Descriptive and Geographical Analysis of Flood Disaster Evacuation Modelling

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ABSTRACT

The planning of evacuation operations for a riverine flood disaster is vital for minimizing their negative impacts on human lives. This paper aims to develop a systematic method to model and plan evacuation trip generation and distribution for riverine floods. To achieve this aim, it adapts the transportation or Hitchcock problem, an operations research technique employed in conventional four-stage transportation modeling, and that is used to plan and model transport in normal situations, so that it is appropriate for flood disaster situations focusing on the first two stages. Concentrating on pre-flood hazard planning, our evacuation modelling considers two types of flood disaster data environments: certain environs, in which all decision variables are known, and uncertain environs, when probabilities of decision variables are considered in the evacuation plans.

Keywords

Flood, Disaster, Evacuation, Planning, Transport Planning for Operations.

INTRODUCTION

Floods in urban and populated areas expose humans to serious threats to life. In light of this fact, evacuation of flood-affected populations is considered the most appropriate protective measure to minimize the negative impacts of floods on human lives (Paul, 2011). Moreover, unplanned or spontaneous evacuations during flood disasters can cause severe traffic congestion that makes evacuees more vulnerable and exposes them to further risk (Petruccelli, 2003; Litman, 2006). Therefore, efficient and effective planning of evacuation operations for flood disasters is important for minimizing the devastating consequences of flood disasters. In Australia, flooding caused by rainfall is the most costly natural disaster. The estimated average annual cost of flood disasters was $314 million a year during the period from 1967 to 1999, with a total cost of $10.4 billion, and 2,292 deaths from 1790 to 2001 (Middelmann, 2007, p.p. 62-63).

This risk continues. The Flood Preparedness Report identified approximately 170,000 residential properties across Australia that are subject to flooding in a 100-year ARI (Average Recurrence Interval) flood (Australian Government, 2009). However, riverine flood related risks are usually manageable due to the gradual development of the flood and the predictability of the factors causing them, such as rainfall, floodplain locations and flooding's spatial and temporal distributions (Australian Government, 2009). Hence, risks related to poorly planned evacuations, such as severe traffic network congestion caused damage to the network or increased traffic volumes created by evacuees, or inadequate relocation shelter locations or capacity, can be planned and managed more efficiently. In particular, safer evacuations are possible when the evacuation is pre-warned, and evacuation can therefore be used as an appropriate protective measure for riverine flood disasters.

The Transportation or Hitchcock Problem and Riverine Flooding Evacuation Planning

The transportation or Hitchcock problem was proposed by F.L. Hitchcock in 1941 as a logistics and supply chain management method for reducing costs, and improving service. It deals with the situation in which a commodity is shipped from a source to a destination (Ford et al., 1956). Transportation problem methods have been developed from a step-by-step illustrative technique that was introduced by Hitchcock-Koopmans, and extended to employ not only linear and deterministic methods, but also stochastic and non-linear methods (Romeijn and Sargut, 2011). Recently, evolutionary computation methods such as differential evolution or Genetic Algorithms (GA) have also contributed significantly to solving fuzzy transportation problems (e.g., fuzzy demand, fuzzy supply) (Feng-Tse, 2010).

Flood hazards range in scale and intensity from regular, planned events to manageable emergencies, and sometimes even to devastating disasters. As well, affected population evacuation modelling methods might range from simple deterministic linear models to complicated, fuzzy, non-linear models. Therefore not every model is appropriate for every flood hazard event. Consequently, this paper illustrates how to adapt the transportation problem for evacuation operations to plan for flood disasters. In this paper, linear, non-linear, deterministic and stochastic models are investigated for evacuation planning.

TRANSPORTATION PLANNING (STRATEGIC TRANSPORT PLANNING)

Because traditional transportation planning focuses on long-term and strategic transport issues, it does not adequately consider short-term operational issues and problems, including planning for disaster evacuation trip purposes. Moreover, evacuation operations planning focuses mainly on traffic assignment modelling, which minimizes the total travel time of evacuation operations, taking into consideration transport network constraints such as number of lanes, length, and lane capacity. Focusing only on the route choice model does not take into account the generated trips from flood-affected areas and the capacities of relocation shelters that the evacuees will be distributed to.

Traditional transportation markets, as for any other economic and trade market, aim to match the future supply (transport networks' capacities and modes) with the forecasted demand (trips) to achieve an equilibrium point. The process begins with forecasting future travel demand, and ends with preparing plans that are forwarded to decision-makers to enable them to manage this future demand. The structure of the conventional four-stage model starts with collecting data that considers existing and planned traffic zones and their socio-economic characteristics (e.g., population, jobs, car ownership, household age structure), and transport networks (e.g. roads, railways, waterways) and their features or characteristics (e.g. capacities, speed, modes of transport). These data are used to estimate four sequential models. The four models are briefly defined as:

1. Trip Generation: This model estimates the total number of trips (demand) produced from and attracted to each traffic zone.

2. Trip Distribution: This model estimates the distribution of each traffic zone's generated and attracted trips using the trip generation model across all trip destinations.

3. Modal Split/Choice: This model estimates the choice of mode of transport, which allocates the trip distribution matrix to different modes of transport.

4. Traffic Assignment: the fourth and last stage is to assign the different modal split matrices to their corresponding transport networks.

The evacuation models we present here combine and adapt the first two strategic transport planning models to plan and model riverine flood evacuation operations. The traffic zone and travel time data were extracted from Canberra's strategic transport planning model, developed by the Snowy Mountains Engineering Corporation (SMEC). Affected area populations and shelter capacities are based upon a potential flood scenario developed from Canberra's past flood events.

EVACUATION TRANSPORTATION PLANNING (TRIP GENERATION AND DISTRIBUTION)

We adapted the transportation problem method for evacuation operations planning to reflect the purpose of emergency movements. We did this by attempting to minimize the total travel time of affected populations from affected areas (origins) to relocation shelters (destinations). The model consists of an objective function and constraint functions.

The objective functions simulate the different knowledge environments during flood disasters (from certain to uncertain) and reflect the types of mathematical relations (linear and non-linear functions) between problem variables as shown in Table 1. The objective functions aim to minimize the travel time needed to transport the affected population from affected areas to relocation shelters as follows:

Table 1: Objective Functions used for Flood Evacuation Models

Mathematical Type \ Certainty	Deterministic		Stochastic
	Absolute Travel Time	Proportional Travel Time	
Linear Programming	$\min(TP) = \sum_{i=1}^{i}\sum_{j=1}^{j} AP_{ij}\,TT_{ij}$	$\min(TP) = \sum_{i=1}^{i}\sum_{j=1}^{j} AP_{ij}\,P_{ij}$	$\min(TP) = \sum_{i=1}^{i}\sum_{j=1}^{j} AP_{ij}\,S_{ij}$
Nonlinear Programming	$\min(TP) = \int_0^i\int_0^j AP_{ij}\,TT_{ij}$	$\min(TP) = \int_0^i\int_0^j AP_{ij}\,P_{ij}$	$\min(TP) = \int_0^i\int_0^j AP_{ij}\,S_{ij}$
Evolutionary Computations	$\min(TP) \cong \sum_{i=1}^{i}\sum_{j=1}^{j} AP_{ij}\,TT_{ij}$	$\min(TP) \cong \sum_{i=1}^{i}\sum_{j=1}^{j} AP_{ij}\,P_{ij}$	$\min(TP) \cong \sum_{i=1}^{i}\sum_{j=1}^{j} AP_{ij}\,S_{ij}$
		$P_{ij} = \left(\frac{TT_{ij}}{\sum_{i=1}^{i} TT_i}\right)$	$S_{ij} = \left(TT_{ij} - \frac{TT_{ij}}{\sum_{i=1}^{i} TT_i}\right)$

Where *TP* is the total travel time of the affected population*, i* is the affected area, j is relocation shelter*,* TT_{ij} is travel time between affected area *i* and relocation shelter *j,* AP_{ij} is the volume of affected population from affected area *i* in relocation shelter *j,* and in the case of stochastic models*,* P_{ij} is the proportional distribution of travel time between affected area *i* and relocation shelter *j,* S_{ij} is the travel time perception's reduction probability, which assumes that affected populations do not have complete and accurate perceptions of travel time between their own affected area *i* and relocation shelter *j.* This reduction probability increases when travel time between the affected area and relocation shelter increases and visa-versa.

Subject to Constraints of:

Affected Population Constraint: The affected population transported from affected area *i* to relocation shelter *j* is exactly equal to the affected population in affected area *i*.
Relocation Shelter Constraint: The affected population transported from affected area *i* to relocation shelter *j* is less than or equal to the relocation shelter's capacity *j*
Non-negativity Constraint: The non-negativity constraint prevents the model from transporting negative numbers of affected population from affected area *i* to relocation shelter *j*.

PRELIMINARY INVESTIGATIONS OF EVACUATION MODELS FOR FLOOD DISASTERS

All nine models have achieved the optimal results, meeting all constraints. Linear models achieved the lowest total travel time, followed by non-linear models and then evolutionary computation models as depicted in Figure 1. However, significant improvements in total evacuation times have occurred in the proportional model in a non-linear implementation, and in the proportional and the stochastic models in the evolutionary computation models, respectively, whereas this has not occurred for the linear models.

The average travel times per evacuee of the nine evacuation models are summarized in Figure 2, which shows slight improvement in proportional linear model evacuee average travel time compared with the deterministic and stochastic linear models. However, considerable improvements were made in evacuee's average travel times in the proportional non-linear and proportional and stochastic evolutionary computation models.

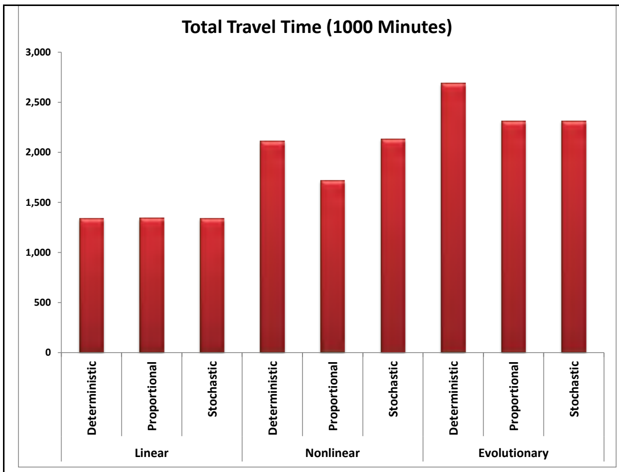


Figure 1: Total Evacuation Model Travel Times

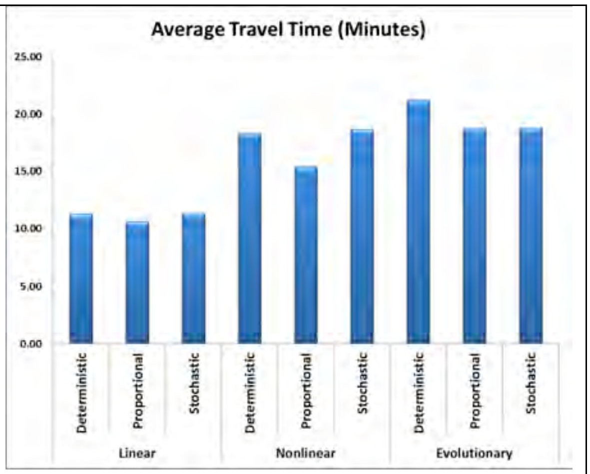
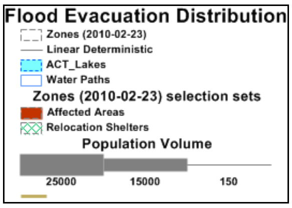
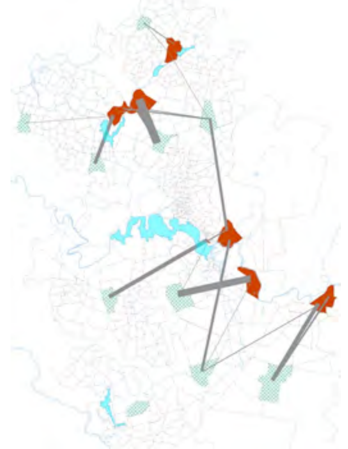
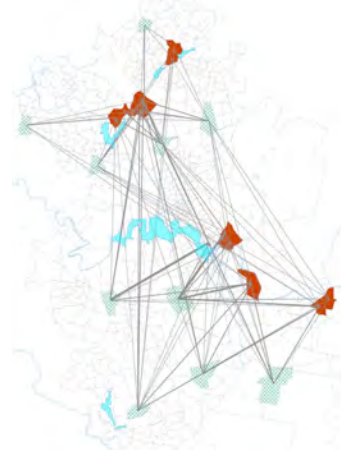
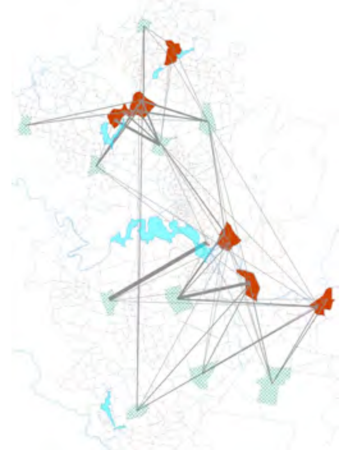
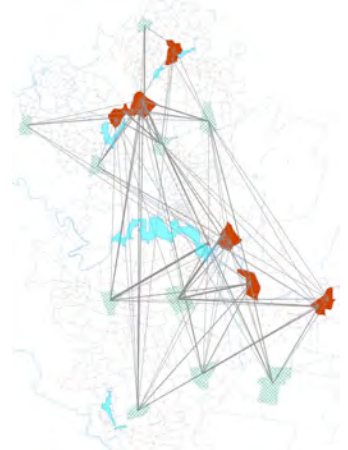
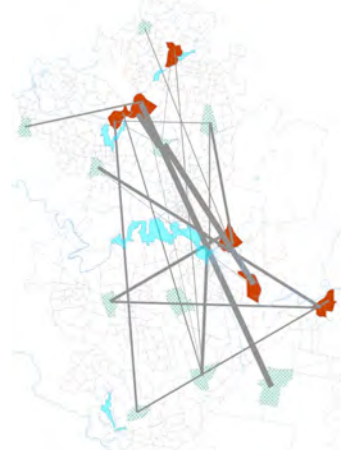
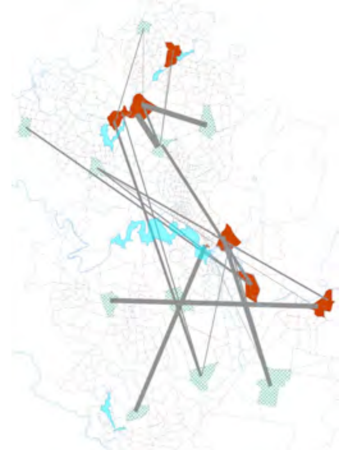
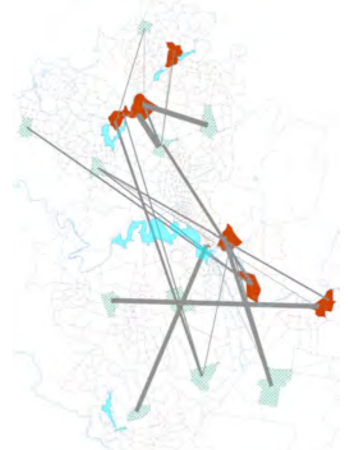


Figure 2: Average Travel Time per Evacuee



<table>
<tr><td colspan="3">Linear Programming Evacuation Trip Distribution Desire Lines</td></tr>
<tr><td>
Figure 3: Deterministic</td><td>
Figure 4: Proportional</td><td>
Figure 5: Stochastic</td></tr>
<tr><td colspan="3">Non-Linear Programming Evacuation Trip Distribution Desire Lines</td></tr>
<tr><td>
Figure 6: Deterministic</td><td>
Figure 7: Proportional</td><td>
Figure 8: Stochastic</td></tr>
<tr><td colspan="3">Evolutionary Computations Evacuation Trip Distribution Desire Lines</td></tr>
<tr><td>
Figure 9: Deterministic</td><td>
Figure 10: Proportional</td><td>
Figure 11: Stochastic</td></tr>
</table>

Geographical visualization shows the spatial distribution of the investigated evacuation models. Visualization might assist emergency managers in choosing which model (deterministic, proportional or stochastic) is operationally manageable. Less nested and simpler spatial distributions of the evacuation trips, especially during the flood disasters, might simplify the management and supervision of evacuation operations.

When comparing linear evacuation trip distributions, the deterministic and stochastic models have similar spatial distributions as shown in Figures 3 and 5, while the spatial distribution of the proportional model changes slightly, as shown in Figure 4. Similarly in the non-linear models, as depicted in Figures 6 and 8, the deterministic and stochastic models have the same spatial distribution, with nested and complicated patterns. However, substantial differences in the spatial distribution of evacuees' movements can be noticed between the proportional non-linear model (Figure 7) and the deterministic and stochastic non-linear models. However, the proportional and stochastic evolutionary computation models have similar spatial distributions as shown in Figures 10 and 11, while considerable changes in evacuees' spatial distributions have occurred in the deterministic evolutionary computation model, as depicted in Figure 9.

CONCLUSIONS

This paper identifies the potential for adapting the evacuation trip generation and distribution stages of the conventional transportation planning model for planning for riverine flood disaster evacuations. Three types of transportation problems (linear, non-linear and evolutionary computations) using three decision variable environments (certain-deterministic, certain-proportional, and uncertain-stochastic) were investigated. The outputs of the nine models have been analyzed descriptively and geographically. Descriptive statistical analysis of evacuee average travel time among deterministic, proportional and stochastic models shows that proportional models achieve better results than other linear, non-linear and evolutionary computation models. However, stochastic linear and non-linear models have deteriorated. In analyzing spatial distributions, all linear models vary only slightly between each other. The spatial distribution in the non-linear proportional model has a less complicated and less nested spatial distribution than the deterministic and stochastic non-linear models. Examining the evolutionary computation models, the proportional and stochastic models have similar spatial distributions, which are less complicated and less nested than the deterministic model. The reason that the linear models achieved the best results is that both the objective and constraint functions in this example are linear functions, which makes linear programming achieve a more optimal solution than non-linear and evolutionary computations. However, if one of these functions is non-linear, linear modelling would not be applicable.

Adaptation of an existing traditional strategic transport model for evacuation of flood disasters can be time-saving for local councils. The availability of prepackaged transportation problem software (such as, Solver in MS-Excel) assists significantly in adapting the transportation or Hitchcock problem for riverine flood disaster evacuation planning. Neither a superior computer nor special data handling are needed, making the method suitable for local councils to use. Future work on this project will consider constraints such as warning and evacuation times in order to integrate the proposed model with existing flood evacuation timeline modelling produced by the State Emergency Services (SES).

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