A Model for evacuation Risk Assessment on Transportation Networks

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Abstract

Cities around the world are vulnerable to many kinds of disasters. Although the disaster risk reduction is widely spoken and attempted, the complex layout of cities makes the risk reduction impossible most of the times. The rescuers cannot always reach out the victims during emergencies due to the congested and concentrated network of city systems. This leads to greater vulnerability of cities and the potential increase of casualties as the hazardous consequences.

The traditional transportation demand related analyses generally focus on analyzing peak travel demands on weekday morning journey to work and evening journey from work trips and provide solutions for acceptable level of service. However, it is also important to give special consideration on analyzing demand and assessing transportation system capabilities during the special events or circumstances. One of these special circumstances involves emergency evacuation. Modeling the complex spatial interactions between people and the environment that occur during an evacuation is an important need in developing a successful emergency plan.

Tsunami is one of the major uncertain disasters which created a severe loss to Sri Lanka in terms of loss of life, damages to infrastructure, and decline to the economic assets in year 2004. When the Tsunami warning is given, the road network has to play a crucial role in responding to city's emergency evacuation. Therefore, it is essential to determine the spatial distribution of transportation difficulties and the most critical locations during the Tsunami pre-disaster situation. Hence, the evacuation risk assessment model presented in this research helps the city emergency planners to identify the most critical road segments and nodes that may hinder the efficient evacuation process because of their deficient configuration.

1.0 Introduction

The spectrum of possible emergency events ranges from natural events like floods, epidemics and earthquakes to human activity-based disasters like terrorism, accidents and nuclear power plant failures. Yet during an uncertain events like radioactive release from a nuclear power plant, Tsunami or hurricanes, the transportation system's response is inadequate. Therefore, the ability for the transportation system to perform under adverse conditions and recover to acceptable levels of service is fundamental to the livability of cities and its people. The advanced planning methods and modeling can help to reduce the likelihood of inadequate response to an emergency.

Hence, this research presents an approach for identifying neighborhoods that may face transportation difficulties during an evacuation. The approach presented here is subjected to the hazards with high degree of uncertainty in its spatial impact. It can also be used to identify small neighborhoods at a given node that have potentially risky combinations of high population and low exit road capacity.

The approach presented in this research is based upon a model integrated with a Geographical Information System (GIS)'s network based approaches. Using the network based approaches it is possible to model risk scenarios by considering pre-disaster factors, rather than largely depending on post-disaster factors which sometimes unreliable to collect such as the realistic traffic conditions during evacuations. In this approach, the evacuation difficulty has measured in terms of bulk lane demand which gives ratio between evacuation demand (in passengers) to exit capacity (in numbers of exit lanes leaving the neighborhood). Accordingly, higher the value of bulk lane demand, the longer it will take to clear the neighborhood in the event of an evacuation. Based on this assumption, the model has prepared using road network data and demographic data to find neighborhoods that have high levels of bulk lane demand.

In most of the cases, even in Sri Lanka, the evacuation planning is more centered on personnel training and resource planning. For an example, in Sri Lanka, many communities have special program task forces for disaster planning that conduct mock drills involving many agencies and organizations to test communication systems, coordination and personnel skills in dealing especially with natural disasters. But less or no concern is pay on determining the critical nodes and links of a transportation network.Hence pre determination of such locations in a network is essential to mitigate the losses from an uncertain disaster.
Indian Ocean Tsunami which occurred on December 2004 was taken as the case study for this research as it was one of the worst natural disasters faced by Sri Lanka in terms of loss of lives and devastation to infrastructure especially railway and the road network. From the lessons learnt from such a massive tragedy, the relevant government institutions have taken necessary steps to issue Tsunami warnings, conduct mock drills for coastal community groups, and establish Tsunami evacuation centers and evacuation routes. But it seems that less or no attention is paid on understanding the reliability of a transportation network on transferring evacuees from emergency zones to safer zones once the Tsunami warning has issued…..

2.1 Objective

The main objective of this research is to develop a model to that could map out the most critical nodes and links in a transportation network during an urgent evacuation.

3.0 Literature Review

3.1 Emergency evacuation

Emergency evacuation can be a life or death situation where the lack of safe exit routes and the time that it might take to safely exit can be directly related to lives lost. The significance of a transport system's utility and value in a support role become more apparent in emergency response and evacuation situations because of the higher demand placed upon them.

Emergency Management activities can be grouped into four tasks: risk reduction, readiness, response, and recovery. These terms capture the types of activities society must undertake in an effort to coexist with a variety of natural and man-made hazards (Lindell& Perry, 1992). The tasks can be described as follows:
Risk reduction: Activities that actually eliminate or reduce the probability of a disaster, such as preventative land-use zoning and the establishment of comprehensive emergency management programs.

Readiness: Development of plans to save lives and minimize the effects of the emergency, such as evacuation plans, and the creation and maintenance of up-to-date spatially referenced data such as property boundaries, utility lines and emergency headquarters locations.

Response: Activities immediately following the emergency. These activities provide assistance to those in need, to stabilize the situation and speed recovery.

Recovery: Activities needed to return all systems to normal or better. These include short-term recovery to provide vital life-support systems (e.g. shelter, food, water), and long term recovery that may continue for many years.

Each of these phases needs careful identification probable risk areas in order to prepare optimum disaster management plan. However, in most of the cases related to disaster management is more concern on assessing the risk or vulnerabilities of hazard prone areas which are also referred to as Emergency Planning Zones (EPZ). But it seems less attention is paid on assessing the risk and vulnerabilities of transportation network which plays a major role in transferring people from risky areas to safer ones as an attempt to alleviate loss of life and property.

3.2 Modeling

In the simplest construct, a model is a simplified version of a real world process, system, phenomenon, or entity. When there exist a multitude of issues and competing needs for resources, models can be a significant aid to decision makers before, during, and after an emergency. Modeling the complex spatial interactions between people and their environment that occur during an evacuation is an important step in developing a successful emergency plan.

The movement of people during a disaster event is happening at spatial and temporal scales. Spatial scale is important in accounting for the location and characteristics of populations that must evacuate the layout of the transportation network, and the area affected by a hazard when formulating an evacuation plan. Temporal scale is crucial as well, as event speed of onset largely dictates the start and end times of an evacuation.

Again the scale-based approach can further divide into two types as, large-scale evacuation that can be occurred due to disasters like nuclear power plant accidents & Tsunami and the small-scale evacuation of a building. Building evacuation is of great importance even in transportation as techniques developed first for building evacuation, now form the basis for most evacuation models in transportation. Some of the earliest research on building evacuation was done by Chamlet, Francis and Saunders (1982). Their paper describes three models they developed to analyze clearing time, bottleneck locations, and general performance of a building in the event of an evacuation.

To model the small scale evacuation of a building each person should be individually represented in the model. This technique is known as agent-based modeling or microsimulation, and is best suited to problems of limited size due to the computational complexity of representing individual people and their interactions. Microsimulation can also refer to the modeling of individual vehicles on a transportation network. These models are most suitable for neighborhood evacuation which could occur at a small spatial and temporal scale.

Microsimulation is less feasible in large-scale evacuation models which can be applied for large scale events like accident at a nuclear power plant, Tsunami, etc. Here the goal is to move thousands of people away from the disastrous area as quickly as possible, thus, need to utilize Macro scale models. These models group population into larger units, which can then be moved through the transportation network under different starting conditions producing a generalized evacuation plan. The benefit of such an approach is that it can simplify the complex interactions of large groups and thus be solved quickly. These models are most suited in deciding strategic disaster management decisions which is made at a large temporal and spatial scales. The major limitation of this model is the probability of unaccounting individuals or groups of individuals who take different evacuation behaviors that are not addressed in the model.

Between these two approaches is the meso-scale model which is neither microscopic nor macroscopic but rather borrows elements from each. A meso-scale model will not represent people individually but may aggregate them into relatively small population units, unlike the macro-scale model, which seeks the largest feasible unit. The spatial extent of meso-modeling can be at the neighborhood or community level, or the entire area affected. These models are models are often used for location-routing problems at a medium temporal scale.

Many evacuation modeling approaches rely on the delimitation of an emergency planning zone (EPZ). This focus was initially motivated by the perceived threat imposed by nuclear power plants during the 1970s and the accidents at Pennsylvania's Three Mile Island in 1979 and Chernobyl in 1986. The general approach involved predefining a circular EPZ around each nuclear site using a 10 mile radius (NRC 1980, Urbanik et al. 1980)and subsequently estimating the time it might take to clear the zone. Cova and Church (1997) point out that defining an EPZ in advance is problematic for fast moving hazards where the population that will need to evacuate is unknown in advance. They have called such models as "Indeterminable EPZ" (IEPZ) problems. In such situations, it is impossible to apply contemporary evacuation simulation models.

3.3 Modeling Evacuation Risk

Risk is understood as the potential inability to find accessible routes, the difficulty of transferring rescue resources, and transporting victims to safety and it is also a static measurement of the vulnerability of the road networks in a certain area in terms of the possibility of experiencing traffic congestion (Chen et al, 2011).

A number of factors can affect the safety of an evacuation. These factors include the number of people needing evacuation (i.e. demand), the transportation capacity provided for evacuation, the rate at which the demand is exerted, the rate at which capacity is actually provided, the differences between these rates, human behavior (Lindell and Perry, 1991), and accidents.

Total demand and transport capacity are the major factors which influence for risk of a transportation network. Previous works have proposed a simple formula to measure the evacuation risk of transportation networks considering the bulk lane demand.

$$\textit{Bulk Lane Demand} = \frac{P}{C}$$

Where;

P = Number of people within a specific region or cluster / Total vehicle demand leaving a neighborhood

C= Number of lanes of roadway leaving a neighborhood

According to the above formula the neighborhoods with high bulk lane demand might have greater problems in evacuation than areas with low levels of bulk lane demand.(Church &Cova, 2000).

Cova and Church (1997) have presented a map of evacuation difficulty using an optimization model that can be used in conjunction with road network data and demographic data to find neighborhoods that have high levels of bulk lane demand. Their model delineates the neighborhood about a point (e.g. an intersection) that maximizes bulk lane demand. The model finds the worst case neighborhood about a point that has the highest bulk lane demand. By applying this model for selected intersections across a road network, it is possible to classify each street segment in terms of worst case bulk lane demand values.

Scholars have used different quantitative approaches in understanding the transporting behavior of evacuees during emergency evacuations. Dial (1971) found that the drivers will often choose routes that are not the shortest distance to their destinations. His approach clearly reflects the dynamic and unpredictable flow of traffic during an evacuation. Other researchers have built on this framework and introduced an element of random route assignment that represents driver behavioral decisions under conditions of distance and network topology uncertainty (Daganzo and Sheffi 1977).

People's decisions and behaviors always have a huge effect on disastrous situation. Chen et al (2011) has developed a model while also considering the factors such as evacuees routing behaviors and spatial impact of the disaster.

In recent years the awareness of the need for tools that assist with the facilitation of mass evacuation modeling for disasters has increased. Advances in computer systems over the past 25 years have provided an excellent opportunity to provide databases which give the sort of information required. In particular Geographic Information Systems (GIS) is one of the valuable tools in evacuation modeling which allow ready access to both spatial and attribute data, on a national or local scale, and provide the opportunity to overlay information for ease of interpretations.

3.4 Application of Geographical Information System (GIS) in emergency planning

GIS is a system of hardware, software and procedures designed to support the capture, management, manipulation, sophisticated analysis and modeling and display of spatially-referenced data suitable for solving complex planning and management problems. It is now a maturing mix of technology and is being a widely applying tool in the fields of government, emergency services, environmental, business, industry, education and transportation.

The four emergency planning tasks identified by Lindell & Perry (1992) can benefit from the application of Geographical Information System (GIS). The GIS technology provides a mechanism to centralize and visually display critical information during an emergency. In an emergency, it is critical to have the right data, at the right time, displayed logically, to respond and take appropriate action.

With regard to *risk reduction*, GIS can be used to identify and model hazards and begin to evaluate the consequences of potential emergencies. It can initially be used for land-use planning as a tool for consultation, zone delineation etc. The relative safety of routes, structures and populations can then be evaluated with respect to potential natural hazards.

Readiness is concerned with activities that prepare for actual emergencies. Here network analysis tools in GIS are used to provide answers to questions such as the optimum location for fire stations if a 10-minute response time is required, the safest location for new hospitals, emergency facilities and headquarters,what evacuation routes should be selected?,will the road networks handle the anticipated traffic?, etc.

The Network Analysis tolls in GIS can also aid the *response* phase by determining the closest emergency vehicles to theincident and assigning them to the area using the optimum or shortest path.This is increasingly possible if the emergency vehicles have GPS units enabling them to be accurately located. In a complex emergency, GIS can help manage the overall status and provide timely information updates.

Recovery phase begin when the emergency is over, and are often in two phases, short- and long-term. Short-term recovery restores vital services and systems. GIS can play a role in damage assessment and information management. Using GPS and telecommunication devices, locations and assessments of damage can be geo-referenced and transmitted back to the emergency headquarters for real-time update of the recovery. For long-term efforts, such as reconstruction of utilities, GIS can be used to locate new services and to track the construction and rebuilding.

4.0 Case study and Methodology

4.1 Case study

The evacuation risk assessment model presented in this research is subject to the hazards with a high degree of uncertainty in terms of its spatial impact. Tsunami is a uncertain disaster during which the road network plays a crucial role in responding to city pre-disaster evacuation. Therefore, it is worthwhile to evaluate the evacuation difficulty associated during the Tsunami pre-disaster situation to better identify the vulnerability of certain road segments.

Sri Lanka has been extremely hard-hit in terms of loss of life, infrastructure, and economic assets; the 2004 tsunami is widely acknowledged as the largest, most devastating natural catastrophe in the history of the country. Two hours after the first earthquake occurred, the Tsunami waves struck an extremely long (more than 1,000 km, or two-thirds of the coastline) coastal area of Sri Lanka across thirteen districts, including Jaffna in the north, the eastern and southern coast, and parts of the west coast as far north as Chilaw.

In Southern Province of Sri Lanka approximately 20% of the coastal population was affected by the Tsunami. Many of the village industries located along the southern coastlines were destroyed which also caused disruptions to livelihood activities of a large number of people.

Among the coastal cities of Southern Province, the city of Galle is one of the most hardly affected (Figure 1). According to the Department of Census and Statistics records, 497 residents were killed, 89 residents were disappeared, 996 residents were injured, 1588 houses were damaged and 8114 residents were affected due to the Tsunami disaster.

Figure 1: Location of Galle Municipal Council Area
Source: Survey Department

4.2 Planar Network Dataset

The spatial data model for the transportation problem was prepared as a planar network (Figure 2) where the arcs represents the road segments and the nodes represent street intersections.

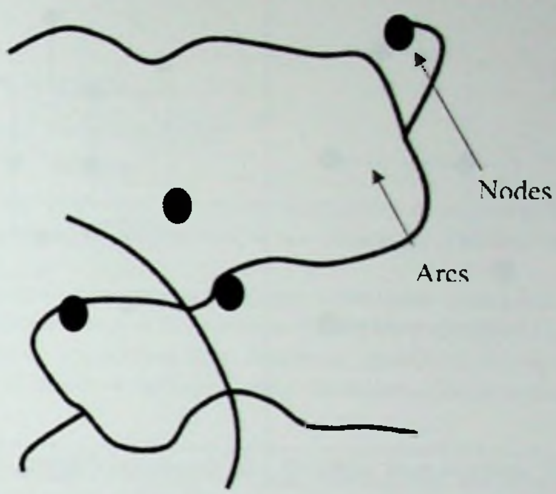


Figure 2: Representation of Planar Network

4.3 Generating Thiessen Polygons

One approach to aggregating population in GIS network analysis studies is to assign and aggregate residents to their nearest street intersection using Thiessen polygons (Flowerdrew and Green, 1992), centered on the street intersections as shown in the Figure 3.

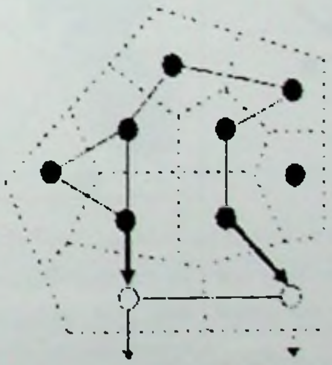


Figure 1: Thiessen polygons centered on the street intersections

A Thiessen polygon is a Voronoi Diagram that is also referred to as the Dirichlet Tessellation. Given a set of points, it defines a region around each point. A Thiessen polygon divides a plane such that each point is enclosed within a polygon and assigns the area to a point in the point set. Any location within a particular Thiessen polygon is nearer to that polygon's point than to any other point. Mathematically, a Thiessen is constructed by intersecting perpendicular bisector lines between all points.

The following diagrams illustrate how Thiessen polygons would be generated manually.

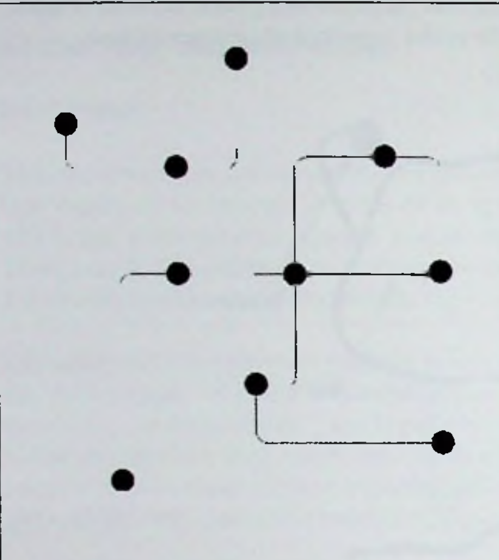
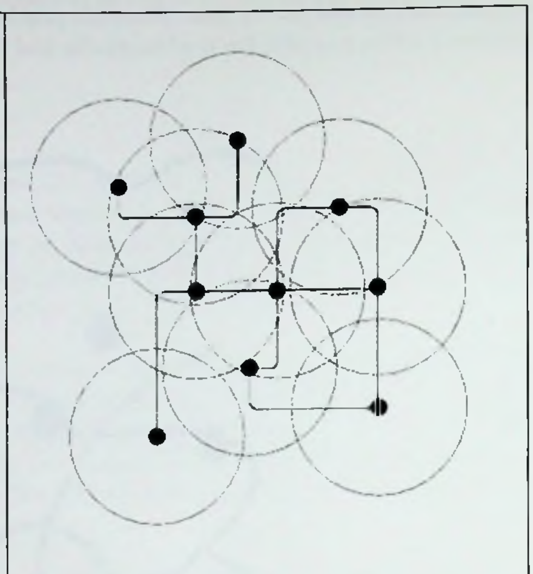
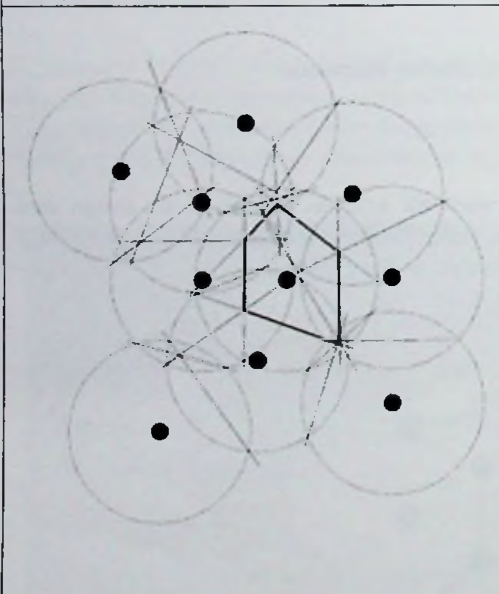
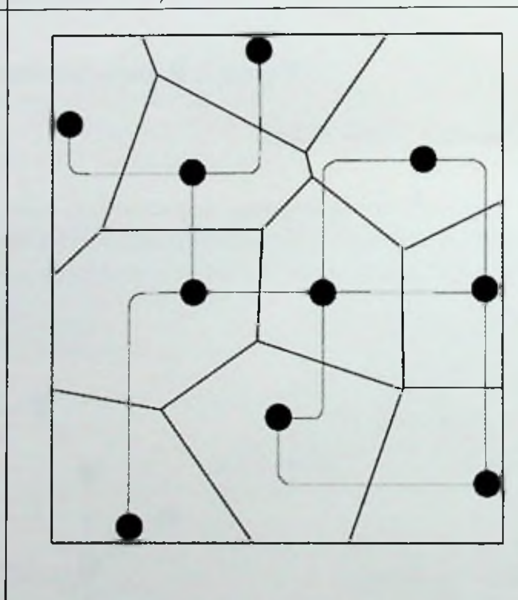
	
The first diagram shows a road segments and junctions in a network	In the second diagram, the circles are drawn around each junction
	
In the third diagram, bisector lines are added by drawing a line where the circles inter-join	In the final diagram, the network is overlaid with the polygons that are created by connecting the bisector lines

Figure 2: The process of generating Thiessen polygons

4.4Dijkstra's Algorithm

The optimum routing of the evacuees were determined by the Dijkstra's Algorithm, which is a fundamental shortest path algorithm. It was discovered by Dutch computer scientist Edsger Dijkstrain in 1956 and published in 1959. The algorithm computes the shortest path from one node to all other nodes in the network. It assumes that the link lengths are always non-negative.

In this method, every node is assigned a label with two components (x, y). A label could either be temporary or permanent. The algorithm stops when all labels are permanent. As will soon become apparent, after completion, the labels give information on the shortest distances as well as the shortest paths from a particular node to all the other nodes. Also a node is referred to being in the open state if its associated label is temporary; it is to be in the closed state if the label is permanent.

5.0 Analysis & Results

5.1 Identification of Emergency Planning Zone (EPZ)

Many evacuation modeling approaches rely on the delimitation of an emergency planning zone (EPZ). The EPZ for this model was demarcated by considering the Tsunami risk boundary.

The information pertaining to demarcation of Tsunami risk areas were taken from the hazard maps developed by Wijayaratna, et.al in 2010 (Figure 5).They have identified High, Moderate and Low hazard prone areas by considering flow directions, inundation levels, run-up distances, number of casualties and extent of damages during the Indian Ocean tsunami on December 26th2004.

Accordingly the entire boundary comprised with high, medium and low Tsunami hazard prone areas were taken as the EPZ boundary to develop the model.

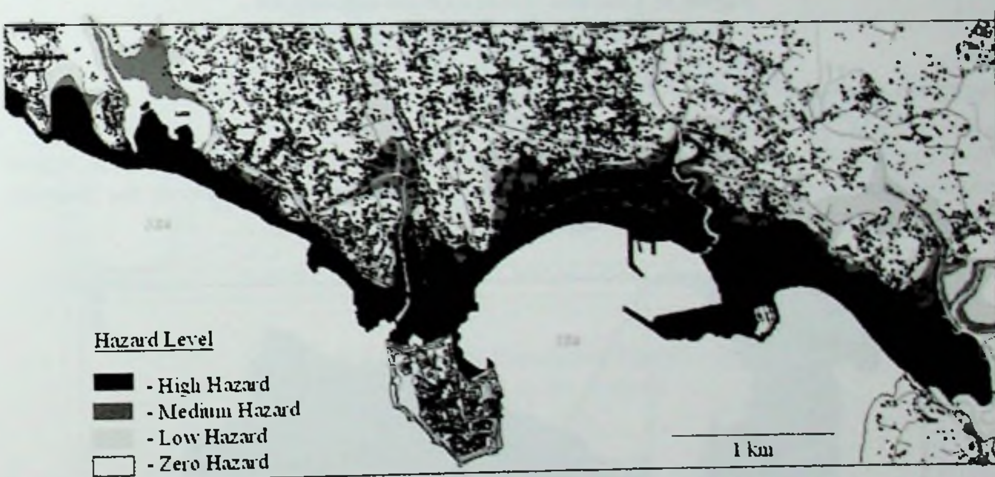


Figure 5: Tsunami Hazard Levels of Galle MC
Source: Tsunami Risk Assessment for Port City of Galle

When developing the model, the road based transportation network which consists of major and minor roads was simplified into nodes and edges. The railway network which is running through the area was not taken into consideration when developing the model. The transportation nodelies within the EPZ was considered as the origins of the evacuees and the nodes located immediate after the EPZ were considered as the destinations of the evacuees (Figure 6).

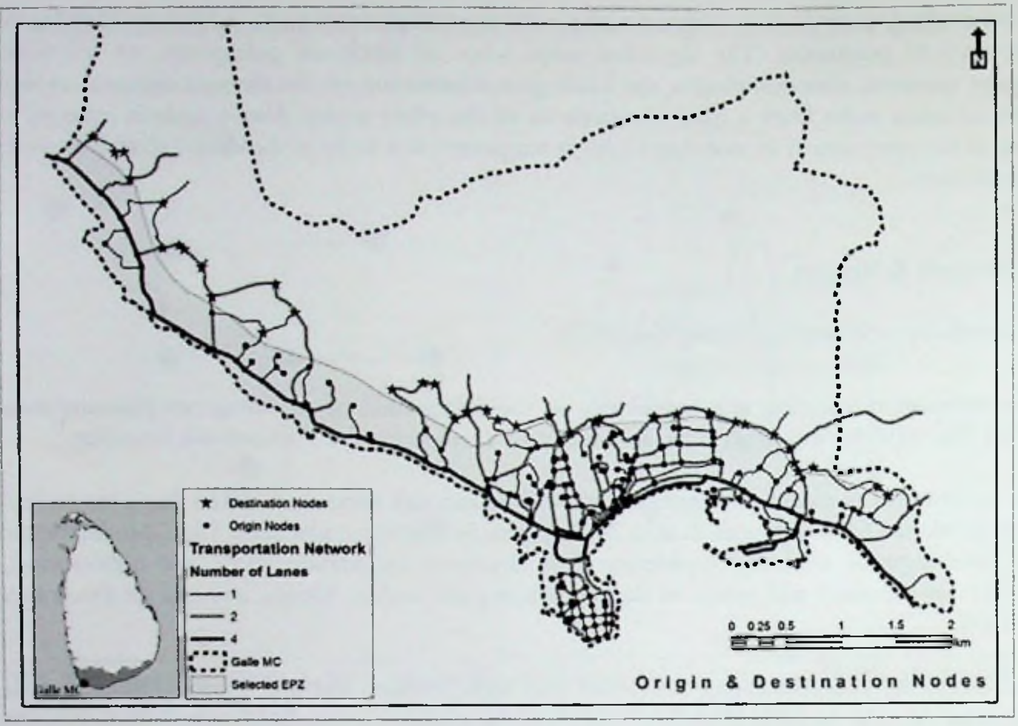


Figure 6: Tsunami Hazard Levels of Galle MC

Source: Compiled by Authors

5.2 Aggregation of population into Origin Nodes

To aggregate the total population of the area onto its closest intersection, the spatial multiplication method of Thiessen polygon method was applied. Figure 7 shows the Thiessen polygons generated for Galle MC area in this manner.

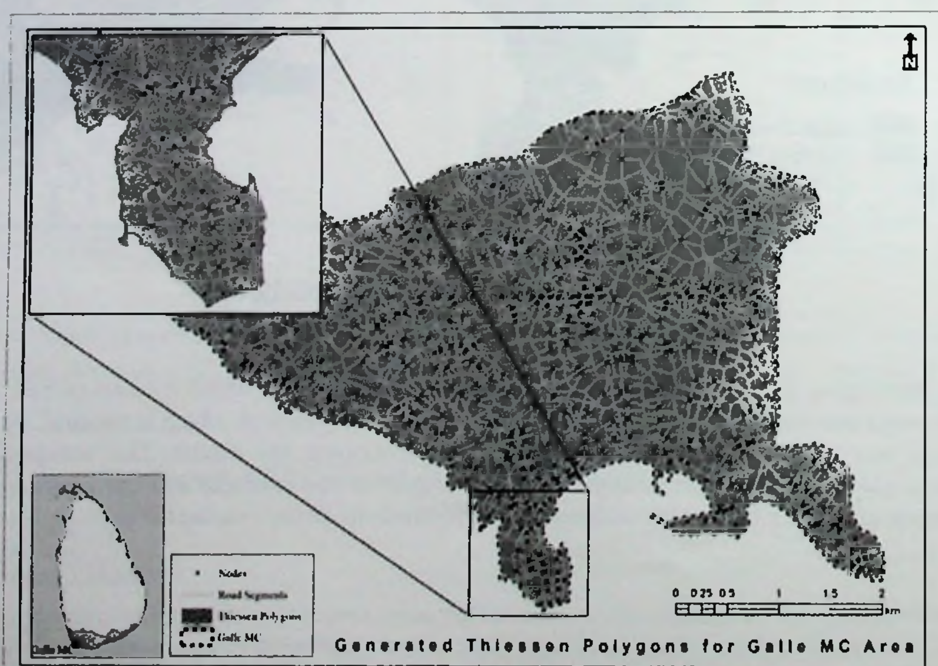


Figure 7: Thiessen polygons generated for Galle MC Area

*Source:*Compiled by the Authors

Due to unavailability of data pertaining to floating population and population working at commercial and industrial areas, the model applied in this research is best suited for emergency evacuation during the night time. Hence, in order to calculate the night time population, the buildings of the area were classified according to the land use of the area and only the residential buildings were selected. Then it was assumed that the average household size of the Galle MC area as four and each household occupies one residential building. Based on these assumptions number of residential population comes under each Thiessen polygon was calculated. Then the population value of each Thiessen polygon was assigned in to its respective node. The Figure 8 shows the estimated population for each transportation node. Hence the nodes with high number of aggregated population are the most critical origins located within the EPZ area.

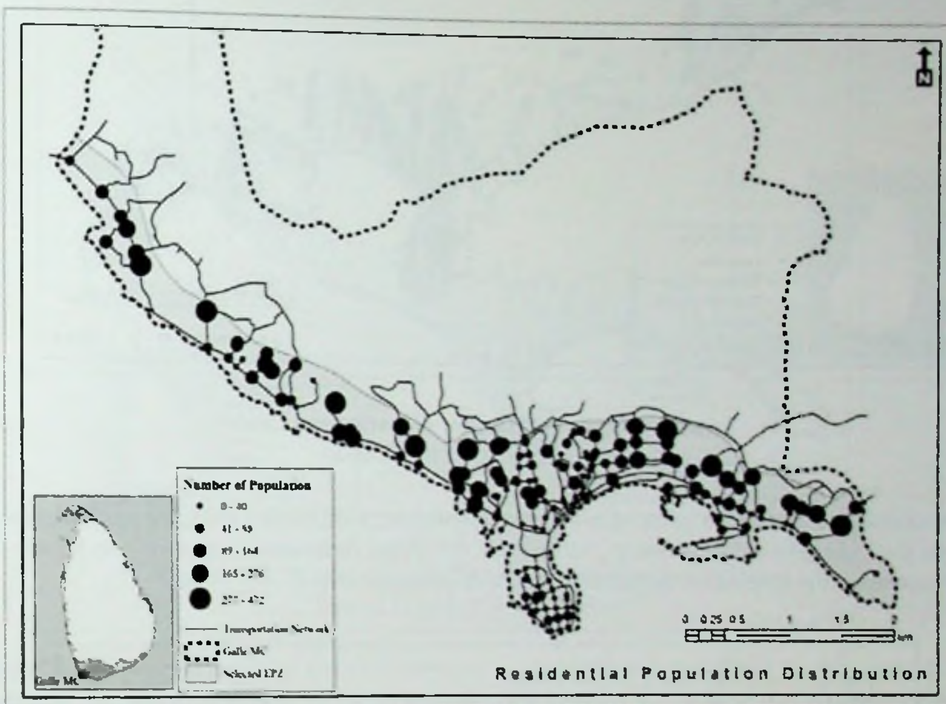


Figure 8: Residential Population Distribution
Source: Compiled by the Authors

5.3 Application of Dijkstra's Algorithm

When deciding the optimal routing of the evacuee, it was considered the nodes located inside the EPZ as the origin of the evacuee and the nearest node outside the EPZ as the destination of the evacuee. The optimal routing procedure can be viewed as a two-step decision-making process. First, evacuees target a shelter as a destination. Second, they move toward the destination by adopting the most efficient route in terms of the shortest distance or the least time expenditure. Dijkstra's Algorithm was applied to find the optimum path in terms of shortest distance, and the nearest destinations. The Dijkstra algorithm finds the shortest path from a given node to all the other nodes in the network. It solves an O–Dassignment problem with one origin and several destinations (1-to-n).

Figure 9 shows the nearest destinations identified for each origin by applying the Dijkstra's Algorithm. Then the optimum route from each origin to destination was identified and population at each origin was accommodated to each road segment comes under that optimum route. In this manner cumulative population (evacuees) was calculated for each road segment of the EPZ area.

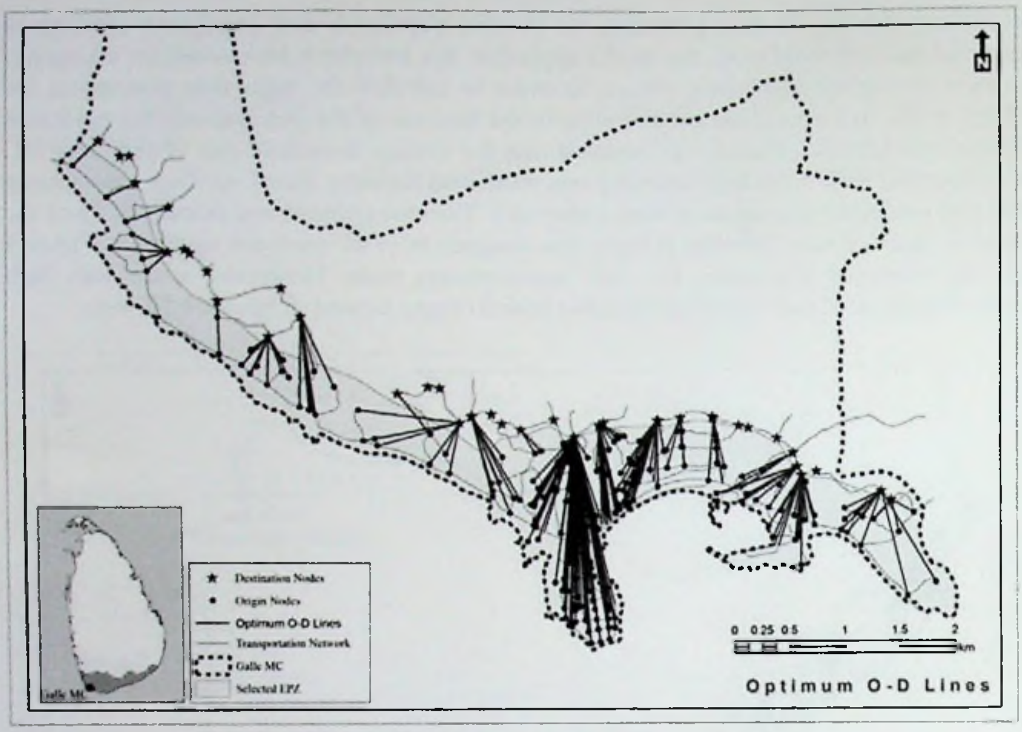


Figure 9: Optimum Origin - Destination Lines
Source: Compiled by the Authors

The critical destinations in terms of number of population, were created from the result obtained from the O-D assignment problem. Accordingly the critical destination map shown in Figure 10 demonstrates the cumulative population at each destination.

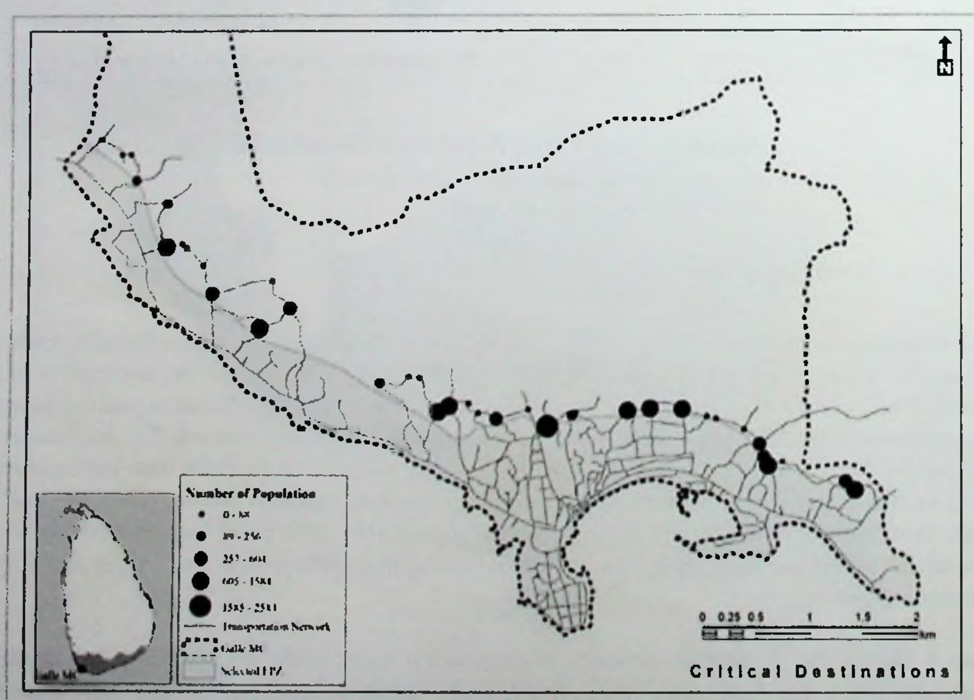


Figure 10: Critical Destinations
*Source:*Compiled by the Authors

The second objective of identification of spatial distribution of evacuation difficulties that might arise during an urgent evacuation was measured according to the formula given below:

Evacuation difficulty = population/number of exit lanes

Accordingly cumulative population (evacuees) at each road segment was divided by its number of lanes, to determine the evacuation difficulty at each road segment. Figure 11 shows the number of lanes of transportation network located at EPZ area of Galle MC.

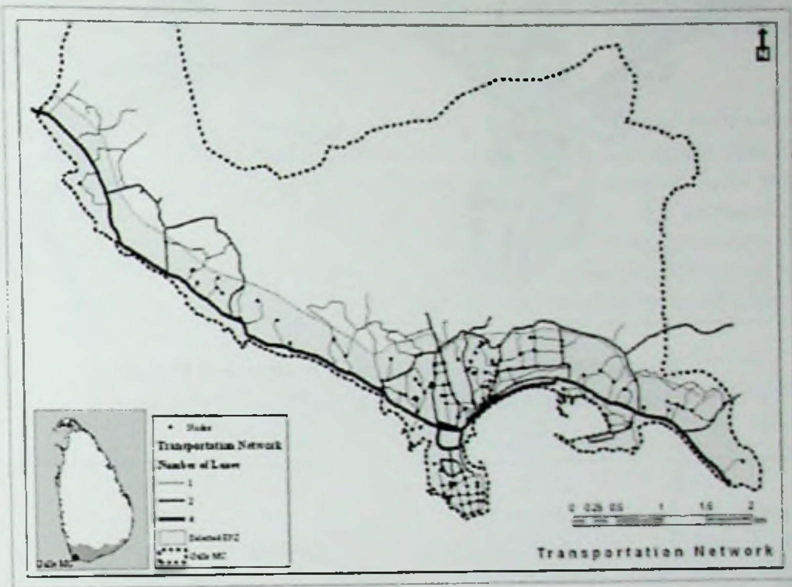


Figure 113: Transportation Network with number of lanes
Source: Compiled by the Authors

Figure 12 shows the result of the evacuation risk map produced according to the evacuation difficulty measuring according to the aforementioned formula.The unit of the map shows the number of people per lane that a road can sustain.

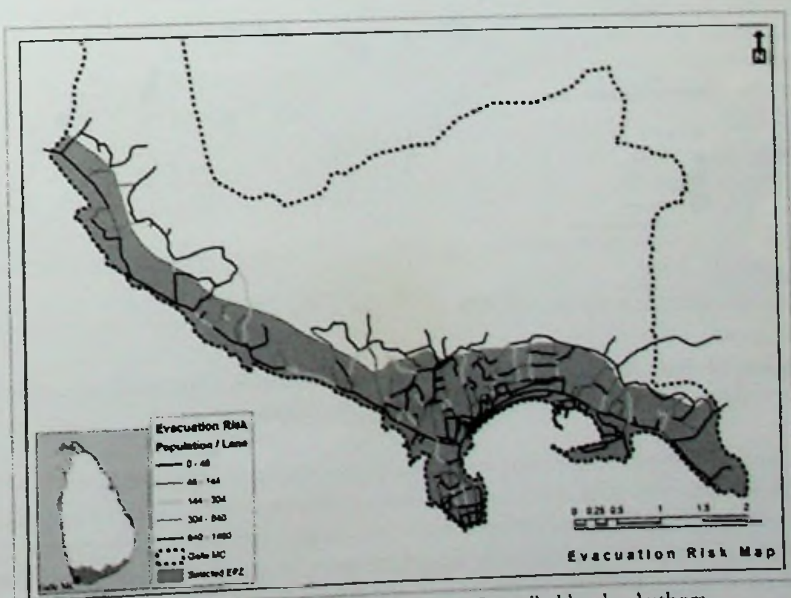


Figure 12: Evacuation Risk *Source:* Compiled by the Authors

Figure 134: Existing Evacuation Routes and Places
*Source:*Tsunami Risk Assessment for Port City of Galle

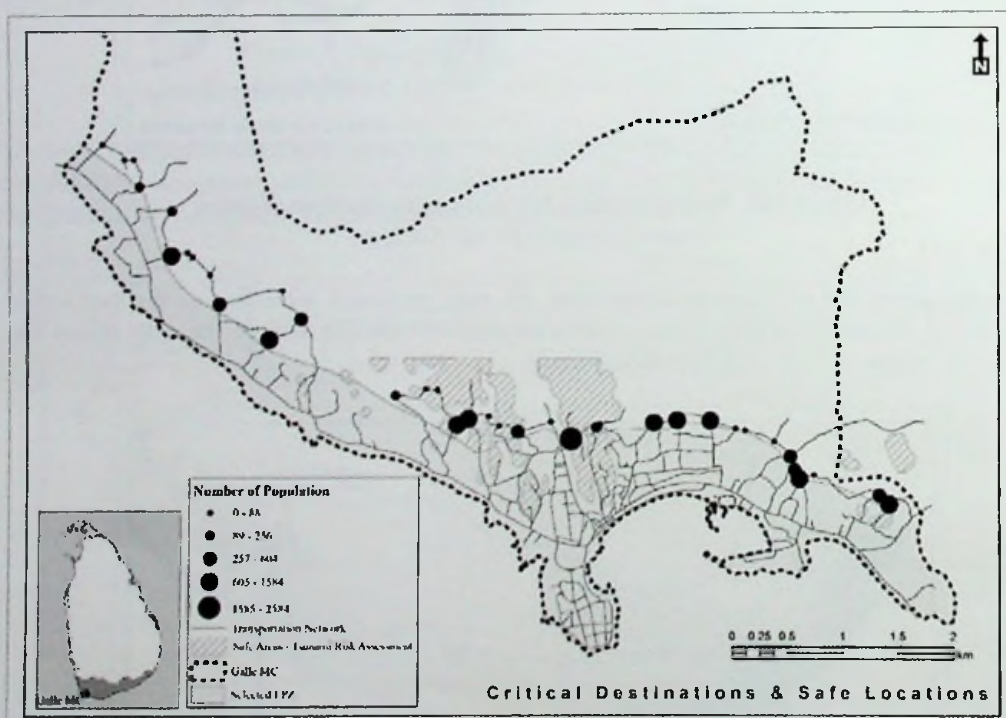


Figure 14: Safe Areas of Tsunami Risk Assessment & Critical Destinations
Source: Compiled by the Authors

Figure 13 and 14 show the evacuation routes, places and safe areas established in Galle city according to the Tsunami Risk Assessment. When comparing Figure 13 with Figure 12 it seems that most of the proposed evacuation routes are located on the road segments with high evacuation risk. Therefore, considerable attention must be paid in planning the evacuation activities in an effective manner on the evacuation routes where the risk is high. On the other hand, it is also possible to re-plan the evacuation routes by avoiding the high risk areas.

As shown in Figure 14, it seems most of the safe areas of the Galle City, as suggested in the Tsunami Risk Assessment, are located within the middle part of the EPZ area where the highly critical destinations are located. Therefore, it is vital to rethink the capability of those safe locations in handling the evacuees who have much probability in travelling across those areas.

5.0 Conclusions and Recommendations

There are various kinds of evacuations. The evacuations that the authors of this paper were concerned are related to major man-made or natural disasters in large geographic scales such as radioactive release from a nuclear power plant, hazardous material spills, fires, terrorist attacks, Tsunami and hurricane.

In this paper, a model has been developed to assess the risk associated with evacuating the affected population during a Tsunami disaster situation by also visualizing the risk. Most of the time evacuation risk is perceived as an abstract concept on the national level and it is not properly visualized on the scale of neighborhoods in a city. Thus, by examining the maps generated by the model, the roads with a higher likelihood of suffering evacuation difficulty in emergencies can be identified. This visualization is of great use for city emergency planners to identify urban infrastructures with deficient configuration that may hinder an efficient evacuation process.

The results presented in the model are also useful in re-planning and managing the existing tsunami evacuation routes and safe areas by also considering the road segments and nodes with high evacuation risk.

Also there are several limitations in the model. The model developed in this research is more applicable for disaster events that can arise at the night time, due to unavailability of data pertaining to floating population and prevailing traffic at the roads. Evacuation difficulty is at each road segment is highly time dependent. The number of evacuees travelling at each road segment varies with the time. However the model developed here is a meso-scale model that does not represent people individually but may aggregate them into relatively small population units using Thiessen polygon method. Hence delays occur at each road segment due to individual travelling speeds, mode of travel, turning movements at intersections were not incorporated when developing the model.

Also during an emergency, evacuees not always select the shortest path, rather they choose least congested routes or roads with which they are most acquainted or have previously used or sometimes they tend to follow the actions of the masses and move away with others. In such a case the shortest path method applied in finding the optimum route may not be sufficient.
The evacuation risk assessment model presented in this research is not applicable for certain events like seasonal floods in which the evacuation paths of the road network cannot be justified when the roads get flooded and when the community takes adaptation measures to live with the flood.

However, by using more accurate data such as floating population, number of vehicles that each Thiessen polygon contains and prevailing traffic conditions at road, more realistic model can be developed to evaluate evacuation risk at road based transportation network during an uncertain circumstance. The composite evacuation risk map shows the number of people per lane that a road segment can sustain. By incorporating such missing information it is possible to measure the evacuation difficulty in terms of passenger car units.

6.0 References

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