A Conceptual Approach to Agent-Based Modelling of Coping Mechanisms in Climate-Driven Flooding in Bangladesh

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Abstract. Bangladesh stands as a prime example of a nation exceptionally vulnerable to the adverse effects of climate change. Its low-lying coastal and deltaic landscape predisposes it to frequent flooding, a challenge exacerbated by a significant portion of its population grappling with poverty. The country is already experiencing the impacts of climate change, including more frequent and severe flooding that has led to the displacement of millions of people and has intensified existing social and economic challenges. Despite these formidable challenges, Bangladesh has also emerged as a global leader in climate resilience and preparedness, having made significant progress in reducing cyclone-related deaths and protecting its population from the consequences of climate change. Notably, non-governmental organisations, like our partners Save the Children, are keen to explore how they can support the most vulnerable communities by establishing the efficacy of current coping strategies for sustained resilience against climate change. To facilitate this, we are in the process of creating an agent-based model that examines the coping mechanisms adopted in response to climate-induced flooding in Bangladesh. This paper presents the initial phase of developing a multiscale conceptual model tailored to understanding this complex situation.

Keywords: conceptual model · agent based model · forced migration · Bangladesh · flooding · internally displaced people · coping mechanisms · climate change

1 Introduction

Bangladesh, with its population nearing 170 million, faces a formidable adversary: climate change. Ranked seventh in the world on the Long-Term Climate Risk Index [1], this densely populated nation grapples with the devastating consequences of rising sea levels, intensifying storms, and unpredictable rainfall

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To cite this paper please use the final published version:
DOI: 10.1007/978-3-031-63775-9_31

patterns. Among these challenges, flooding stands out as a defining threat, displacing millions, disrupting livelihoods, and eroding communities [2].

Exploring how people cope with and adapt to this ever-present threat is vital for understanding the intricate relationship between climate-induced flooding and forced migration. While floods pose significant challenges, communities have historically developed remarkable resilience, coexisting with these events for centuries. The intricate interplay between vulnerability and resilience calls for a nuanced approach, that acknowledges the multifaceted impacts of flooding on people and their environment. Understanding these wide-ranging coping mechanisms, from asset protection to reliance on social networks, is essential for designing effective humanitarian interventions.

This study aims to assess the 'push' and 'pull' factors that force individuals and communities to migrate. 'Push' factors, such as the increasing frequency and intensity of floods destroying homes and livelihoods, can make certain areas uninhabitable. Conversely, 'pull' factors, like the promise of greater safety, economic opportunities, or established communities in new locations, can drive migration. Furthermore, we will explore factors that trigger individuals to rebuild their lives within their hometowns, to gain a deeper understanding of both migratory pressures and potential return pathways.

Agent-based models (ABMs) simulate complex systems by modelling people as individual 'agents' with rule sets governing their interactions with their environment, allowing for the study of how bottom-up interactions lead to emergent phenomena. ABMs are especially good at representing decision-making processes, which is vital for understanding coping mechanisms. Compared to machine learning approaches, ABMs allow for straightforward implementation of easily comprehensible decision rules, avoiding the 'black box' nature of machine learning algorithms. This transparency allows for a deeper understanding of how individuals interact with their environment and their choices. Furthermore, ABMs enable the testing of multiple scenarios to pinpoint the specific drivers of migration, leading to more accurate models.

This research utilises Flee [3], an established ABM for conflict-driven migration in developing countries, recently adapted to simulate flood disasters under the title DFlee [4]. Existing flood ABMs often focus on developed countries, with detailed data to enable modelling of the flooding, infrastructure, and transportation networks [5]. Producing an ABM for a developing nation poses greater challenges due to data limitations for geography, population, migration, and flooding. Moreover, Flee is unique in that it leverages heuristic methods to understand migration behaviour. The DFlee model better represents the decision-making processes involved in flood-induced migration in developing countries.

This paper discusses the development of our conceptual ABM that directly considers the individual decision-making processes underlying forced migration in flood-prone Bangladesh. We address the challenges and limitations of data sources considered during its development and outline our plans for future model refinement and validation.

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DOI: 10.1007/978-3-031-63775-9_31

2 Conceptual Model Development

2.1 Identifying and Prioritising Coping Mechanisms

Understanding the coping mechanisms of individuals and communities in managing the negative impacts of flooding is critical. These mechanisms can be preventative (proactive), such as storing food, or reactive (response-based), like seeking shelter after a flood warning. Whilst our comprehensive literature review identified over 75 potential mechanisms in Bangladesh (e.g. [6] [7]), limited research exists on their relative importance in driving migration. Due to time constraints, we prioritise modelling only the most important ones based on the knowledge of humanitarian experts and ease of numerical implementation in the model. An iterative development approach allows for future expansion.

The literature highlights the importance of preparedness, as individuals exhibit varying degrees of awareness and readiness for floods [8]. Accessibility and language barriers can limit the effectiveness of flood warnings. Consequently, individual knowledge of impending floods becomes crucial for both evacuation decisions and the success of other coping mechanisms. For example, common pre-flood preparations include stockpiling food, safe drinking water, and essential items like medicine or livestock. Additionally, people often seek temporary refuge in nearby cyclone shelters. Furthermore, disruptions to medical care after floods can necessitate relocation to access treatment. The next section explores the implementation of these coping mechanisms in greater detail.

2.2 Conceptual Model of Coping Mechanisms

Weather Forecaster - Agent Awareness of the Flood The proposed ABM incorporates a modified weather forecaster mechanism to influence agent movement during floods. Each potential destination's favourability score is calculated to account for the standard ABM rules (such as travel distance), the severity of flooding, the agent's awareness of the forecast and how important they consider the forecast to be. This mechanism penalises agents for moving through flooded areas and encourages them to avoid predicted flooding by moving to the most favourable destination. This approach captures the impact of varying levels of preparedness and information access on individual migration patterns.

Storage of Food, Water and Essentials The conceptual model includes an asset storage coping mechanism, to link an agent's ability to store food with their awareness of impending flooding, the flood severity and their economic status. This mechanism is coupled with the weather forecasting mechanism. An agent's economic status determines the number of asset parcels they store, which decreases over time due to consumption. As resources become scarce during flooding, consumption is then limited to two parcels per day. If the agent's location reaches the maximum flood level, some agents will lose all or most of their food assets. Movement likelihood is then tied to the abundance of assets, with agents having less than two days of food parcels being more likely to move.

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Cyclone Shelters Agent's may migrate to cyclone shelters during floods. The shelters do not flood and have a capacity based on government registers. Although capacity does not limit the number of agents who can seek refuge in a shelter, a full shelter may encourage continued migration.

Medical Facilities Access to adequate healthcare likely influences internally displaced people's (IDP's) movements after floods, as injuries and healthcare disruptions are common. We'll incorporate health facility data from OpenStreetMap [9] and model their influence on migration using the methods discussed in Jahani et al. [10].

2.3 Simulation Development Approach

In our work, we take a novel approach to simulation development by prioritising the ultimate goals of our non-governmental organisation (NGO) partners. Unlike traditional scientific methods, which typically build upon existing knowledge and ask 'What new questions can we answer?', we start with the end goal in mind: understanding when, where, and what methods people use to cope with flooding, to establish which interventions are likely to be most effective. We then work backwards, gathering and analysing data to develop a robust and useful simulation.

This approach addresses the scenario complexity and the scarcity of data in the humanitarian field. By creating a model first, we can use it to guide data collection efforts and maximise the value of the data we receive. This model can then be continuously refined, incorporating real-world experiences and insights from experts. This collaborative, iterative process ensures a swift model development approach that means the model remains relevant and practical, ultimately leading to more effective, timely interventions and improved outcomes for those in need.

We follow the multi-step simulation development approach proposed by Groen et al. [11], to develop a conceptual model. This approach emphasises simulation selection and data acquisition for both modelling and validation. This approach also guides the model's implementation, including iterative refinement.

2.4 A Multiscale Model

This paper presents a multiscale conceptual model to analyse climate-induced flood displacement in Satkhira, Bangladesh. The scale separation map, in Figure 1a, shows how processes at different scales interact and influence each other. It showcases the model's ability to capture the interplay between individual-level decisions and large-scale emergent phenomena, highlighting the critical role of spatial scales in understanding human responses to complex environmental challenges.

The model captures various levels of granularity. From individual actions, such as food storage (around 100 metres), to large-scale migration (exceeding

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100 kilometres). The weather forecasting mechanism operates across the entire local domain, while the shelter evacuation mechanism reflects the behaviour of individuals seeking refuge within a few kilometres for short periods (days). The food storage mechanism is personal to each agent and is impacted by consumption and potential flooding within a localised area. When food falls below a critical threshold, individuals are driven to migrate within the domain. The model also emphasises the interconnectedness of these multiscale processes. For instance, forecasts of flooding can trigger local migration, evacuation to nearby shelters, and food storage. Additionally, return migration from shelters can occur as the flood subsides. Furthermore, food scarcity can prompt longer-term long-distance migration.

We built a location graph, shown in Figure 1b, using demographic data from the City Population website that collates global census data [12]. Our small-scale model focuses on Satkhira and encompasses locations with populations exceeding 1,000 inhabitants at the first-order administrative level. The larger scale model includes mega cities such as Bangladesh's capital Dhaka, and Kolkata in nearby India. Government-registered cyclone shelters are included as safe locations for agents to migrate to. Locations prone to flooding are classified as flood zones based on historical inundation data [13] that identifies the severity and location of flooding. This data provides precise representations of flooded areas, minimising uncertainty when assessing the impact of coping mechanisms on migration patterns.

3 Challenges in Constructing the Conceptual Model

While the conceptual model captures critical coping mechanisms influencing IDP movement, it's pertinent to acknowledge the challenges in constructing the model and its limitations. Most significantly, focusing on a subset of mechanisms prioritises development efficiency and model parsimony, potentially underestimating estimating real-world complexity and losing vital information.

Moreover, due to a wide range of difficult-to-define model parameters, mechanism construction has been simplified until these parameters are better understood. Future iterations could increase the sophistication of the mechanisms. For example, extending the asset storage mechanism to include varied rule sets for each asset type. Furthermore, the distribution of food by humanitarian organisations could be incorporated. However, this may be challenging due to local decision-making processes involved in the rapidly evolving situations.

The multiscale nature of both mechanisms and data creates additional challenges. For instance, government registers are likely to underestimate total shelter capacity, potentially missing major evacuation locations, as registered shelters are often significantly smaller than the neighbouring towns and there are entire administrative regions with no registered shelters. Comprehensive shelter data collection encompassing location and capacity is necessary to address this. As educational facilities are often used as shelters, mapping data could potentially bridge this gap. Additionally, aggregating shelter data to match town sizes

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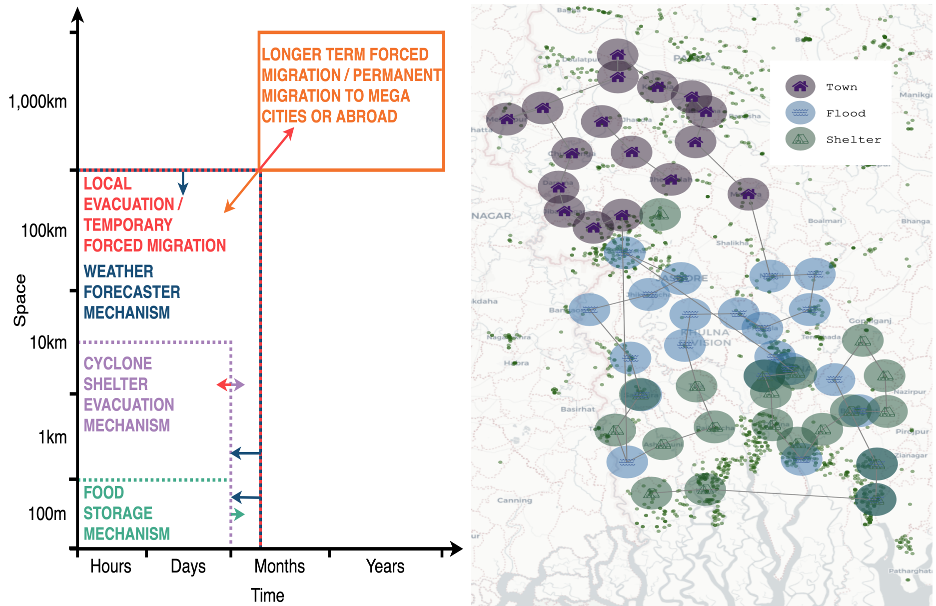

(a) Scale Separation Map (b) Khulna Division Location Graph

Fig. 1a: Illustration of the hierarchical spatial scales in the conceptual multi-scale ABM. The ABM's location networks for local (red dashed) and larger-scale (orange solid) migration are represented. The remaining dashed boxes depict sub-models for specific mechanisms within the ABM, including the weather forecasting (blue), cyclone shelter evacuation (purple), and food storage (green) mechanisms. Arrows visualise the interactions and feedback loops between different spatial scales. Fig. 1b: Khulna division location graph, with flood zones based on flood inundation data, towns with more than 1,000 people, government-registered shelters and connecting routes. Green dots represent educational facilities (potential shelters) obtained using Open Street Maps [9].

could also enhance model accuracy. Another limitation arises from the coarse spatial and temporal resolution of satellite inundation data, particularly during cyclones when there is increased cloud cover, which hinders capturing the details of small-scale flooding. Once the mechanisms have been fully refined, the incorporation of additional weather data, as demonstrated in previous Flee models [14] may be beneficial.

Finally, our conceptual model treats people as individual agents to address our partner NGO's focus on the specific vulnerabilities of children. This approach may limit our ability to capture the full complexity of household-level decision-making. However, we can still capture family dynamics by linking the attributes of individual agents to decision rules. For example, children may have prioritised access to food.

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4 Discussion on Validation Data Collection

Acquiring data on displaced persons is inherently complex and ethically sensitive. This challenge is particularly pronounced when it comes to obtaining comprehensive and reliable data on climate-induced displacement in Bangladesh. Existing resources, such as the International Organisation on Migration Displacement Tracking Matrix and the International Disaster Database, lack comprehensive IDP entries for Bangladesh. Moreover, access to valuable data sources like Meta Data for Good Displacement Mapping is restricted. While mobile phone records provide some insights, they fail to account for vulnerable populations without access to mobile phones, lack sufficient time cadence and regional specificity, and cannot distinguish between forced and non-forced migration.

Despite the challenges, several valuable data sources were identified for model development and validation. Post-disaster reports provide event-specific displacement statistics [15], while national statistics reports offer demographic data [8], and ongoing surveys from the UN Food and Agriculture Organisation Data in Emergencies Hub offer insights into broader migration patterns, recent shocks, and food security within the country [16]. However, this source covers the entire nation rather than the specific area of interest, so it can only be used to validate the mechanisms with a national model.

5 Conclusions

This study proposes a multiscale agent-based conceptual framework for exploring how communities in Bangladesh adapt to climate-driven floods. The initial focus is on identifying key coping mechanisms that influence migration. An iterative development process, informed by data acquisition and collaboration with humanitarian experts, will guide the refinement of the final ABM. The planned ABM will then simulate the effectiveness of these mechanisms to identify the most impactful interventions for building a more sustainable future for vulnerable communities in Bangladesh.

Developing a comprehensive conceptual model for this complex scenario has presented significant challenges. There are inherent difficulties associated with conceptualising this multiscale model, particularly due to limitations in data availability and the need to balance model complexity with efficiency. However, these challenges highlight the importance of our iterative development approach. Future work will focus on implementing the model, data-driven refinement, and rigorous validation to ensure an accurate and relevant ABM for informing effective and timely humanitarian interventions.

Acknowledgments. This study was funded by an STFC Dirac Innovation Placement.

Disclosure of Interests. The authors have no competing interests to declare.

ICCS Camera Ready Version 2024
To cite this paper please use the final published version:
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DOI: 10.1007/978-3-031-63775-9_31