GIS-based Evacuation Routing using Capacity Aware Shortest Path Evacuation Routing Algorithm and Analytic Hierarchy Process for Flood Prone Communities

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Keywords: Decision Theory, Flood, Uncertainty, Evacuation Routing.

Abstract: Evacuation routing is one of the fundamental instruments for flood risk mitigation. In this study, features extracted from LiDAR data are used to create dynamic network composed of buildings and roads. Flood prone areas identified through flood models from Phil-Lidar 1 Project are considered by Capacity Aware Shortest Path Evacuation Routing algorithm to determine optimal routes. Road capacity and location of building features were also considered. Uncertainties among possible paths taken are evaluated through Decision Theory. Specific DT technique implemented to generate alternative routes for the possibility of detours is the Analytic Hierarchy Process. This study can help city governance in terms of planning and disaster risk reduction management.

1 INTRODUCTION

The Philippines experiences an average of 20 typhoons every year making it as one of the most flood-prone countries in the world (Ortega, 2014). One of the most destructive typhoons to have ever been recorded in history, Super Typhoon Yolanda (Haiyan) entered the Philippine archipelago on 08 November 2013 leaving 6,300 people dead, 28,688 injured, and 1,062 missing (NDRRMC, 2014). Despite the early warnings issued by the Philippine Atmospheric Geophysical Astronomical Services Administration (PAGASA) to the general public, these were not translated into appropriate actions in every coastal village in the Central Philippine Region (Lagmay et al., 2015), which resulted to the loss of lives by the thousands. This can be prevented if the warnings were also accompanied by appropriate information to the people concerning with what to do in case the signal is raised. Evacuation planning is one fundamental instrument for risk mitigation that is taken into focus in this study.

Routing is part of the evacuation planning process that determines the best routes to relocate the affected population to the nearest shelters—usually, within the shortest amount of time possible for an individual. However, it is not enough for an evacuation routing problem to just generate the best routes for each evacuee, it should also be able to adjust to the dynamic changes that might occur within the road network while the evacuation process is ongoing. These dynamic changes can affect the road network and consequently, the evacuation process. This uncertainty can be dealt best with decision theory (DT).

In many real world situations like evacuation routing, decision can be settled through various mathematical tools. Decisions based on mathematical reckoning present a quantified proof on why such decision was made with the assurance that subjectivity, bias and rationality of decision maker and the decision making process itself is not magnified. DT is used to select the optimal decision given a set of alternatives to choose from. It also covers the concepts of negativity and selection of the worst among choices which can be taken into consideration in routing process especially if a sudden change in the road network occurs.

The general aim of this study is to implement a

Manliguez, C., Diche, Z., Jimenez, M., Agrazamendez, M. and Acosta, J.
GIS-based Evacuation Routing using Capacity Aware Shortest Path Evacuation Routing Algorithm and Analytic Hierarchy Process for Flood Prone Communities.
DOI: 10.5220/0006327402370243
In *Proceedings of the 3rd International Conference on Geographical Information Systems Theory, Applications and Management (GISTAM 2017)*, pages 237-243
ISBN: 978-989-758-252-3

decision theory technique to cope with the uncertainties in the dynamic road network. Specifically, the study aims to:

1. Introduce the Analytic Hierarchy Process to the Capacity Aware Shortest Path Evacuation Routing (CASPER) Algorithm to allow the algorithm to adjust to the dynamic changes within the road network; and
2. To apply the proposed CASPER-AHP algorithm to a dynamic network, composed of buildings and roads, which was created using LiDAR data and the ArcGIS Network Analyst Tool.

As previously mentioned, changes in the road network are likely to happen at the time of a disaster. Therefore, it is entirely possible that these changes could affect some evacuation routes where no other feasible routes can be achieved at that point, indicating a dead end and the possibility of a bottleneck occurring on the affected routes, leaving the population extremely vulnerable when the disaster strikes. The proposed algorithm can identify such bottlenecks. In addition, if a change in the road network occurs such that the affected roads are those roads that connect to the destination point, instead of re-routing the evacuees, this information can aid the city officials by finding an alternative destination point for the evacuees in order to minimize evacuation time. Also, the generation of the optimal evacuation routes can help in determining which roads should be made available for the evacuees by the time the disaster occurs.

This study only concerns the generation of the optimal evacuation routes for the population residing near the Lipadas River in Davao City. Their geographical location, being close to the river channels, leave them highly susceptible to flood hazards. The residential areas close to the Talomo River are considered in this study as a means to test the effectiveness and the scalability of the proposed solution.

2 BACKGROUND AND RELATED LITERATURE

In the face of a natural disaster, evacuation planning refers to the process of relocating the endangered population to safer areas as soon as possible. The study of Shahabi (2015) proposed a new taxonomy to the evacuation planning problem in which the problem is divided into three stages: preparation, evacuation execution, and post-disaster response.

The evacuation execution stage refers to those actions that are taken immediately, once the nature of the disaster becomes known, to reallocate the potentially endangered population to safety. At this stage the location and time of the disaster is the key information (Shahabi, 2015). The post-disaster response stage is characterized by emergency personnel caring for the affected population, shelter maintenance, and disaster assessment. For example, Eguchi et al. (2008) studied post-disaster damage assessment using integrated GPS sensor network and GIS. Lue et al. (2014) studied disaster damage assessment by utilizing geo-tagged videos taken from the affected areas.

Disasters can either be static or dynamic. Dynamic disasters are characterized by their changing behavior, location, or severity. Disasters such as tsunamis and terrorist attacks are considered as static whereas hurricanes, wildfires, and flood are dynamic (Shahabi, 2015). These dynamic disasters would evidently add to the complexity in evacuation planning and has to be considered in a realistic evacuation solution.

The evacuation routing problem refers to the process of relocating the potentially affected population towards safe destination points such as shelters and hotels. The objective of this problem is usually to minimize exposure, global evacuation time, average travel time, or traffic congestion. An effective routing solution should consider the characteristics of the transportation network, available transportation vehicles, as well as the capacity of the potential destinations (Shahabi, 2015).

2.1 Flood Hazard Maps

Flood hazard maps are designed to identify the areas that are at a risk of flooding and to increase the awareness of the likelihood of flooding among the public. They also encourage the population residing in flood-prone areas to find out more about the local flood risk and to take the appropriate action (Linham and Nicholls, 2010).

To benefit from the flood hazard mapping, it is important to provide the local community residing in the flood hazard zone with the appropriate information about emergency procedures and ways of reducing the risk of flood, otherwise, presenting the flood hazard maps may only serve to increase the fear and anxiety of the residents.

2.2 Application of GIS Techniques

A geographical information system (GIS) is a computer system that is designed to support the capture, management, manipulation, analysis, and modeling and display of spatially-referenced data suitable for solving complex planning and management problems (Cole et al., 2005).

All stages of the evacuation planning problem identified by Shahabi (2015) can greatly benefit from the application of GIS. Gaining access to the appropriate data is the key. In an emergency, it is critical to have the right data, at the right time, displayed logically, to respond and take the appropriate action. By utilizing GIS, this data can be shared throughout different agencies or departments with the use of spatial databases held in one central location. GIS provides a mechanism to centralize and visually display critical information in the midst of an emergency (Cole et al., 2005).

With regards to preparation, GIS can be used to provide answers to particular questions such as identifying the safest location for the critical facilities, selecting of evacuation routes based on the anticipated or actual flood, or determining whether the transportation network can handle the sudden increase in traffic flow.

Lastly, in the post-disaster response stage, GIS can play a role in the disaster damage assessment and information management. With the use of GPS and telecommunication devices, assessments of the damages can be geo-referenced and transmitted back to the emergency headquarters for real-time update of the recovery (Cole et al., 2005).

2.3 Evacuation Routing Methods

The existing evacuation routing methods can be divided into the following classifications: simulation, network flow, and heuristic methods (Shekhar et al., 2012).

2.3.1 Simulation Methods

Simulation methods are solutions that visually simulate an emergency situation. It tries to visualize what could possibly happen as realistically as possible. Flow-based modeling, agent-based modeling, and cellular automaton modeling are just some of the methods that would fall into this category (Santos and Aguirre, 2004). These tend to focus more on the individual evacuees' movements and their interaction with one another (Mahmassani et al., 2004).

2.3.2 Network Flow Methods

Many research works have been done to model the evacuation problem as a network flow problem and to find the optimal solution using the linear programming (LP) methods. Hamacher and Tjandra (2002) gave an extensive literature review on the models and algorithms used in these linear programming methods. It initially models the evacuation network into a network graph (denoted by G), then it requires the user to enter an estimated upper bound T of the evacuation egress time. Second, it converts the network graph G into a time-expanded network (denoted by GT), by duplicating the evacuation network G for each discrete time unit t = 0, 1, 2, ..., T. Then, it defines the evacuation problem as a minimum cost network flow problem (Ford and Fulkerson, 1962) on GT. Lastly, it feeds the GT to the minimum cost network flow solvers, such as NETFLO (Kennington and Helgason, 1980), to obtain the optimal solution.

2.3.3 Heuristic Methods

Unfortunately, in a real-world urban evacuation scenario, the evacuation demand can easily overwhelm the capacity of the evacuation routes, resulting to traffic congestion (Bish et al., 2013). Congestion is not only inconvenient, but can also cause potentially dangerous situations because it discourages evacuation from potentially affected areas and it can leave the evacuees extremely vulnerable if they are trapped in the affected areas and it can leave the evacuees extremely vulnerable if they are trapped in the affected roadways when the disaster strikes. Furthermore, congestion can make the entire evacuation process itself hazardous (Bish et al., 2013). One of the limitations of CCRP is that it assumes that the maximum capacity of an edge does not depend on the traffic flow amount on the edge (Lu et al., 2005). In other words, it does not consider the traffic congestion realistically.

2.3.4 Casper Algorithm

The Capacity Aware Shortest Path Evacuation Routing (CASPER) algorithm is a heuristic evacuation routing method that connects each source node (evacuee) to its nearest destination while taking into account the capacity of the transportation network and the traffic flow in order to minimize traffic congestion and system-wide transportation times (Shahabi and Wilson, 2014). The algorithm first sorts the evacuees based on their distance from the closest destination area. Then, starting from the evacuee with the longest distance, it finds the shortest path and assigns the evacuee to that path. It iteratively continues this process until there are no more evacuees left, indicating that the affected population has successfully been removed from the hazard area. During the analysis, CASPER dynamically updates the edge travel costs based on the number of assigned evacuees and the capacity of the edge (Shahabi, 2012).

Each source point *s* is metered (*interval(s)*) so it will generate a different flow on each edge. For example, evacuees leaving from a source point at 20s intervals have *interval(s)* = 20. Each source point also has only one path P_s assigned to them. A path P_s is an ordered set of edges that will guide all the population from source point *s* to safety (*t*). From here, the total flow on edge *e* can be calculated by summing up all flows of all paths that pass through *e* (Shahabi and Wilson, 2014).

Traffic Model. The traffic model is defined as a function with two parameters *T(f,c)*. The traffic model predicts the congestion on an edge based on its capacity and total flow. From there, the cost of traversing an edge, and consequently the cost of traversing a path, can be calculated (Equation 1 and 2).

$$cost_T(e) = \frac{imp(e)}{T\big(flow(e), cap(e)\big)} \tag{1}$$

$$cost_T(P_s) = interval(s) \times w(s) + \sum_{e \in p_s} cost_T\,(e) \tag{2}$$

The main objective here is to minimize the cost of the path with the highest cost.

$$cost_T(e,s) = \frac{imp(e)}{T\big(flow(s,e) + flow(e), cap(e)\big)} \tag{3}$$

The calculation in Equation 3 considers both the previously reserved paths and the new population flow (i.e. *flow(s,e)*) so there is a need to record all the reserved paths. Lastly, the costs of all the paths are re-calculated. This step is important since the record of the reserved paths is not complete during the path finding process and therefore the costs are just a lower bound. Once all the paths are reserved, their costs need to be re- calculated to find the most accurate global evacuation time (Shahabi, 2015).

2.4 Dynamic Evacuation Routing Problem

The dynamic evacuation routing problem describes the problem of generating as well as maintaining evacuation routes in a dynamic environment. In a realistic evacuation scenario, unpredictable situations can occur within the environment whilst the evacuation process is still ongoing. For example, changes in the road network such as road blockages, car accidents, and flooded underpass can affect the road network and consequently the evacuation process. If a change in the transportation network occurs, the evacuation routing system should be able to detect that change, inform those evacuees whose routes might be affected from the change, and update these routes in a timely manner (Shahabi, 2015).

2.5 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) method was developed by Saaty (2008) and has been widely used to solve multi-criteria decision making problems. Some examples of multi-criteria decision making problems are: choosing a telecommunication system, choosing a product marketing strategy, etc. (González-Prida et al., 2012). These decision problems are decomposed into a hierarchy of criteria and alternatives.

In AHP, values like price, weight, or time, or even subjective opinions such as feelings, preference, or satisfaction, can be translated into measurable numerical relations. The core of AHP is that it does comparison of pairs instead of sorting (ranking), voting (e.g. assigning points), or free assignment of priorities. Individuals and groups use the AHP preference scale to formulate the comparison matrices (Alexander, 2012)).

Saaty (2008) provided a measure of consistency, called the Consistency Index (CI), as a degree of consistency. Once the consistency index is calculated, its value is compared with the appropriate one. The appropriate consistency index is called the Random Consistency Index (RI) which was obtained from associated random matrices of order n to compute the error due to inconsistency (Nieto et al., 2015). This comparison of values is called the Consistency Ratio (CR).

If the value of the Consistency Ratio is smaller than or equal to 0.10, then the inconsistency is considered acceptable, otherwise, it must be reviewed to improve its consistency (González-Prida et al., 2012).

3 METHODOLOGY

In this study, the Analytic Hierarchy Process will be introduced to the Capacity Aware Shortest Path Evacuation Routing (CASPER) algorithm. This proposed algorithm will be applied to the road networks along Lipadas River. The results will be compared to those results obtained from using previous evacuation methods.

3.1 Benchmark Data Sets

The flood hazard maps of Lipadas and Talomo will be used in this study to identify the areas within the road network that are at a risk of flooding. Road networks and building features will also be used for the dynamic network. All data were generated through the use of LiDAR data obtained from the Phil-LiDAR 1 Office of the University of the Philippines Mindanao.

3.2 Road Network

In this study, the ArcGIS Network Analyst Tool will be used to build the road network. It provides network-based spatial analysis including point-to-point routing, travel directions, closest facility, and service area analysis. By using an advanced network data model, networks from their geographic information system (GIS) data are built. It enables users to dynamically model realistic network conditions (i.e. turn restrictions, speed limits, traffic conditions) at different times of the day (ESRI, 2014).

3.3 Source Points and Destination Points

The flood hazard maps of Lipadas and Talomo will be used in this study to identify those areas within the road network that are at a risk of flooding. Areas that are marked red indicate a high flood hazard (>1.5m). Those that are marked orange indicate a moderate flood hazard (0.5 – 1.5m). Areas that are marked yellow indicate a low flood hazard (<0.5m). Figure 1 shows the 100-year return period flood hazard map of the Talomo area (Project NOAH, 2016).

Figure 1: 100 Year Flood Hazard Map of Talomo (Project NOAH, 2016).

3.4 Evacuation Framework

The evacuation framework is initially specified which includes all the discussed requirements. It will also include some steps needed for the experimental evaluations. The pseudo-code, as shown in Figure 2, outlines the overall system.

```
input: G(V,E), S, t, T(f,c)
P ← GetEvcRoutes(G, S, t, T )
EvcTime ← max{$P_s$ | $P_s$ ∈ P}
SimTime ← Simulation(G, S, P )
return P, EvcTime, and SimTime
```

Figure 2: Evacuation Framework.

The system inputs the road network in the form of a directed graph *G*. Let set *S* be the source population with their intervals *interval(s)*. The function *T* denotes the chosen traffic model. The *GetEvcRoutes* function processes the inputs to generate one evacuation route for each source point. All the paths end at vertex *t*, which serves as the destination point for all the source points. The *EvcTime* variable serves as the predicted global evacuation time based on the routes generated for the source population. Based on the lengths of the generated paths and the traffic predictions, it takes *EvcTime* time to get everyone to the destination point (safety). *SimTime*, on the other hand, is the simulated global evacuation time. This is only included for evaluation purposes. The *Simulate* function takes the graph, source points, and the generated paths as inputs. Instead of predicting the time, it simulates every person (vehicle) moving from *s* to *t* on the road map (graph) whilst taking into account the interactions between evacuees (vehicles). *SimTime* is recorded time for the last evacuee to reach his or her destination. The accuracy of the traffic model is measured by comparing the two times (Shahabi and Wilson, 2014).

3.5 CASPER-AHP Algorithm

The CASPER algorithm will be hybrid with the Analytic Hierarchy Process to allow the evacuation routing algorithm to adjust to the dynamic changes that might occur within the road network whilst the evacuation is still ongoing. The changes to the road network are not initially known; hence, the algorithm can only adjust once it learns about them. In this study, road blocks will be introduced to the road network during evacuation. The selection of the paths in which the road blocks occur will be done at random.

The AHP will be embedded into the CASPER algorithm once a change has been detected in the road network. As mentioned earlier, each edge *e* has a positive nonnegative impedance (*imp*) and road capacity (*cap*) associated to it. Neither of these values are constant since the road network can change during evacuation. In other words, the graph edges are allowed to change their values at some time after the evacuation starts.

Once a road block is introduced on the edge, the edge becomes no longer accessible. When this happens, the algorithm should be able to backtrack to the previous edge. The embedded AHP will decide which alternate path the evacuees should take (detours). This study will implement a two-level hierarchy AHP. The first level deals with the factors to consider in choosing the alternative route for the evacuees whose original path is affected by the road block. The second level deals with the alternative routes.

The steps in formulating the solution to the decision problem using AHP as summarized by Goepel (2013) are answered as follows:

1. Define the goal of the decision — the purpose of this decision is to have the evacuees adjust to the changes within the road network by selecting the best alternative route to them.
2. Model the decision problem into a hierarchy — the following criteria are considered in deciding the best alternative route for the evacuees: road capacity, road type, road status (in terms of flood risk), and the traffic congestion on that road.
3. Pair comparison of criteria in each category — In level, there will be one comparison matrix corresponding to the pair-wise comparisons between the four criteria with respect to the goal. Thus, the comparison matrix of level 1 has a size of 4 by 4. Since each choice is connected to each factor, then there is a total of four comparison matrices at level 2. The size of the matrices on that level depends on the number of choices.
4. Calculate the priorities and consistency index — Use the Consistency Index (CI) and the Consistency Ratio (CR) to check for the consistency of the comparisons. The Random Consistency Index (RI) value in this case is 0.90.
5. Evaluate alternatives according to the calculated priorities — Compute the overall weight of each alternative choice based on the weight of level 1 and level 2. The overall weight is the normalization of linear combination of multiplication between weight and priority vector.

In the proposed CASPER-AHP algorithm, it is assumed that the changes in the road network are not initially known. Therefore, the beginning steps are similar to that of the CASPER algorithm with a static problem. It loops over all the evacuee source points. The algorithm finds the shortest path to the destination point and is assigned to the source point. The changes in the road network are known once a path has already been assigned to the source point. The changes in the road network are known once a path has already been assigned to the source point. The selection of the edge to where the road block is introduced done at random. As previously mentioned, once a road block is placed on the edge, that edge becomes no longer accessible, so it is logical to remove that edge from the road network. If the selected edge is part of the reserved path for source point *s*, the AHP function is called to allow the evacuees at that source point to backtrack to the previous edge (remember that a path P_s is defined as an ordered set of edges that will guide all the population from *s* to safety). From there, the AHP function will decide which alternate path the evacuees should take from that edge. This allows the algorithm to adjust to the dynamic changes within the road network.

4 EXPECTED RESULTS AND FUTURE DIRECTION

The proposed combined algorithm is expected to be used during the flood event given that there is already a flood hazard map downloaded in a specific device. In the future, this proposed method will be optimized so that it can be integrated into an application that can be used on any devices that is portable during flood event such as smartphones, tablets, etc.

ACKNOWLEDGEMENTS

This study is under the Phil-Lidar 1.B.13 research project of the University of the Philippines Mindanao that is funded by the Department of Science and Technology (DOST) and the Philippine Council of Industry, Energy and Emerging Technology Research and Development (PCIEERD) of the Philippines.

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