Evaluating the effects of consecutive hurricane hits on evacuation patterns in Dominica

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ABSTRACT

The Caribbean island of Dominica is at constant risk of being hit by tropical storms during the hurricane season. Therefore, Dominica and areas in similar situations need to raise their resilience to natural hazards. The potential consequences of climate change intensify this risk. After a hurricane hit, repair of damage to buildings and infrastructure can take several months. As hurricane frequency is increasing and time between hurricanes fluctuates, modeling sequences of hurricane events can help to determine different evacuation strategies. This paper introduces an agent-based model, simulating two hurricane events in one season. The prototype simulates the movement of evacuees over a road network and damage to buildings and infrastructure. Initial results show marked differences between road movements of evacuees during a second evacuation. Although shifts in the average shelter occupation are small (up to 2%) for our case study, this can indicate that adjustments to shelter capacities are necessary.

Keywords

Agent-based modelling, evacuation simulation, multi-event scenario, NetLogo, OpenStreetMap

INTRODUCTION AND BACKGROUND

Natural hazards like tropical storms and hurricanes pose a permanent risk to many regions and their population. They can cause a direct threat to life, destruction of homes and basis of life, a breakdown of the economy or the outbreak of diseases in the aftermath and more. Depending on the location, the exposure of a population towards natural hazards varies, as well as the preparedness and the resilience of a society towards a potential catastrophe (Lam et al. 2014). Small island states in the Caribbean have a high exposure to natural risks, especially to tropical cyclones and their strongest category: hurricanes. In addition to this, many countries in the Caribbean have limited resources and are vulnerable, yet not resilient to the impacts of those risks (Jetten et al. 2014).

In the Atlantic Hurricane season of 2017, 17 named storms affected Central America and the South-Eastern States of the USA (Shultz et al. 2018). Among those storms, ten developed into hurricanes. Hurricane Maria was a category five hurricane, passing directly over the island of Dominica, and affecting other islands as well. Being hit directly by the hurricane, the destructions on Dominica were disastrous. Thirty-one people died during the event, and a considerably larger number of people were severely injured (ACAPS 2018). Houses were destroyed, as was the majority of the island's infrastructure. While this event alone revealed the danger the people of Dominica are exposed to, the effects of climate change might lead to even more severe tropical cyclones and hurricanes in the future (Lam et al. 2014). As more tropical cyclones will eventually develop into hurricanes, an increase of the number of hurricanes per season can be expected too (Knutson et al. 2010).

Therefore, it is necessary to increase the preparedness and resilience of the island and its population. This is supported by an ongoing shift from an ex-post response and recovery to an ex-ante approach with a focus on minimizing the disaster risk by reduction of vulnerability, capacity building and better information and institutional strengthening. The planning and organization of shelters and evacuation routes in case of an emergency are crucial (World Bank 2012). To optimize shelter and route planning, estimations of the population's behavior and their resulting movement in case of evacuation are needed. Due to the impacts of climate change, it is likely, that in the near future multiple high category events occur in one season, affecting the same island. Roads and bridges, previously designed to be part of an evacuation route, may be impassable and the recovery time between storms might not be sufficient to allow for reconstruction. The planning authorities and other responsible bodies need to be aware of these circumstances.

Having limited resources and capacities, the island of Dominica and its authorities need methods to be developed to help to raise resilience to catastrophes (Lam et al. 2014). Agent-based modeling offers great potential for simulations of such events and generates valuable information. The concept of agent-based modeling tries to simulate a system by representing its individual components and behaviors. In agent-based models, "individuals or agents are described as unique and autonomous entities that usually interact with each other and their environment locally" (Railsback and Grimm 2012, p. 10). Thereby it can be analyzed how the system's behavior is constituted by the characteristics and behaviors of its individual components.

There has been extensive research in the field of agent-based modeling in evacuation contexts. Chen et al. (2006) created a model for hurricane evacuation in the Florida Keys. The focus was put on the clearance time of the entire area and on how many residents would need accommodation once the route became impassable. Liu and Lim (2016) developed a simulation model for the 2011 Brisbane flood, concentrating their research on shelter assignment and routing strategy, and thereby integrating GIS-based spatial analysis. Focusing on the interactions among evacuees during an evacuation process, Zhang et al. (2009) analyzed how different behaviors of agents during the process may change the overall movement in the network. Furthermore, D'Orazio et al. (2014) designed an agent-based model approach for simulating pedestrians' evacuation in urban outdoor scenarios by analyzing videotapes of real events.

What most of the studies share is that they either focus on motorized traffic simulation, or on building or urban (public places / events) evacuation. Moreover, clearance of the affected area is often the focus of other evacuation simulations. Compared to the former-mentioned studies, this study differs as it is not possible to clear the affected area and most people evacuate via walking. Being a Caribbean island, Dominica is cut off once the hurricane hits the island. Additionally, in this study infrastructure disturbances are simulated in a multi-event scenario (two events in one season) to detect differences in shelter occupation and evacuation routes, and the resulting movement patterns, which makes the approach deviate from other comparable evacuation simulation concepts.

The main objective is to develop a system that facilitates the combined analysis of infrastructure disturbances, especially road damages, and evacuation behavior for planning purposes. It aims to do so by creating a prototype model that integrates both, infrastructure disturbances and people's behavior in evacuation events. How can agent-based modeling with an integration of a multi-event scenario based on a road network be used to improve preparedness to hurricanes in Dominica?

APPROACH, METHODS, MODEL

Model Concept and Implementation

The model's purpose is to simulate the movement of evacuees during different phases of two consecutive storm (hurricane) events and to integrate road damages done by the first storm for the following event, influencing and potentially altering the movement and shelter allocation. The phase between the events is not simulated explicitly.

The model consists of three phases per event. The phases are as follows: 1) Evacuation phase: population moving to shelters, 2) Hurricane phase: hurricane taking place, population in shelters, damages are occurring, 3) Post-hurricane phase, population returning home. The phases are repeated for the second event under different circumstances (i.e. road network affected by damages). Additionally, one phase between both blocks represents the time between two events, meaning that the population is at home, after the first event (Figure 1, Table 1). The time steps (ticks) are defined as seconds during the evacuation and the return home phase of the model run. The moment in time when the hurricane takes places, and the exact duration of a hurricane evacuation, are not simulated. Neither is the time in between two hurricanes. This is because we are simulating differences in road movement and shelter occupation rather than evacuation time.

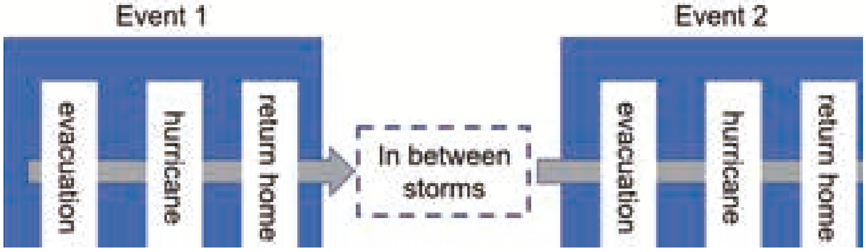


Figure 1. Schedule of the model concept and the corresponding phases per event

Table 1. Model concept phases and the corresponding actions in the simulation

1	1	ation phase	Households moving to shelters
-	4	ween events	Households at home

1. Evacuation phase

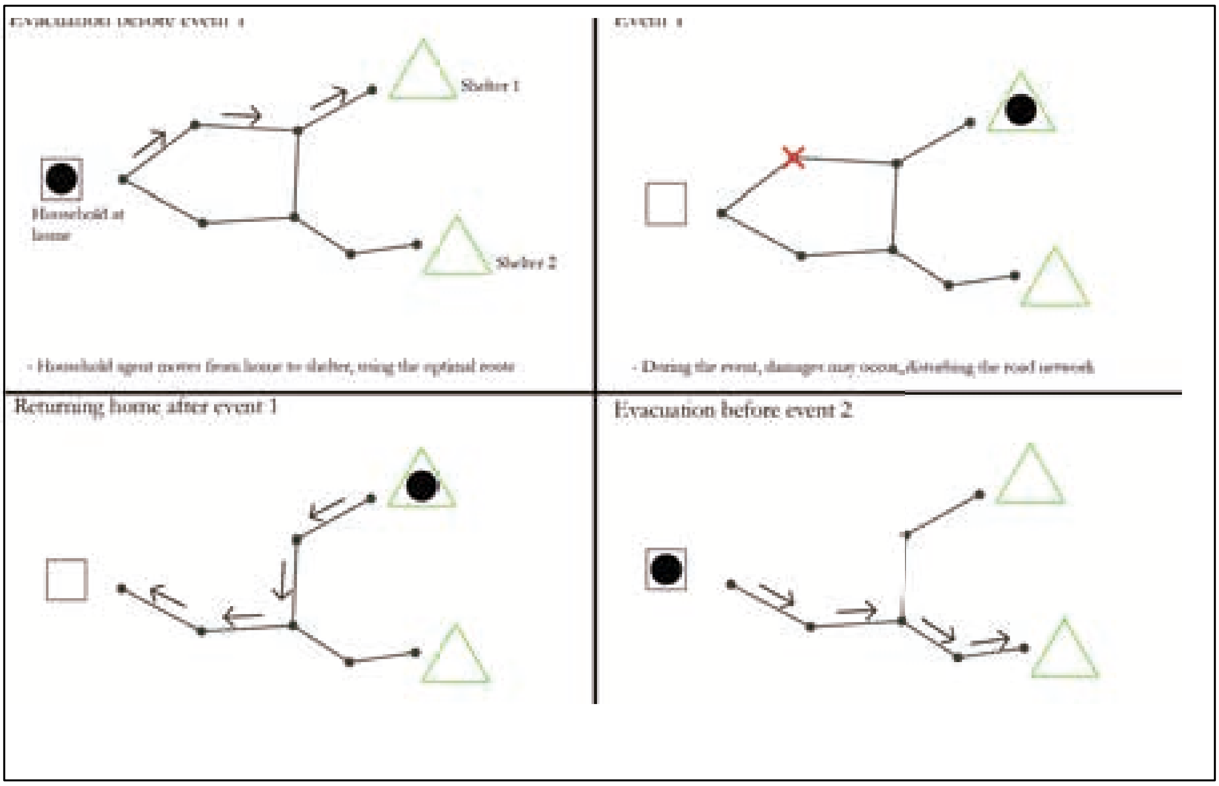
The evacuees are aggregated to households. At initialization, each household is assigned a building as a home. Households calculate the optimal route from their starting location to all shelters and know which shelter is the closest, based on the distance of the routes, and will always try to go the nearest shelter (Figure 2). From the home node, the distance to each shelter node is calculated, based on the optimal route and the weight value of the links (length of roads between nodes). The network extension in NetLogo 6.0.4 (Wilensky 1999) is able to find the best route using the Dijkstra algorithm, comparing different options on the network and choosing the one with the least sum of weight (distance) values (Dijkstra 1959). The distances to all shelters are compared, and the shelter node of the shelter with the least distance is defined as the destination for the household agent. The path from the home node to the destination node is now stored as an ordered list variable of the household agent, containing all links (edges). Also, all nodes along the route are stored as an ordered list. The list of nodes will be used for the movement, following node by node on the path. Once the first evacuation starts, all households start their movement at the same point of time without hesitation and without decision making of whether or when to evacuate. They move over the road network at a constant walking speed of 1.4 meters per second (Mohler et al. 2007) until reaching the destination and the list of nodes to visit is empty.

2. Hurricane phase

Once all household agents have arrived at their destination, the damage-to-nodes procedure starts, making road nodes die with a probability based on the risk zone class they are located in. The procedure uses the patches (pixels in NetLogo logic) own variable of the risk-zone-class for a probability for a node to die if it is located on the patch. On a patch with the highest value of the risk class (3), there is a risk of 10% for a node to die, 3% on a patch with a risk class of 2, and 1% on a patch with a risk class of 1. The values are an approximation based on the work with landslide and flood hazards of Jetten et al. (2014) in the CHARIM project. The CHARIM project aims to support the generation and application of landslide and flood hazard risk in the Caribbean region. Some nodes on the road network are defined as the home node for households. These can also be affected by the damage-to-node procedure. If a home node dies, it is assumed that the home of the household was destroyed. The household will then stay in the shelter.

3. Return home phase

After the hurricane phase, households will return to their home locations. The calculate-path-home procedure calculates the best way home. This does not necessarily have to be the inverse of the route the household has taken to the shelter, as the road network may have changed due to the previously mentioned damage-to-nodes procedure. If a household cannot find a path leading to their home location, which may occur if all connecting roads were destroyed, they stay at the shelter. When all household agents arrived at their home location, the steps are repeated. However, the road network will stay altered, representing the damages done by the hurricane in the second phase. The route calculation of the households in the next evacuation phase takes these changes into account.



Study Area and Data Description

The prototype model will be tested on Roseau, the capital of Dominica. This area has a relatively dense population with a good road coverage, multiple shelters, and potential damage to infrastructure (Figure 3). The number of household agents in the model should reflect the population of the study area. Five thousand households is a realistic number, considering the population of Roseau (14.725) (Commonwealth of Dominica 2011). This is supported by the number of potential dwellings in the study area (5030), after data editing. For this study, the following data is needed: roads, buildings, the location of shelters and areas of potential risk (damage).

Roads and buildings

OpenStreetMap (OSM) data was used for retrieving data on the street network and building locations, using the OSM keys “highway” for streets and “building” for buildings. The Humanitarian OpenStreetMap Team (HOT) carried out an activation (actively pursuing the creation of map data with the help of volunteers in response to a crisis) for data improvement, reacting to the disaster caused by Hurricane Maria. It aimed to improve the buildings and road data coverage by performing multiple projects in the Caribbean, including one explicitly for Dominica (OpenStreetMap contributors 2018).

Figure 3. Study area (Roseau) and location of shelters

For the methodology of this study, it is advantageous to have a relatively high number of nodes for the road network, as the nodes are used for the placement of the agents, for defining road damages and for route calculation. Thus, long segments without nodes were edited manually, adding more nodes and splitting the segment into multiple parts.

Buildings were identified as residential (dwellings) or non-residential based on building size (area). To exclude non-residential buildings, only those larger than 20m² and smaller than 300m² were kept as potential dwellings. The selection of these values is partially arbitrary, as no more information (e.g. attributes of buildings data) is available for the study area.

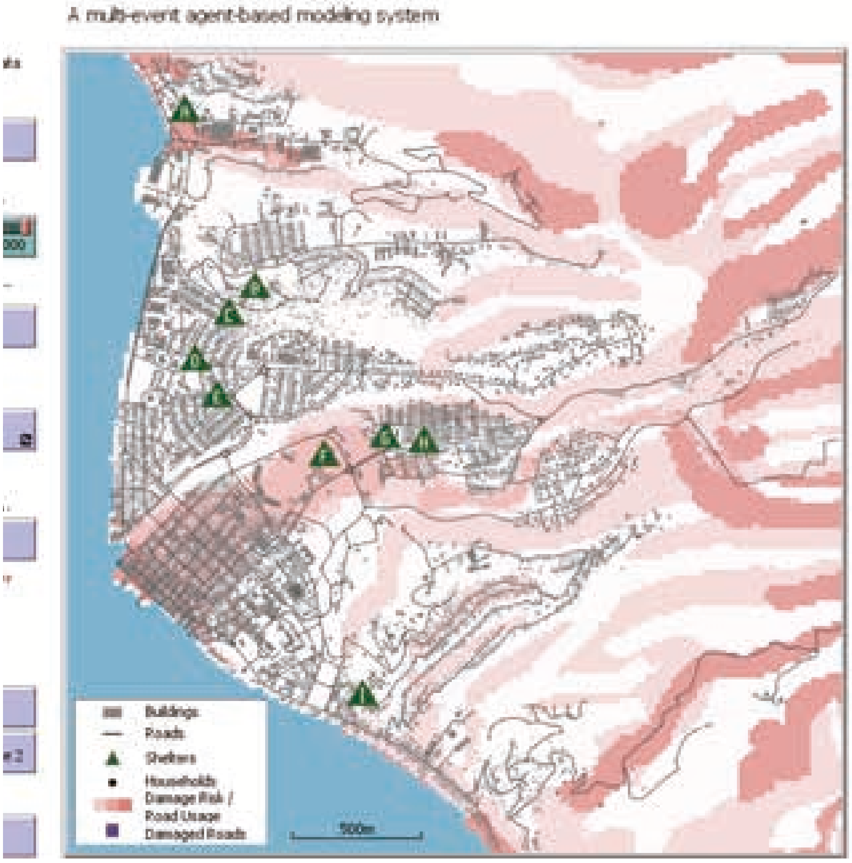
Some of the buildings represent hurricane shelters. The data about locations of hurricane shelters in Dominica was downloaded from the GeoNode data-sharing platform of the Caribbean Handbook on Risk Information Management (CHARIM) project (Jetten et al. 2014). Nine shelters are defined in the respective study area of the city Roseau and surroundings.

Risk zones

For estimating the probability of road damage during a hurricane event, road damage risk zones have been created based on flood-risk and landslide susceptibility, classified within the CHARIM project. Combining both raster datasets and reclassifying the combinations, three classes of potential risk zones were defined (Table 2, Figure 4). A classification value of 1 means a relatively low chance of a road being damaged, a value of 3 a high probability.

Table 2. Risk zone definition: Reclassification of a combination of flood hazard and landslide susceptibility datasets, resulting in three classes of potential risk (1 – low chance of a road being damaged, 2 – medium, 3 – high)

dslide)tibility	1	2	2	2	3



Model output and experiments

The described conceptual model was implemented in, and the described geodata was imported into the NetLogo 6.0.4 software. Experiments with multiple simulation runs were conducted. Two types of model output are defined to evaluate the model performance: the number of evacuees in each shelter during the hurricanes and the movement pattern of the evacuees during evacuations. As two consecutive events are simulated in each simulation run, we can determine the difference in shelter occupation and road network use between the two events.

A counter procedure was defined to detect differences in the movement pattern of evacuees as a result of a changed road network. Each patch has a counter variable, counting the number of households located on the patch at each time step during the evacuation phases. These counter values lead to a pattern, which can be interpreted as a relative usage of the roads. For both events, one individual counter exists and thereby allows the comparison of road usage (and route choices) in the evacuation phase.

Additionally, the number of households per shelter for each hurricane event is tracked. The comparison of shelter occupation reveals a possible over-occupation (above the available space) and changes in occupation between two events. The combined observation of relative road usage and numbers of evacuees per shelter will allow a first interpretation of the influences of road damages on movement patterns and shelter allocation.

As the procedure of road damages, i.e. nodes dying during the hurricane phase, includes a probability based on the predefined risk zones, the patterns of damages will be different for each simulation run. To assess the influence of the stochastic elements, the simulation was run 100 times with the same setup. Observing the development of the average number of road damages in the first event, the variation of the resulting values is relatively stable after 25 runs (Figure 5).

For those 25 runs, the values for road usage (counted households on a patch) for the first event without road damages and the second event including road damages are compared by computing the difference between the events for each model run. The average of those differences is calculated and visualized. Furthermore, the average number of household agents per shelter for both events is calculated.

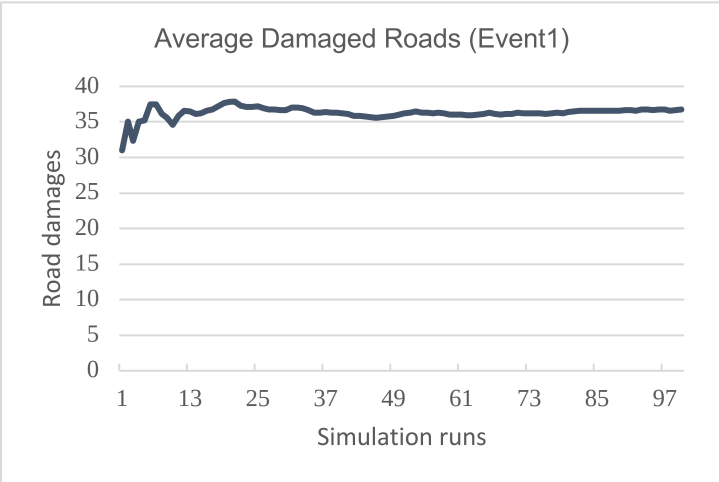


Figure 5. Average damaged roads during the first event after a number of runs

RESULTS AND DISCUSSION

In this study, it was examined how road damages caused by storm events would affect the movement of evacuees, changing their route choices and thereby influencing the shelter allocation. Results for the movement pattern (Figure 6) show that changes are mainly occurring on main roads running in an east-western direction and that the difference in road usage between the two hurricane events is considerable. This can be interpreted as an effect of the combination of the high number of households living in the area, the damage caused to these roads, and the fact that multiple shelters are located along the main roads.

The interplay of shelter allocation to shelter E, F, and I is of main interest for the interpretation of the results. On the route leading from the southwest to shelter F road damages frequently occur, making the road inaccessible in many runs. Additionally, alternative routes around shelter F are commonly damaged. This leads to an increase of road usage from the respective area on a route north towards shelter E, and south towards shelter I. Another interesting aspect is the movement from the eastern outskirt settlement, being connected by one road only to shelter H. Damages that occur here, make movement between the settlement and the shelter impossible, leaving a high number of households in need to stay at the shelter. Consequently, the road usage towards shelter H is reduced. Furthermore, roads leading to shelter I (at the coast from the southeast and from the inland from the northeast) are frequently damaged. Therefore, the adjacent roads are being used as alternative paths in many runs, explaining the substantial increase of usage.

Another interesting fact is the average number of households per shelter for both events (Table 3). Due to the road damage issues explained before, the average percentage of households seeking shelter in shelter F reduced by 2%. At the same time, the number of households in shelters E and I increased by 1.4% and 1.1%. As the eastern road to shelter H is frequently being damaged and inaccessible, a slight reduction of the average shelter allocation in shelter H can be observed (0.5%). If a household cannot find a path back home in the return home phase, it needs to stay in the shelter. As the numbers of Table 2 reveal, these numbers differ among the shelters. Especially the shelters F (115.5), H (81.4) and I (128.7) show relatively high average numbers of stuck households. These shelters are connected to some residential areas by a single road only and lack alternative routes. Therefore, they host a high average number of households, which cannot return home.

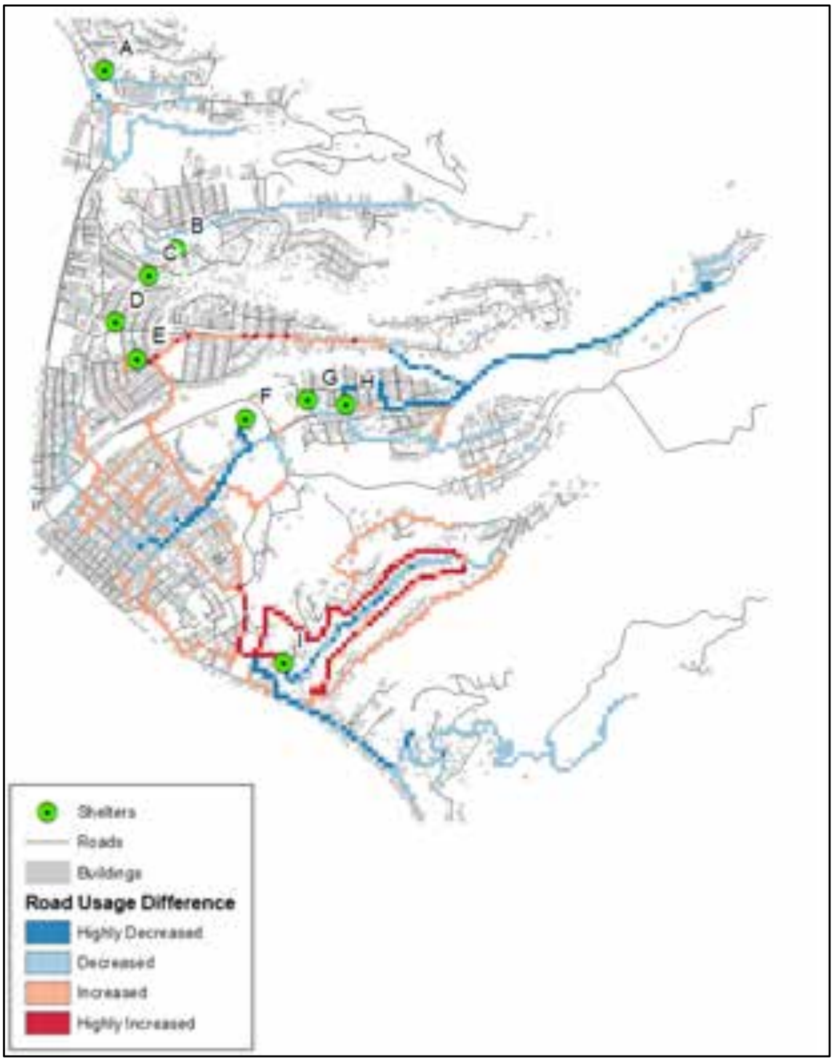


Figure 6. Average difference in road usage between event 1 and event 2 (during evacuation phases)

Table 3. Average shelter occupation per event per shelter

	Event 1		**Event 2**			
Shelter	**Number of households**	**Percentage of total households**	**Number of households**	**Percentage of total households**	**Tendency**	**Households staying in shelter**
A	281	5.7	277	5.6	=	51.1
B	717	14.6	717	14.6	=	10.9
C	106	2.2	110	2.2	=	4
D	222	4.5	222	4.5	=	0
E	1192	24.2	1258	25.6	↑	34.4
F	573	11.6	471	9.6	↓	115.5
G	247	5	245	5	=	14.8
H	394	8	373	7.5	↓	81.4
I	1191	24.2	1244	25.3	↑	128.7

The changed road usage and route choices for a second evacuation event, depending on the damages occurring during the first event, deliver valuable information about critical road segments and sections. If a shelter is connected to a highly populated area by a limited number of roads, and if these roads are at risk of being disturbed, the movement pattern of the evacuation changes. Using this information, planners can identify critical road segments and plan road fortifications or define alternative routes leading to the corresponding shelter. Additionally, prioritization of road reconstruction can be done. The information provided by the model might lead to the realization that the location of a specific shelter is unsuitable, as the risk of it becoming inaccessible is high.

Furthermore, the results of the model run revealed, that a disturbed road network leads to changes in the numbers of people (or households) per shelter. The model results and the derived information can be used for evaluation of shelter allocations. One effect may be that if a shelter is not accessible for a second evacuation, other shelters in the area are used by a larger number of evacuees. By using a model that takes this into account, the planner is able to prepare and avoid an unexpected over-occupation of a shelter. Also, a shelter might be cut off from the network, preventing evacuees to return home, as the roads leading back to populated places and settlements are not usable anymore. To be prepared for this, shelters, which are identified as being at risk of inaccessibility after one event, and that therefore need to house evacuees for a longer time, need to stock up their supplies or alternative shelter locations should be defined.

CONCLUSION AND FUTURE WORK

In the course of this study, a prototype agent-based model was created, combining disturbances of infrastructure and the evacuation movement of the population in the case of two consecutive hurricane events on the island of Dominica. The prototype makes use of a multi-event scenario and a network-based routing systematic. Initial runs of the simulation model revealed that damages to infrastructure have a significant influence on the movement patterns and route choices of the population, leading to changes in the road usage and shelter allocations.

Multi-event modeling can be used to find critical road segments and problematic shelter locations. This can give planners a tool that can help to take measures to improve the preparedness for hurricanes. The current prototype has some limitations, as it assumes that all people evacuate and that all evacuees select the nearest shelter as destination. This is not true, as people may decide to stay home or evaluate the safety of the shelter and select a different one based on multiple criteria. A more advanced evacuee behavior model can be integrated in the prototype to simulate the number of evacuees, and the route and shelter choices they make, using more advanced mechanisms (e.g. artificial intelligence).

The model should be tested for other areas in Dominica or other Caribbean islands and more detailed analysis can be done on the simulation results, e.g. by examining individual routes of evacuees to gain a better understanding of the evacuation behavior. The simulation phase in between the two hurricane events can be filled. During this period, road repairs can be conducted. By varying the length of the repair period, a more realistic picture can be obtained about the consequences of multiple hits. Also, it is possible to simulate more than two events in one simulation. Further tests should be conducted in this regard. The risk of road damage for the different areas can be calibrated by analyzing previous hurricane events (e.g. by using remote sensing technology). The current risk function combines two different causes: landslide and floods. These two hazards could also be separated to come to a better risk prediction.

The integration of more data, e.g. attributes of the population, building types, road surfaces etc., can lead to further details. However, the quality and availability of data should be evaluated first. As the road network, derived from OpenStreetMap, is of crucial importance for the model, specifically this data should be assessed more in future work before extending the model. Using intrinsic quality measure based on the analysis of the historic development of OpenStreetMap data could be an option (Auer et al. 2018). The model concept and its results should be validated, once the development of the model has advanced further. Sensitivity, uncertainty and robustness analysis need to be performed to test the quality of the simulation. There are several elements, which could be evaluated. By analyzing satellite or aerial images taken shortly after a hurricane occurred, the road damage function of the model could be adapted to represent a realistic damage pattern. Another option could be to compare the occupation rate of the shelters during real evacuations with the simulated occupation rate.

In general, future research need to be conducted for multi-event and routing based concepts. The implemented prototype and its applicability should be developed and assessed further, striving for a more complete and realistic model. This could finally lead to important information and insights to improve the planning of evacuation events and beyond. Further interpretation of the results, potentially with direct exchange of ideas with decision makers, should be considered. Additionally, extensive user research, such as user requirement and usability studies, also taking visualization options into account, are required to support the further development of the model concept and its implementation.

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