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Agent Based Modeling for Flood Inundation Mapping and Rerouting

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Abstract

Natural disasters like earthquakes and floods can have a serious impact on road networks, which are critical to supply chain infrastructure and to provide connectivity. These extreme events can result in isolating people in the affected area from hospitals and emergency response. This paper presents an agent-based model for understanding flood propagation and developing inundation mapping. The results from the mapping are used to identify the roads prone to floods based on elevation data and flood simulation. A simulation environment was set up in SUMO, and the costs associated with the traffic disruption are evaluated. This paper discusses the integration of various techniques for a comprehensive flood prediction and rerouting system.

Keywords: Flood mapping; Traffic Rerouting; Agent-Based Modeling; SUMO; Traffic Simulation

1. Introduction

In recent times, floods are one of the most frequently occurring natural disasters in the United States. Floods are usually caused by extreme rainfall events, which are often combined with soil conditions, such as saturated or frozen ground, making it harder for water to percolate down into soil, increasing river runoffs. Over the years, there has been a significant increase in the frequency of the flooding events was observed across different gauge stations in Midwest [1]. Floods cause serious impact upon the economy and human life as several homes and infrastructure are destroyed displacing large sections of population [2].

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This increased the demand for effective two-dimensional modeling. As a result, flood inundation mapping and prediction have been some of the emerging research topics in climate change, earth sciences and natural hazards [3].

Robust and realistic methodology for evaluating and predicting flood risk is crucial. These techniques should incorporate accurate flow modelling and prediction of flooding events [4]. Storm and river water runoff models are of the most importance for evaluating flooding dynamics [5] and risk assessment [6]. A lot of such simulation models and algorithms use grid-to-grid approach to estimate and predict the spread of flooding. A flood is usually modeled as the dispersal of water from one cell to its neighbors [7]. Two dimensional (2-D) hydraulic models with high spatial details along with effective water flow dynamics resulted in better accuracy for simulation of flood flow [8]. The Cellular Automata (CA) approach offers a versatile technique for modeling complex systems using simple rules [9]. It is a suitable modeling approach for the flood inundation mapping due to its ability to accommodate both spatial and time-related dynamics. CA have a relative advantage over other techniques for simulating physical systems with its ability for spatial and temporal discretization (Ghimire et al., 2013). That's the reason in the recent years, CA have been used in a lot of research articles focused on developing flood mapping models.

Impact on the road transportation network with an emphasis on travel demand is one of the major concerns during the floods. It can result in huge financial loss and lost time. Developing effective traffic management strategies to avoid traffic jams and congestion can be crucial to resolve such situations. A lot of research has been published involving evacuation modeling. Network traffic flow under demand uncertainty and traffic constraints has been studied based upon the network fundamental [10]. Agent-based behaviour has been used to model household behaviour during hurricanes [11]. Roads are usually modeled as being completely available or flooded. However, researchers have used serviceability of the roads instead of availability to give a more realistic approach to flood rerouting models [12].

The objective for the paper is to integrate the vulnerability of flood flow mapping and traffic rerouting to develop a methodology that can be easily applied to any region using agent-based modeling.

2. Model

2.1 Flood Inundation Model

The methodology consists of CA framework, which includes the cellular space, neighborhood, parameters, transition rules and time step. Cellular space is a set of regular cells used to discretize the geographical area. The model uses a 2-dimensional lattice which represents the transportation network. Nodes are intersections, and edges are the roads. And the 10×10 network is as shown below in figure 1. Minutes were chosen as the time step for the simulation.

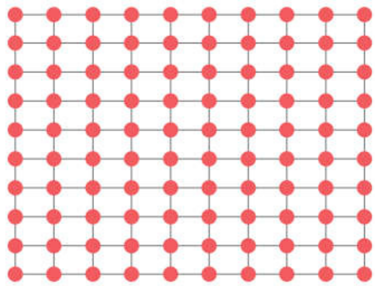

Fig. 1. Road Network Layout

Moore neighborhood is employed, allowing the water to be distributed to any of the 8 neighboring cells surrounding the central cell in each iteration depending on the parameters and rules as shown in figure 2.

Von Neumann type of neighborhood can be a more simplistic representation resulting in lesser computation, but Moore's neighborhood is a more realistic approach for the given problem as the water flows in all directions.

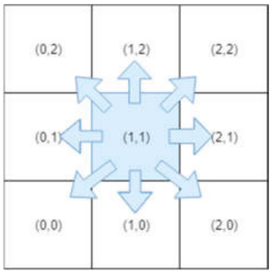

Fig. 2. Moore Neighborhood for water flow

The parameters consist of the functions describing cell transitions and cell states. For this model, surface elevation, precipitation, infiltration rate, roughness coefficient and water depth are the parameters. During a storm event, surface water flow dynamics consist of two major processes: infiltration to pervious surface and surface runoff of excess water. Evapotranspiration can be neglected due to the short duration and atmospheric conditions of a storm event. Surface Runoff and Water Surface Elevation for every cell at each time step are calculated by the following equations.

$$\textit{Surface Runoff} = \textit{Precipitation} - \textit{Infiltration rate} \quad (1)$$

$$\textit{Water Surface Elevation} = \textit{Surface Elevation} + \textit{Surface Runoff} \quad (2)$$

Table 1. Parameter ranges

Parameter	**Minimum**	**Maximum**
Precipitation	30 mm/h	90 mm/h
Infiltration	5.8 mm/h	11.7 mm/h
Roughness coefficient	0.01	0.04

The model is calibrated by a storm event occurred on 19 April 2012 in Guangzhou of southern China [11]. All the parameters for a given cell are obtained from a uniform distribution ranging from minimum to the maximum as given in table 1. And finally transition rules are based on SCIARA model to simulate lava flow [13]. A minimization algorithm similar to it was applied to Von Neuman's neighborhood for flood water mapping [14]. The distribution of surface water from the central cell to the neighbors is done by minimizing the surface elevation difference between the cells. The algorithm is given below.

Let wse_i denotes the water surface elevation of the central cell, i = 0 and its neighboring cells (i = 1, 2, 3, 4, 5, 6, 7, 8).

Step 1: The average water surface elevation of the cells is computed by the below equation.

$$\textit{Average} = (wse_0 + \sum_{i=1}^{8} wse_i)/n \quad (3)$$

Where 'n' is the total cell count of the central cell plus the neighboring cells.

Step 2: Eliminate cells with wse_i >average

Step 3: Calculate the average water elevation for rest of the cells using Eq. (3) and further eliminate cells where $wse_i > average$.

Step 4: Repeat step (3) until no further cells can be eliminated.

Step 5: Partition the outflow from the central cell such that the remaining neighboring cells have the same elevation as the central cell.

2.2 Traffic Routing Model

Agent-based approach has been used to model the traffic management. Two components of traffic rerouting are identifying shortest paths and dynamic traffic assignment. Vehicles are the agents, and they are provided with significant autonomy and ability to take decentralized decisions. To simplify the problem, distance is converted into time, which is the cost for any given route. In order words, cost is the time taken to complete a route. Agents select their routes based on a few parameters (cost and availability). Each edge has the assigned capacity. It is assumed that if the number of vehicles on the edge equal to its capacity, no need vehicles will be allowed on that edge.

Some of the most popular algorithms for solving origin destination pairs on a graph are A*, Dijkstra and Floyd-Warshall algorithm. A* is suitable for a single source and a single destination. Dijkstra works best for a single source and multiple destinations. So, Floyd-Warshall algorithm was chosen for this problem as it used to find shortest distances between all the pairs in the graph.

It is computationally expensive compared to A* and Dijkstra, but having all the information can be very useful for quicker travel assignment during disaster scenarios. In general, the elements of the graph are represented using adjacency and incidence matrices [16]. An adjacency matrix contains the interactions among the different vertices in a network or a graph, and the incidence matrix includes the relationship between vertices and edges in a network or a graph. In this paper, the road network has been represented as a distance matrix, which is a variation of an adjacency matrix). Each element, $a_{i,j}$ in the distance matrix A can be defined as follows:

$$a_{i,j} = \begin{cases} w(i,j)\,, & if\ (i,j)\ has\ an\ edge \\ 0, & if\ i\ = j \\ \infty, & \text{otherwise} \end{cases}$$

Where w(i,j) is the weight of the edge, and in this case, the time taken to complete traveling on that edge. Weights for the current problem are defined as distance divided by the vehicle speed. For simplicity, vehicle speed is assumed to be maximum allowable speed on any edge. The value of the weight on any edge is obtained from a uniform distribution of 0.18 to 10. The capacity on any road comes from another uniform distribution of 10 to 50, which is the range of vehicles allowed on any road per minute.

Traffic Assignment is performed in an open-source traffic modeler and simulator SUMO [17]. A Stochastic User Equilibrium algorithm is used for assigning traffic.

3. Results

The experiment was conducted in 2 stages, starting with flood propagation mapping and then traffic rerouting. The simulation for flood mapping was performed in python. 'Networkx' was the library used to generate road transportation network and 'Matplotlib' was the library used to visualize the data.

Initially, the flood inundation is performed on the 10 × 10 lattice grid. The parameters and rules for the agent-based model implementation are as mentioned in part A of section II. The flood is introduced in the cell (3,6) as shown in figure 3.

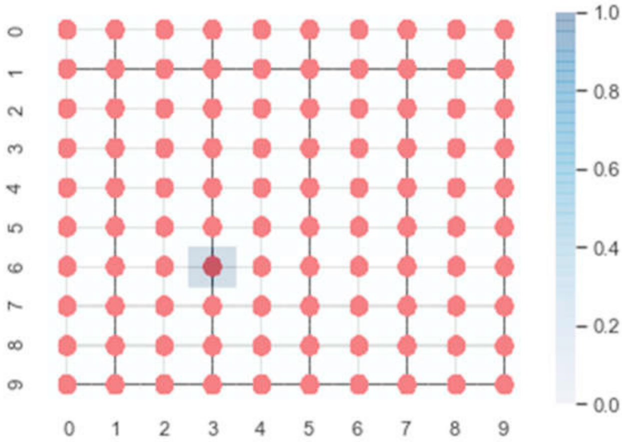

Fig. 3. Flood Initialization

The water level in the region at the starting point is assumed to be 10 meters. The simulation was started with these initial conditions. The simulation was continued until 1000 iterations. The resultant flooding scenario is shown in figure 4(a). Based on the parameters and rules, the cells (1,5), (2,6), (2,4) and (3,4) are flooded.

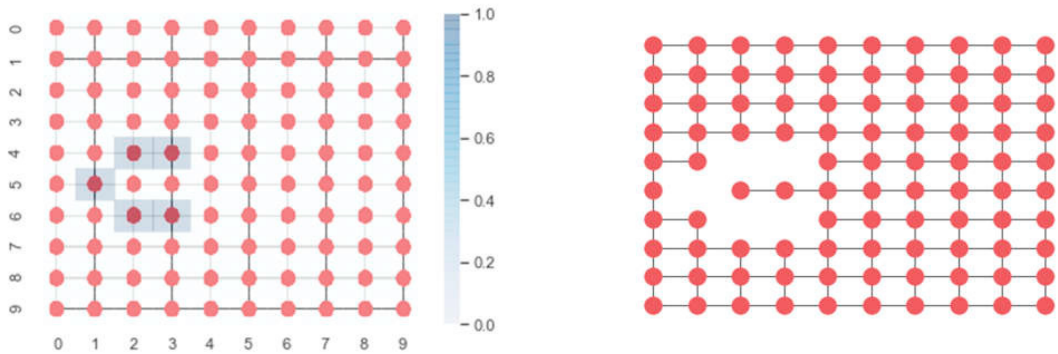

Fig. 4. (a) Flood Simulation results, (b). Updated Road Network

All the above nodes are flooded and are not accessible by the people. As a result, all the connecting edges are now unusable. The road network is modified accordingly, and all the flooded intersections and their corresponding roads are eliminated as shown in figure 4(b). All pairs shortest path algorithm (Floyd-Warshall algorithm) is applied to the current network to identify all the shortest path creating a lookup table for the agents to navigate.

This updated road network is used as an input to the Traffic Assignment model in SUMO. All the roads are bidirectional and single lane. The traffic is generated over a period of 60 hours with origin and destination selected from a uniform distribution at random. The simulation period assumes that total time the roads are disrupted before being restored is 60 hours. Furthermore, the reason for travel (work or leisure) is assigned at random with uniform distribution.

In figure 5, the number of vehicles that are running at every minute during the simulation are plotted. The initial spike represents the vehicles starting at different times. After a while around 400 minutes, the curve is somewhat stabilized as vehicles start reaching their destinations, and they are balanced by the new vehicles entering the simulation.

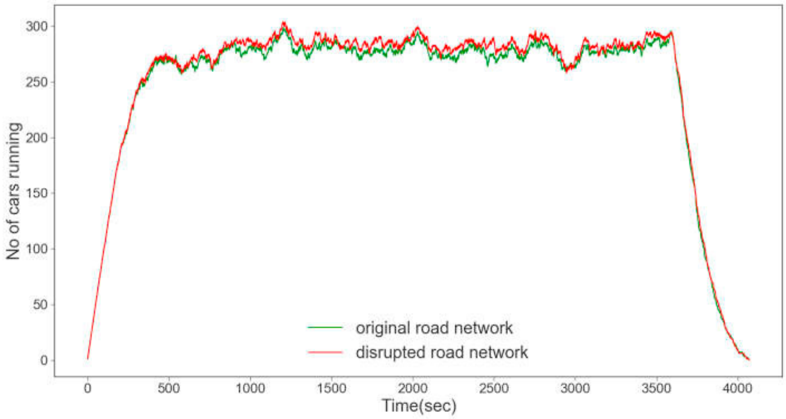

Fig. 5. Traffic Simulation results

Finally, a steep decline at the end starting at 3600 minutes (60 hours), as no new vehicles are starting and the ones which are already running, reach their destinations. The green line is for the vehicle running on the original network and the red line for the disrupted network.

Delay Factors	
Low Time Savings (0-5 mins)	
Work	0.064
Social	0.013
Others	0.001
Medium Time Savings (6-15 mins)	
Work	0.322
Social	0.231
Others	0.145
High Time Savings (>15 mins)	
Work	0.538
Social	0.6
Others	0.645

Table 2. Traffic Delay Factors

Costs related to the traffic delays are obtained from Engineer Regulations (ER 100-2-1150 Appendix D) published by the U.S. Army Corps of Engineers [18]. The values depend upon the percentage of driver's income in the entire household. For simplification purpose, this variable is not considered. The final detour costs are calculated by the following equation. Average hourly wage of the drivers is assumed to be $ 20.

$$Detour\ costs = Delay\ Factor \times Average\ Hourly\ Wage \quad (4)$$

The total delay cost for the people in the simulation is $115,920, which is significant. The simulation can be performed on different flood sites to estimate the indirect cost associated with rerouting and the results would be useful for city planners to identify when to close the roads based upon the flood predictions and resulting economic impact on the people.

4. Conclusion and Future work

This paper integrates multiple agent-based models to evaluate economic losses during flooding scenarios. Modeling the dynamic and uncertain features of various properties involved in these models can result in a very useful tool for city planners and Disaster

Restoration personnel. The models are based on a lot of assumptions related to geographical properties, weather predictions and human traffic behavior, which simplify the problem but do not replicate a real situation as of now.

The model can be improved by using information from Digital Elevation Maps (DEM)[19] and Shape files provided by Missouri Department of Transportation (MoDOT) and United States Geological Survey (USGS). This network along with the accurate weather data and traffic data can be a robust tool for flood and traffic simulations. Average daily traffic data published by the MoDOT can be used to create realistic traffic for the simulations. Considering the dynamic nature of the flood flow and uncertainty of the weather predictions can also be beneficial.

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