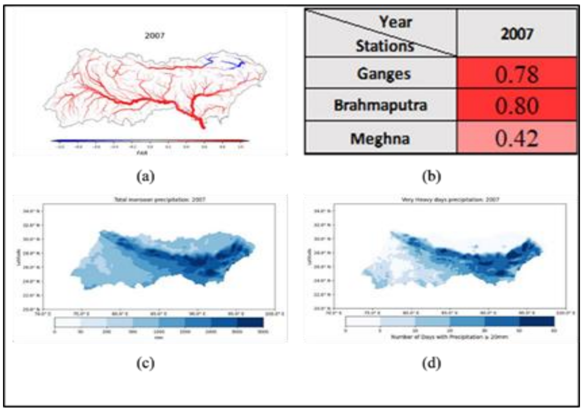

Figure 9: Hydro-metrological conditions of GMB basin,2007

Attribution analyses of the 2004 and 2007 flood events indicate a marked escalation in anthropogenic influence throughout the GBM basin (Figures 8a, 9a). The 2004 floods exhibited notably high Fraction of Attributable Risk (FAR) values: +0.81 for the Ganges at Hardinge Bridge, +0.74 for the Brahmaputra at Bahadurabad, and +0.67 for the Meghna at Bhairab Bazar—demonstrating that human-induced climate change was the primary contributor, increasing flood likelihood by over 67% across all three river systems. This strong attribution pattern continued in 2007, with FAR values of +0.78 and +0.80 for the Ganges and Brahmaputra, respectively, underscoring climate change as the dominant factor driving flood risk. Although the Meghna's FAR remained significant at +0.42, it was comparatively lower than the other basins and its 2004 level. Corresponding precipitation data (Figures 7c-d, 8c-d) revealed extreme and widespread rainfall. These post-2000 floods further reinforce the intensification of the climate change signal relative to earlier events in 1988 and 1998, with FAR values often exceeding 0.75, confirming anthropogenic forcing as the leading cause of flood risk across much of the GBM basin.

6. CONCLUSIONS

Based on the results and discussions, the following conclusions can be drawn:

i. Attribution analysis shows a growing trend of anthropogenic climate change driving flood risk in the GBM basin, with FAR values surpassing 0.75 in post-2000 flood events, indicating dominant human influence on extreme flooding.

ii. Climate change impacts exhibit strong spatial variability; the Ganges basin consistently shows the highest FAR, while the Brahmaputra and Meghna basins demonstrate variable but increasingly significant attribution across different years.
iii. In the flood year of 1955, the FAR value was zero for the Ganges, and for the Brahmaputra this value was +0.38. But the flood event in 2004, the FAR value for the Ganges reached +0.81, and +0.80 for the Brahmaputra in the 2007 flood year, highlighting a shift toward synchronous, climate-driven flooding affecting all three river basins simultaneously.
iv. The 1987 and 1974 floods underscore regional sensitivity, with the Meghna basin emerging as the most vulnerable in specific years due to intensified localized rainfall and evolving climate conditions
v. A clear increase in FAR values after 2000 confirms a strengthening climate signal, necessitating region-specific adaptation strategies and climate-resilient flood risk management across the transboundary GBM basin.
vi. These findings highlight the dynamic and spatially uneven nature of climate change impacts, emphasizing the need for integrated, long-term planning to mitigate flood risks under future climate scenarios.

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DECLARATION OF USE OF AI

The authors used artificial intelligence (AI) only to improve the language, grammar, clarity, and structure of the written content. The research concepts, methodology, data analysis, result interpretation, and technology findings were developed independently and without the use of AI technologies. The authors meticulously reviewed and confirmed every aspect of the work to ensure accuracy, originality, and compliance with academic and ethical standards.

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