Developing an Agent-Based Simulation Model to Forecast Flood-Induced Evacuation and Internally Displaced Persons

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Abstract. Each year, natural disasters force millions of people to evacuate their homes and become internally displaced. Mass evacuations following a disaster can make it difficult for humanitarian organizations to respond properly and provide aid. To help predict the number of people who will require shelter, this study uses agent-based modelling to simulate flood-induced evacuations. We modified the Flee modelling toolkit, which was originally developed to simulate conflict-based displacement, to be used for flood-induced displacement. We adjusted the simulation parameters, updated the rule set, and changed the development approach to address the specific requirements of flood-induced displacement. We developed a test model, called DFlee, which includes new features, such as the simulation of internally displaced persons and returnees. We tested the model on a case study of a 2022 flood in Bauchi state, Nigeria, and validated the results against data from the International Organization for Migration's Displacement Tracking Matrix. The model's goal is to help humanitarian organizations prepare and respond more effectively to future flood-induced evacuations.

Keywords: Forced Displacement · Natural Disaster · Flood · Internally Displaced Persons · Agent-based Modelling and Simulation.

1 Introduction

The impact of climate change on the world has caused an increase in humanitarian needs [1], particularly in poorer countries. The resulting extreme weather events, such as droughts, floods, wildfires, hurricanes, and tornadoes, are directly linked to rising temperatures and sea levels. Flooding is the leading cause of climate-related displacement, accounting for over 9% of natural disaster displacements [2]. The number of flood-related disasters has been increasing in recent years due to global warming and deforestation. In 2021, more than 10 million people were internally displaced due to 749 flooding events [3]. There is a common misconception that the effects of climate change on displacement are temporary. However, in most cases, people are permanently displaced due to the

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destruction of their homes and communities by floods. For this reason, climate change is now widely considered a humanitarian disaster.

Despite the ongoing devastating effects of flooding worldwide, little research has been done to investigate the displacement of affected people and provide useful information for humanitarian organizations and governments. Therefore, this study focuses on simulating the evacuation caused by floods and the movement of internally displaced people who are seeking a safe shelter. Previous research on flood and disaster-induced evacuation has mainly focused on behavioural models, pre-evacuation behaviour, and risk perception. In addition, computational techniques such as random forests and agent-based modelling have been widely used in flood and disaster management, especially in relation to the reasons for evacuation and predictors of displacement [4]. However, this project has identified a gap in the literature regarding individual movement, distribution of internally displaced persons (IDPs), and evacuation destinations.

To simulate flood-induced evacuation, this study employed the Flee agent-based modelling toolkit, which is typically used to simulate the geographical movement of people fleeing from conflict and violence [5]. The aim was to extend its applications and adapt the Flee toolkit to simulate flood-induced evacuation during a specific flood event, with the intention of providing insights to prepare for future extreme flooding. While Flee has not been used to model flood-induced evacuations before, there are similarities between climate-driven events and conflict-driven events in terms of the mass forced displacement of people. However, there are differences in the locations of shelters and camps between the two events. In this study, some shelters are located within the flooded areas but at lower flood levels, rather than refugees being displaced to neighbouring countries. Moreover, Flee has not been used to model a small region instead of an entire country or state, but this study aimed to repurpose the model to investigate the movement of IDPs during a flood event in small regions.

The paper is structured into six main sections. The second section is a literature review that provides an overview of the current research on flood-induced evacuation and the existing models used to simulate the movement of people during flood events. The third section explains the research problem and the approach taken to develop the simulation and describes the conceptual model. It also discusses the construction of an instance and the necessary parameters and data sets needed to run the agent-based model for flood-induced evacuation. The fourth section contains a case study, while the fifth section discusses and evaluates the model's results. The final section summarizes the study's findings, identifies opportunities for future research, and reflects on the study's limitations.

2 Literature Review

Severe flooding has the potential to displace individuals temporarily or permanently, leading them to seek inadequate accommodations and limited resources [6]. Displacement can be particularly challenging for vulnerable individuals, em-

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phasizing the need to understand the composition and quantity of people who may be evacuated due to floods and displaced to shelters and sites [7]. By comprehending the movement of people in affected areas and meeting their specific needs, there is an opportunity to increase their resilience to flood events. To aid in resource planning for those who are least equipped, a reliable and robust simulation of people's movement is essential.

Previous studies have focused whether on evacuation modelling for smaller scales or on migration modelling for larger scales, especially after conflicts, but little research has been done on the movement of people after natural disasters. While flood-induced evacuation models have considered the behaviour and decisions of people during a flood event, they have neglected the outcomes of these decisions, such as the destinations of evacuees and their distribution across shelters and sites.

2.1 Evacuation Modelling Approaches

Several studies have been conducted to comprehend the evacuation process by considering human behaviour and decision-making. These models are not restricted to flood evacuations; rather, they are developed for various types of disasters such as hurricanes, cyclones, and war-related evacuations. Lim et al. [8] used discrete choice modelling and determined that demographic and household characteristics, as well as the perception and movement of the hazard, play a role in the decision to evacuate. Hasan et al. [9] expanded on this work and examined the effect of these characteristics on departure timing by utilizing a random parameter hazard-based modelling approach. These studies highlighted that evacuation choices are not binary and require interconnectivity of parameters to reproduce human behaviour accurately. This type of modelling is useful in decision-making and parameter significance determination. However, to simulate forced displacement, a more robust modelling approach is required, such as behavioural, spatial, and agent-based modelling approaches, as described below.

Behavioural models aim to understand the required time for people to evacuate during a disaster, how they decide to evacuate, and their actions leading up to the evacuation [10]. Researchers such as Coxhead et al. [11] and Lovreglio et al. [12] have studied displacement decisions in Vietnam and building occupants' behaviour during emergencies, respectively. However, these studies do not focus specifically on flood-induced displacement and natural disasters in general. The primary focus of this method revolves around pre-evacuation modelling and does not delve into the evacuation process itself or the related movements.

Spatial models can be utilized to simulate the movement of evacuees during a flood event by incorporating travel behaviour and traffic networks. Hybrid route choice models [13] and multiple criteria evaluation approaches with traffic microsimulations [14] have proven to be effective in transport and route modelling. These approaches can provide flood and disaster management recommendations by predicting the movement of evacuees in terms of their travel choices across the

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transportation network. The mode of transport taken by evacuees can greatly influence their movement, and the routes they take may be determined by their pre-trip knowledge of the area and their destinations. However, transport models do not account for the final destination choice of evacuees. It is important to note that during a flood, an effective evacuation requires clear routes and a functioning transport network, which may not always be available.

Agent-based modelling is a widely used technique to simulate forced displacement and the behaviour of agents. It is capable of handling complex decision-making processes, making it suitable for modelling human behaviour and the effects of a flood event [15]. Agents can be assigned various attributes to model flood-induced evacuations, and agent-based modelling is an appropriate approach to consider and simulate human behaviour in the context of flood risk. SiFlo is a model that integrated emotions and social norms into individual behaviour and considered various motivations and priorities people may have when facing flood risk, such as escaping or helping others, or protecting their belongings [16]. The model could predict the decisions that would reduce or increase damage and casualties, but it did not model or describe the journeys and destinations of the evacuated people. Agent-based models can incorporate demographic data, which is known to impact evacuation decisions and risk perception [9,8,13,17]. Characteristics like age and gender can affect an individual's behaviour during a flood event, including their pace of movement and need for assistance. By modelling the interactions between agents of different demographics and the influence of their characteristics on one another [18], agent-based approaches can capture the effects of demographic data on flood-related behaviours.

The objective of this study is to use agent-based modelling to simulate the displacement of people during floods and analyse the behaviours of different demographics. While there is limited literature on quantifiable movement during flood-induced displacement, understanding how evacuees move towards shelters and accommodation sites and the time it takes them to reach their destinations can aid policymakers and authorities in designing better evacuation strategies and allocating resources during prolonged floods. By knowing the routes people are likely to take, authorities can keep these routes open and accessible during emergencies and provide necessary supplies to those affected. Additionally, this simulation can help identify gaps in monitoring infrastructure and forecast the supplies required based on the demographics of displaced individuals.

3 Development Approach

The primary objective of this study is to use the modified version of the Flee modelling toolkit to simulate the movement of IDPs in response to a flood event. To achieve this, several objectives need to be accomplished. First, we must establish the assumptions regarding flood-induced displacement, based on reports from organizations such as the International Organisation for Migration (IOM), to create a general set of rules for an agent-based model and establish the constraints for autonomous decision-making within the model. Next, we need to

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create a conceptual model based on these assumptions to provide a clear understanding of what the final simulation aims to accomplish. Once we have chosen a case study, we can modify the general rule set to better reflect the specific requirements and processes of the flood-induced displacement scenario. Figure 1 illustrates the different stages of the proposed simulation development approach for DFlee. Regarding the quality of the data used, it is important to note that there are incomplete data sets for some flooding events and in certain situations, there is a high level of uncertainty and bias in the reports that have been published. The authors suggest that collaborating more with the relevant organizations could help reduce these issues.

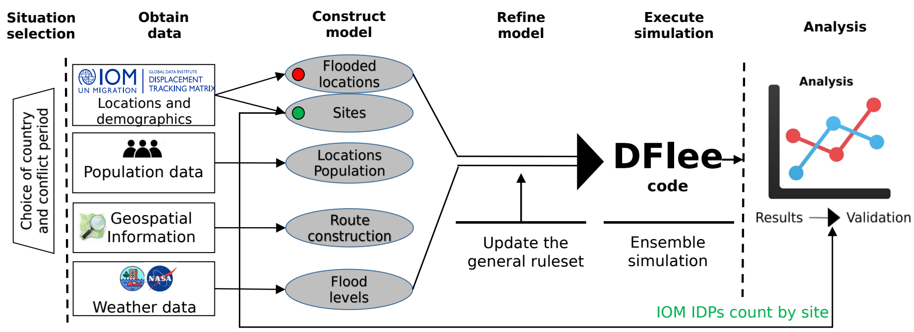

Fig. 1: DFlee simulation development approach

3.1 Assumptions

This particular section outlines the assumptions we utilized to comprehend the design prerequisites of the conceptual model for flood-induced displacement. These assumptions were derived from pertinent literature and will require further confirmation from additional specialists in the future.

Assumption 1 - Floods cause internal displacement: In the event of natural disasters, people usually seek shelter in safe locations such as temporary shelters, with their relatives, or in hotels and other accommodation facilities that are located away from the affected areas. Displacements caused by climate-related disasters are often temporary and local, with individuals returning to their homes once the threat has passed. However, if homes are destroyed and residents are unable to return, the displacement can become permanent. Since floods typically occur in specific regions, individuals are typically displaced within their country's borders, making them IDPs, unless they are close to a border and seek refuge in a neighbouring country.

Assumption 2 - Floods need immediate response and evacuation: In contrast to other types of mass movement and forced displacement, which might take months or years in terms of the time scale of the displacement, natural

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disasters such as floods require immediate evacuation and demand a prompt response from authorities and humanitarian organizations. Therefore, simulation scenarios for these situations may require shorter time scales, hours, days, or weeks.

Assumption 3 - People might use various ways of transportation (i.e., walking, driving, and river crossing): Floods can rapidly inundate communities, forcing them to evacuate as quickly as possible by any means necessary, such as walking or using boats [19]. This is particularly true when the water level is high and the transportation infrastructure is inundated. Factors related to transportation also play a role in how evacuees reach and choose their evacuation destination, including the distance to available shelters, the method of transportation, and access to private or alternative means of transportation, among other factors that may not be immediately apparent [20]. However, certain individuals may lack means of transportation and consequently become stranded in their current positions. This matter has not been scrutinized in this paper, but we plan to explore it in forthcoming research.

Assumption 4 - Based on the available reports on people displaced by natural disasters, people might want to return to their homes after the flood recession: When floodwaters eventually subside after a period that may range from days to weeks, those displaced by the flood may want to return to their homes, making their displacement temporary. However, if the damage caused by the flood is severe enough, individuals may become permanently displaced and may need to resettle elsewhere because they cannot or do not want to return home.

Assumption 5 - The evacuation decision includes when, how, and where to go questions: Once an individual decides to evacuate, they will also need to consider various factors such as when, how and where to evacuate. The choice of destination may be based on socio-economic and demographic factors. Available destination options include public shelters, hotels, and the homes of friends or relatives. Wealth and ethnicity may influence a person's preference for shelter or non-shelter destinations [13]. However, this research only focuses on the movement of flood-induced IDPs towards official shelters and camps, and private accommodations are not taken into account.

Assumption 6 - Some forms of shelters include higher grounds or even high buildings: It is important to note that unlike in situations of conflict, refugees in flood-prone areas do not necessarily have to leave the area if they can find safety in buildings or homes that are located at higher elevations or have more floors that are closer to their homes. Typically, residents of areas with a high risk of floods, such as Bangladesh, are accustomed to relocating to higher ground during the wet season with their belongings. However, since we could not find any dependable data to support this assumption, we have decided to exclude it from our research.

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Assumption 7 - Cities and areas can have different levels of floods: In the event of a flood, the risk level of various locations within a city or area can vary, resulting in differences in the likelihood of people choosing these areas as safe havens or leaving them as high-risk areas. These variations can occur during each simulation period and in every time step.

3.2 Conceptual Model

In this section, we will first create a conceptual agent-based model using a hypothetical flood event for the purpose of refining the model. Then, in the next section, we will develop a model for a selected country and run a simulation. To validate the accuracy and performance of the model, we will compare the simulation results with data obtained from historic flood events and IOM reports and data sets. Figure 2 illustrates a conceptual model that showcases the evolution of a flood event in an imaginary scenario with four locations, each with the potential to flood at three different levels. The flooding level affects the agent's decision to either move towards the nearest safe location or stay in their current location. It is important to note that agents will return home once the situation improves. At each time step, following the update of flood levels, types of locations, population, as well as the number of internally displaced individuals from adjacent areas and those evacuating from the current location, the agents will be spawned to the adjacent safe location.

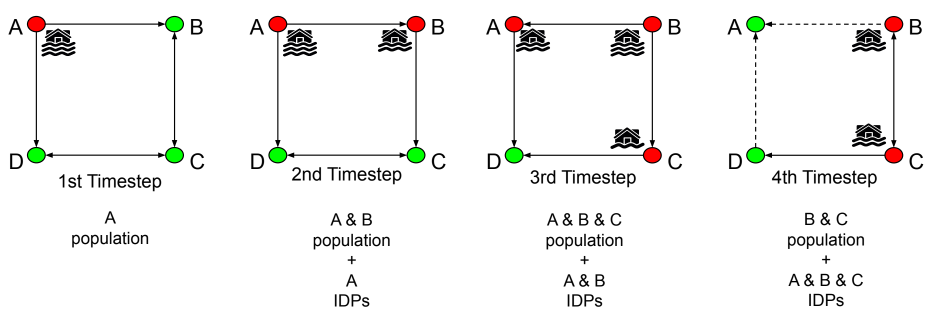

Fig. 2: The conceptual model, represented by a simple location graph and the evolution of a flood event over four timesteps

In this particular case, during the first time step, only location A is inundated with the most severe level of flooding, level three. As a result, the residents of location A will relocate to the nearest safe locations, which are locations B and D. During the second time step, location B is flooded at level two, resulting in its residents fleeing to the safer location, location C. Furthermore, the newly arrived and displaced inhabitants of location A from the previous time step will be combined with the overall number of people seeking refuge. In the third time step, location C will be flooded at level one, while the flood levels of locations A and B will be updated to level two and level three, respectively. This indicates

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that residents and internally displaced individuals in location B, who have not yet evacuated, may choose whether to go to location A or C since their flood levels are lower. As in previous time steps, the total number of people seeking asylum must be updated to include all three flooded populations and IDPs from the two flooded locations from the previous time step. In this scenario's fourth and last time step, the situation in location A has changed to safe, and its residents can decide whether to stay in their current shelter or return home, which is represented by dashed arrows, depending on how much damage their homes have sustained as a result of the flood. Naturally, the overall number of agents seeking shelter must be updated in the same manner as in the previous time steps.

The proposed model's flowchart is presented in figure 3. The flowchart highlights probabilities and variables that can be changed by users to explore different rule sets. These variables are shown by dashed shapes, while the probabilities are shown by dotted shapes. The authors have selected the present parameters for the rule set in accordance with their previous experience and the reports on displacement modeling, to suit the given scenario. The flowchart runs through every time step, during which agents will decide whether to move towards their destination or return home or stay at their current location due to lower flood levels compared to adjacent areas. The model will use the provided data by IOM's DTM from the studied areas to determine the demographic makeup of the agents. This will allow the model to estimate the age and gender of the agents in each location and link at each time step. The number of male and female agents and their ages in the camps are then compared to reference data to validate the model's results.

3.3 Model Inputs

The main input data is provided by IOM's Displacement Tracking Matrix (DTM) reports which contain important details about the number and demographic characteristics of IDPs affected by a flood event and their destinations. The reports also provide insights into the transportation methods used by the affected people, the capacity of shelter sites, and their geographical coordinates. To determine the flood levels at the affected locations during an event, we collected climate and weather-related datasets. For this purpose, we utilized maps of flooded areas provided by the National Aeronautics and Space Administration (NASA) to extract the location graph. This information will be used to update the flood level of affected areas.

4 A Case Study: Nigeria, Bauchi State

We conducted a case study of Bauchi state, located in the northeastern part of Nigeria, which experienced flooding due to heavy rainfall and strong winds. As a result, a total of 2,185 people were affected, with 90% of them being displaced to neighbouring communities in seven Local Government Areas (LGAs): Damban,

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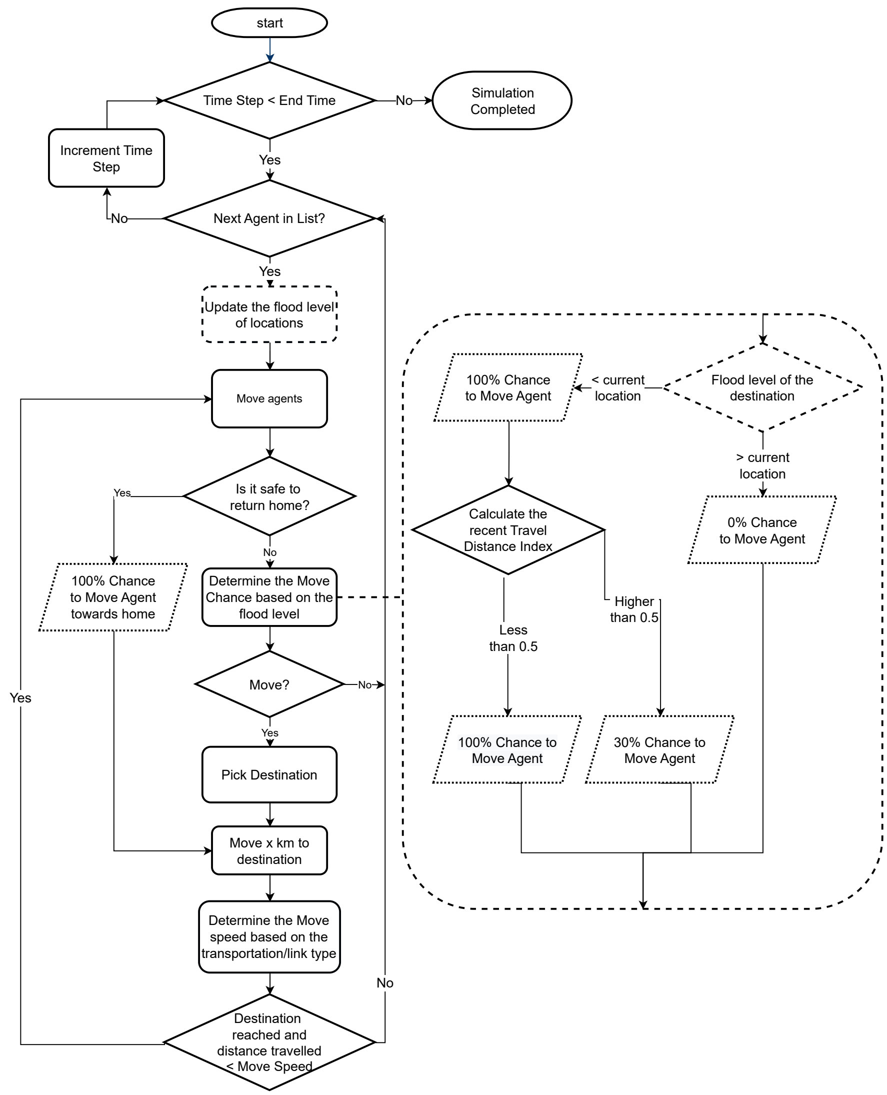

Fig. 3: A flowchart of algorithm assumptions in the DFlee agent-based code to demonstrate the rule set predicting forced displacement destinations updated with flood level data

Gamawa, Ganjuwa, Jama'are, Ningi, Warji, and Zaki. Based on an assessment by the IOM's DTM program conducted between September 1st and 12th, 2022 [21], Filin Shagari, a community in the Kariya ward of Ganjuwa LGA, was the worst-hit site, with 78 houses damaged and an estimated 868 people affected. In Ariya, Kubdiya LGA, 68 individuals were displaced to Kore primary school, and 33 individuals were displaced from Kubdiya in Kubdiya ward of Gamawa

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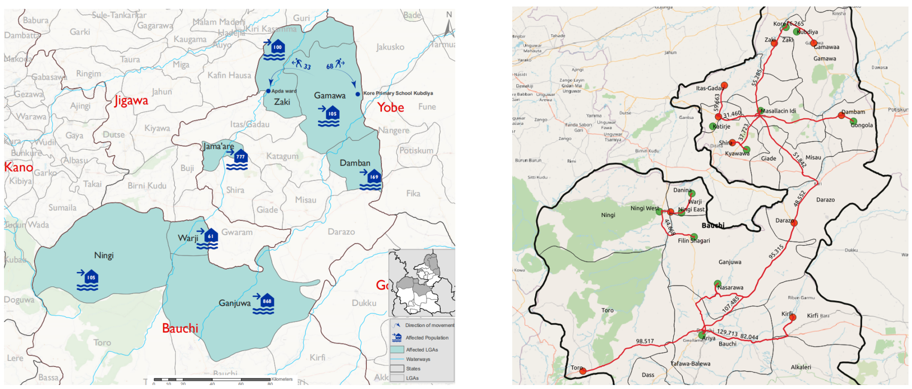
LGA to Apda Ward in Zaki LGA. The flooding affected a total of 222 houses, leaving 256 households in need of shelter, repair kits, and non-food items as most houses need re-enforcement with brick blocks. According to the IOM [21], 120 casualties were reported as a result of the Flood. Figure 4 (a) depicts the map of the affected areas in the Bauchi state and (b) shows the location graph extracted from the IOM's report.



(a) (b)

Fig. 4: Nigeria, Bauchi state location graphs: (a) The map of the affected areas by heavy rainfalls and floods in Bauchi state [21] and (b) The location graph extracted from the IOM's report

Our proposed simulation model aims to forecast the evacuation patterns of people after flood events in the case study and compare the results against the IOM's DTM data. Figure 4 (b) depicts the location graph, which includes all the flooded locations and shelters where the agents would go to find asylum. These locations are interconnected with routes found using the ORS tools plugin in QGIS [22]. The agents move through these routes using a weighted probability function based on route length, with distances estimated using driving, walking, and river-crossing routes. The total number of displaced people is extracted from IOM reports using linear interpolation between data points. Agents representing people move with a probability of movechance to different locations to find safety, with a chance of returning to their homes when the flood level decreases, according to the fourth assumption. As mentioned above, we modified the original Flee toolkit in Python to run the simulation and compared the results against IOM-published data, calculating the sum of absolute differences in agent counts for each shelter location as a proportion of the total number of displaced people [5].

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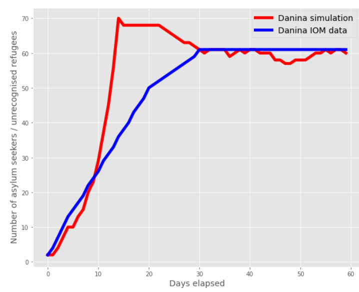
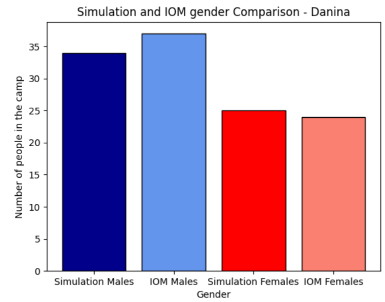
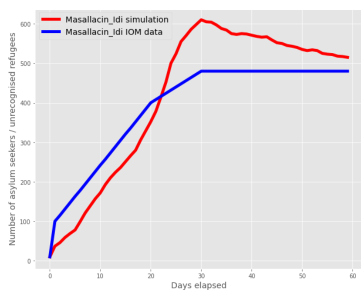


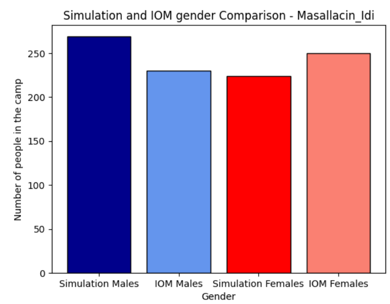
(a) Validation of registered people at a Danina site



(b) Validation of the registered people in terms of their gender (Danina)



(c) Validation of registered people at a Masallacin-Idi site



(d) Validation of the registered people in terms of their gender (Masallacin-Idi)

Fig. 5: Sample camp simulation results

5 Results and Discussion

In figure 5, we compare simulation results with data from the International Organization for Migration's (IOM) Displacement Tracking Matrix (DTM) for two sample sites: Danina (a) and Masallacin-Idi (c). IDPs arrived at these sites from their hometowns in Bauchi state. The first 30 days of the simulation, with the highest level of floods, showed a steep initial increase in displaced persons, both in data and in the simulation. However, subsiding the flood level in many cities across Bauchi decreased the number of arrivals to these sites after Day 30. Our simulation predicted more arrivals than the IOM data reported, possibly because the IOM report only included major affected towns and cities, which we used as flooded locations in the simulation. The lack of geospatial knowledge about the region caused a preliminary location graph, which likely did not reflect the complete set of locations and routes in this region. Despite these limitations, the average relative difference remained below 0.4 after the 20 days of simulation (see figure 6), when most agents have settled in shelters and sites and the flood has subsided. Furthermore, the total number of agents in sites in the simulation

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was slightly less than reported in the data, as some agents remained in transit within the region. The simulation results for the gender of registered people in the sites were very close to the number of males and females in these sites, as shown in figure 5 (b) and (d).

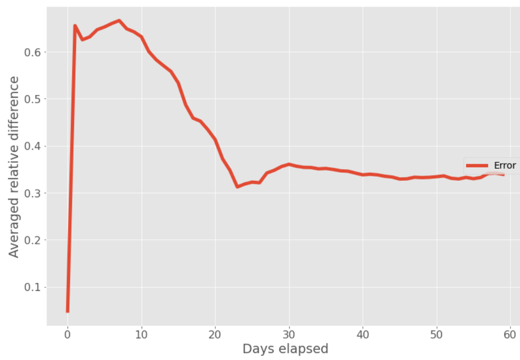

Fig. 6: Overview of the averaged relative differences for the flood event in the Bauchi state in August 2022

6 Conclusion

In conclusion, this study addresses the gap in the literature regarding the simulation of flood-induced evacuations and the movement of internally displaced people. The study employs an agent-based modelling toolkit called Flee, originally used to simulate conflict-based displacement, and modifies it to be used for flood-induced displacement. The resulting model, DFlee, simulates flood-induced evacuations and the movement of internally displaced people seeking safe shelter. The model is tested on a case study of a 2022 flood in Bauchi state, Nigeria, and validated against data from the International Organization for Migration's Displacement Tracking Matrix. The results suggest that the model can help humanitarian organizations prepare and respond more effectively to future flood-induced evacuations. This study contributes to the existing literature by providing a novel approach to simulating flood-induced displacement and highlights the need for further research to address the complexities of natural disasters and displacement. Furthermore, it should be noted that the current study considered a longer period of evacuations after the flood events and did not examine the initial actions taken by evacuees, such as seeking refuge on nearby higher grounds. It may be necessary for future research to take into account such alternative safe locations for temporary shelter. Additional investigations into these aspects could refine the model's precision and effectiveness in forecasting and respond to natural disasters, and utilizing supplementary climate-related

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data resources such as European Centre for Medium-Range Weather Forecasts (ECMWF) could further augment its capabilities. Moreover, our plan is to expand this research in the future by coupling additional datasets and models using a multiscale methodology.

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