Development of a Geographic Information System for Riverine Flood Disaster Evacuation in Canberra, Australia: Trip Generation and Distribution Modelling

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Abstract

Given the importance of geographic information for riverine flood evacuations, a geographic information system (GIS) is a vital tool for supporting successful flood evacuation operations. This paper discusses the development of a GIS-based riverine flood evacuation model which used to model trip distributions between flooded areas and relocation shelters. As the ultimate goal of this research is to simulate, model, and optimise a planned evacuation, all components of evacuation time have been considered (e.g., travel time between flooded areas and relocation shelters, warning time for each flooded area, and the time needed for evacuation before these areas get inundated). As well, variation in population (static and dynamic population) within the flooded areas has been considered.

Keywords

Geographic Information System, Riverine Flooding, Evacuation, Trip generation, Static and Dynamic Population

Introduction

Floods in 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 (Paul, 2011). Yet, 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 flood disaster evacuation operations 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 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 Average Recurrence Interval (ARI) 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 by damage to the transportation network or increased traffic volumes created by evacuees, or inadequate relocation shelter locations or capacity can be planned and managed. In particular, safer evacuations are possible when the evacuation is pre-warned, and evacuation can therefore be used as a protective measure for riverine flood disasters.

In this paper, the Australian Capital Territory (ACT) as shown in Figure 1, the home of the nation's capital, Canberra, and the Queanbeyan region are used as a case study due to availability of the strategic transport planning model (STPM) and information about expected flooding events.

Figure 1: Study Area of ACT and Queanbeyan

GEOGRAPHIC INFORMATION SYSTEM AND FLOOD DISASTER EVACUATION OPERATIONS

Geographic Information Systems (GIS) are utilized in all phases of a disaster: planning, mitigation, preparedness, response, and recovery (Cutter, 2003). GIS applications in the mitigation and preparedness phases may prove to be most cost-effective for saving both lives and property (Pelman & Robinson, 2011). Some studies focus specifically on using GIS to support flood hazard risk analysis and management. For example, using GIS applications combined with remote sensing could assist in preparing flood hazard maps to reduce and mitigate a flood disaster's impacts (Abdel-Lattif & Sherief, 2012). Furthermore, Fuhrmann et al., (2005 p. 4) indicate that GIS capabilities are not limited to database queries and mapping. They can also provide a wide range of spatial analysis methods, such as navigation for emergency relief workers and responders, and buffering tools that outlining the hazards' areas. They can also assist in the estimation of the population at risk, an essential requirement for preparedness for and response to any disaster (Garb et al., 2007).

GIS-BASED RIVERINE FLOOD EVACUATION MODEL

The proposed GIS-based riverine flood evacuation model aims to estimate the evacuation travel time matrix between affected areas and disaster relocation shelters. This travel time will later be used as an objective function that needs to be minimised in an evacuation trip generation and distribution model. Hence, the requirements of developing a travel time model are illustrated in this paper in detail. Similar to any information system, the riverine flood evacuation information system consists of three main components (inputs, processing and outputs), as shown in Figure 2. The data and information that are required to build the riverine flood evacuation model include potential flood-affected areas, disaster relocation shelter locations, population distribution, traffic analysis zones (TAZ) and the road network. These data have been provided by the relevant ACT government agencies or their websites.

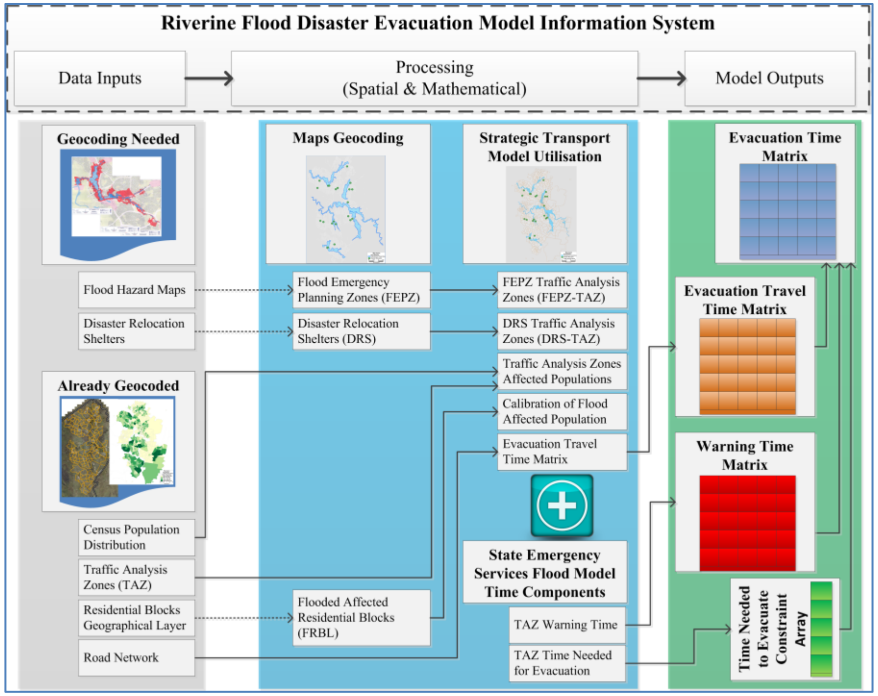


Figure 2: Riverine Flood Evacuation Model Information System

EVACUATION MODEL DATA INPUT PHASE

Geographical Data and Information needed for Flood Evacuation Modelling

Data relevant to riverine flood evacuation modelling were requested from ACT Government agencies. Some data were provided as scanned paper maps, such as flood hazard maps, flood emergency planning zones, and the locations of the 100 year ARI. Disaster relocation shelter locations were available in text file format.

Other data were provided in digital spatial format (shapefile), such as the road network or traffic analysis zones with related population data. The Australian Census 2011 Mesh Block geography files for ACT and Queanbeyan were also downloaded from the Australian Bureau of Statistics (ABS) website (ABS 2011a, b).

EVACUATION MODEL DATA PROCESSING PHASE

The flood emergency planning zones and the disaster relocation shelters are considered the origins and the destinations of the riverine flood evacuation model, respectively. During the model's processing phase, first, the data are georeferenced if necessary. We then converted the source and destination layers into traffic analysis zones, and estimated and calibrated flood-affected populations.

Georeferencing of Riverine Flood Emergency Planning Zones (FEPZ)

The ACT Government provides flood hazard maps through the ACTMapi website for Lake Burley Griffin as the 100 year ARI, as shown in Figure 3. However, the other ACT and Queanbeyan 100 year ARIs were only available as raster scans of paper maps as depicted in Figure 4 for the Ginninderra Creek Flood Emergency Response Map. In Queanbeyan (a neighbouring city in another state that is part of the Canberra metropolitan region), we used a 40m buffer zone in the Molonglo River flood areas to represent areas of potential flooding.

Ungeoreferenced raster data, such as scanned maps, do not include spatial reference information. Thus, in order to utilise these raster maps in conjunction with the other spatial data, these raster maps need to be aligned or georeferenced to a map coordinate system. All data are referenced to the Australian Map Grid 1966 (AMG66).

We used TransCAD software to process these rasters as follows:

- We georeferenced the scanned paper maps of ACT-Queanbeyan potential flooding using the "Imagery Registration Tool" (Caliper Corporation 2007, p. 695-697).
- We heads-up digitized the 100 year ARI to create Flood Emergency Planning Zones.

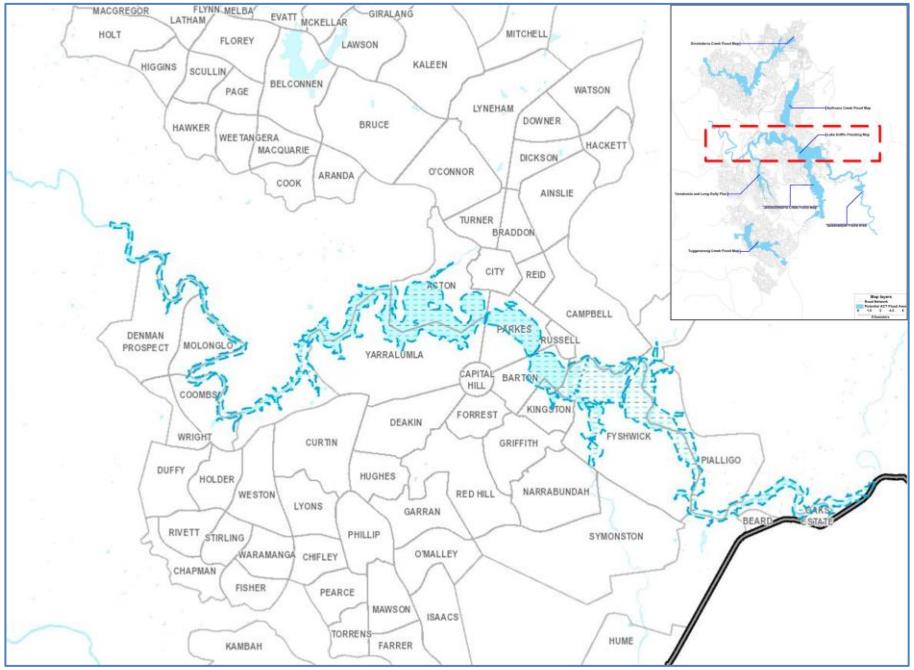


Figure 3: Lake Burley Griffin Flooding Areas

Source: ACTMapi Website

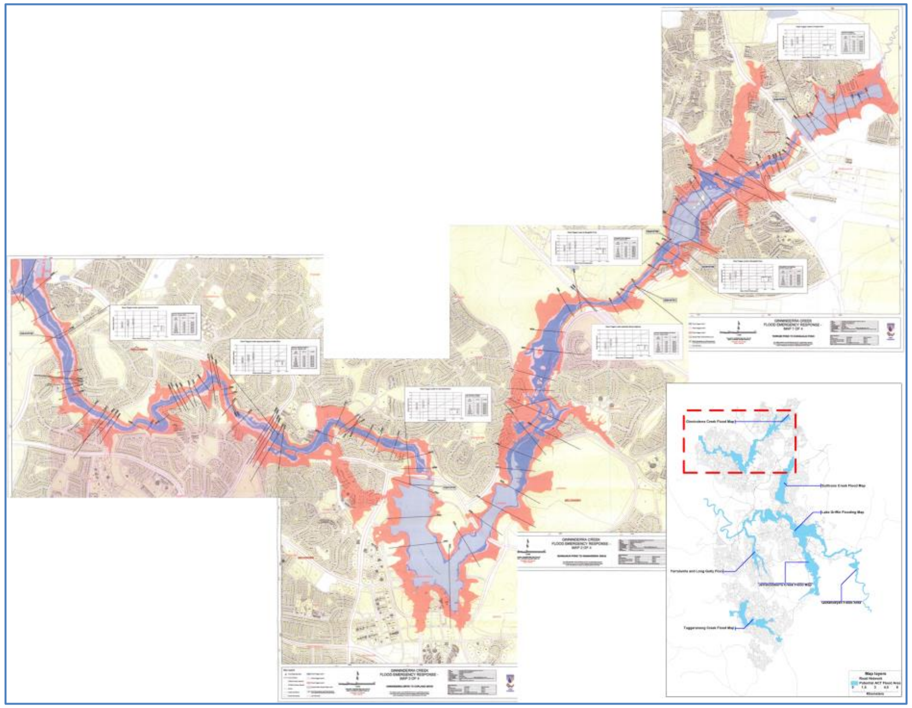


Figure 4: Example of Georeferenced Scanned Flood Extent Image (Ginninderra Creek Flood Emergency Response)

Geocoding of Disaster Relocation Shelters (DRSs)

The ACT Community Recovery Plan (2008) identifies the locations that can be used as DRSs. These locations were georeferenced using heads-up digitizing of their addresses using Google Maps.

Strategic Transportation Planning Model (STPM) Utilisation

We used the geographical capabilities of the ACT's STPM, implemented in TransCAD, to develop our model. While it would be possible to implement our process in another GIS package (e.g., MapInfo, ArcGIS), we used TransCAD because it is what the local council already uses, and it is therefore more likely to be actually used in practice for planning evacuation operations by the local council. We used the STPM to convert the FEPZs and DRSs into traffic analysis zones (TAZs). This allows the estimation of the flood-affected populations and extraction of the evacuation travel times from the STPM modeled congested travel times. Next, we describe the stages of this process.

Converting FEPZs and DRSs to Traffic Analysis Zones (TAZs)

The TAZ is the geographical unit that the STPM uses to distribute the produced and attracted trips between origin and destination TAZs. We used a spatial join (TransCAD's "Selecting by Location" tool) to convert FEPZs and DRSs into TAZs to determine the flood-affected TAZs as shown in Figure 5 (Harlow, et al. 2004, p. 410). This tool creates two selection sets from the TAZ geographical layer as follows:

1. FEPZs-TAZ selection set: selecting the TAZs that are geographically located inside and touching the FEPZs.
2. DRSs-TAZ selection set: selecting the TAZs that geographically contain the DRSs.

Figure 6 shows the resulting FEPZ-TAZs and DRS-TAZs, depicted in red and green TAZs, respectively. A FEPZ-TAZ that overlaps with a DRS-TAZ indicates a shelter located in the potential flood zone. While residents may still try to drive to the closest shelter (whether or not it is safe), and police and other evacuation authorities would need to communicate to the public that particular shelters are unavailable, official planning for evacuations should not include shelter locations that place residents at further risk. Therefore, the overlapping DRS-TAZs are excluded from evacuation trip destinations as unsafe relocation shelters. It would be possible to use the model in its trip distribution phase, to see the potential effects on network congestion from residents evacuating to the wrong place (the closest shelter, even if it is at risk).

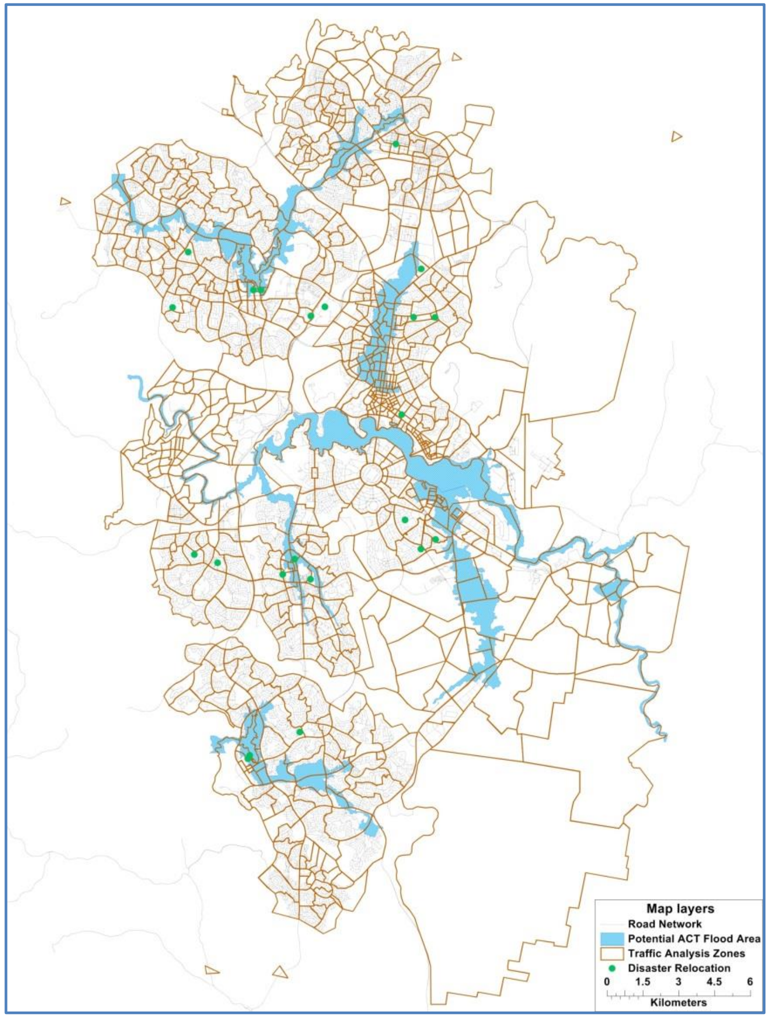


Figure 5: Flood Emergency Planning Zones (FEPZs), Disaster Relocation Shelters (DRSs) and Traffic Analysis Zones (TAZs)

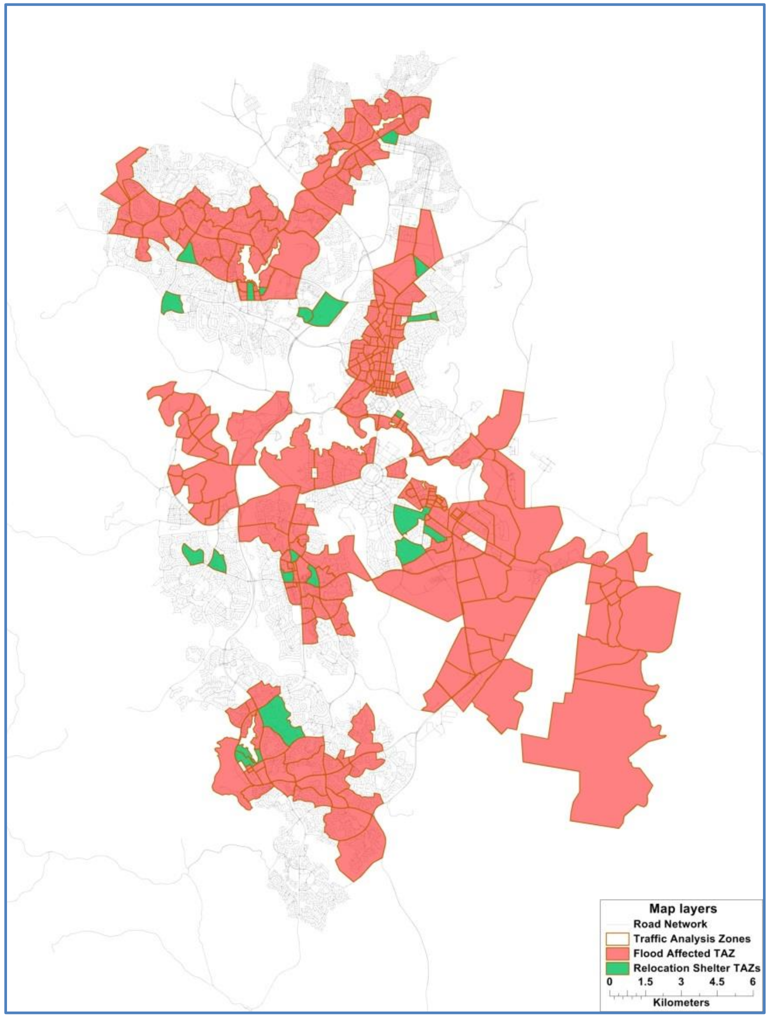


Figure 6: Flood Emergency Planning Zones-TAZ and Disaster Relocation Shelters-TAZ

Estimating Flood-Affected Static and Dynamic Populations for Flood-Affected TAZs

The Australian Bureau of Statistics (ABS) conducts residential population and total dwelling counts in Australia every five years, aggregating to geographic regions containing 30 to 60 dwellings, called Mesh Blocks (MB). Usually urban MBs are smaller than the TAZ. Therefore, using MB populations gives a more accurate estimation of flood-affected populations than the TAZ population data. Figure 7 shows the MB populations in 2011.

Because natural disasters may occur at any time, the populations at risk of experiencing a disaster might vary depending on when it occurs. Parrott and Stutz's method (1991) utilises the outputs of an existing STPM to estimate the dynamic population. This method was used to calculate the affected dynamic population per each TAZ based on the following formula:

$$\mathrm{Pop}_i^d = \sum \mathrm{CFP}_i^s + \left[(\mathrm{A}_i - \mathrm{P}_i) \times \frac{\sum \mathrm{CFP}_i^s}{\sum \mathrm{CP}_i^s}\right]$$

Where:

Pop_i^d: is the cumulative diurnal/dynamic population of TAZ i,

$\sum \mathrm{CP}_i^s$: is the census MB population of TAZ i (as a static population),

$\sum \mathrm{CFP}_i^s$: is the total census MB flood-affected population located in TAZ i, as an apportioned percentage of the TAZ i's area,

Ai: is the cumulative attracted trips to TAZ i,

Pi: is the cumulative produced trips from TAZ i,

The comparisons between static and dynamic populations, accounting for this travel, are depicted in Figure 8 and Figure 9, respectively.

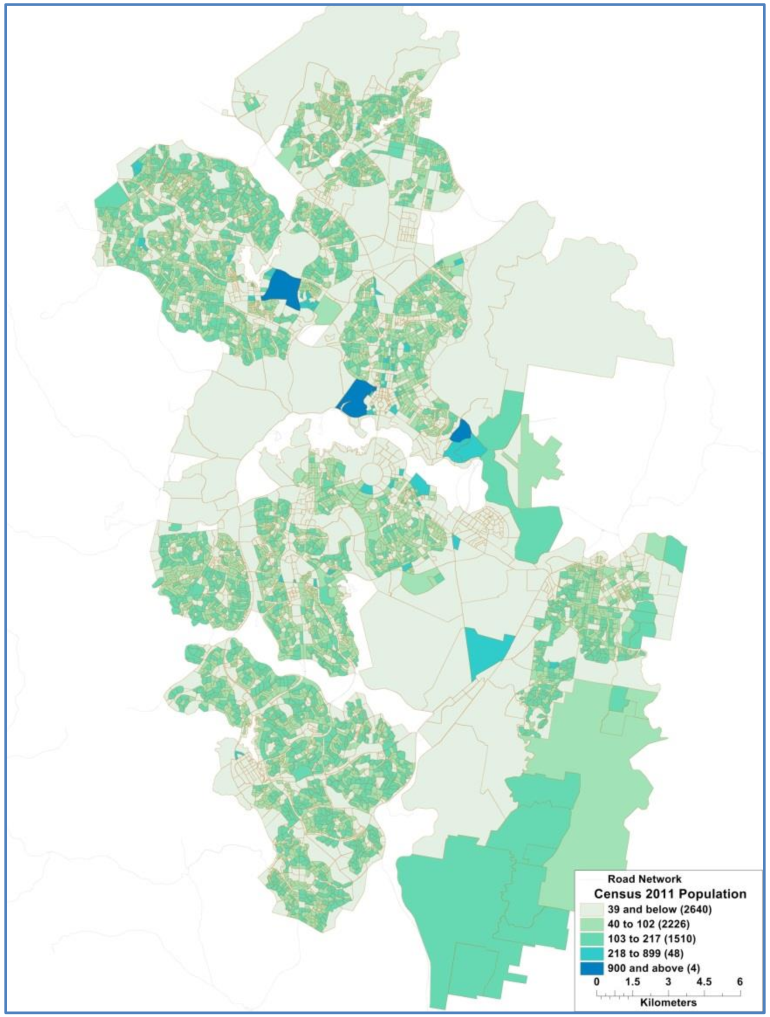


Figure 7: 2011 Mesh Block Population Counts for the ACT and Queanbeyan

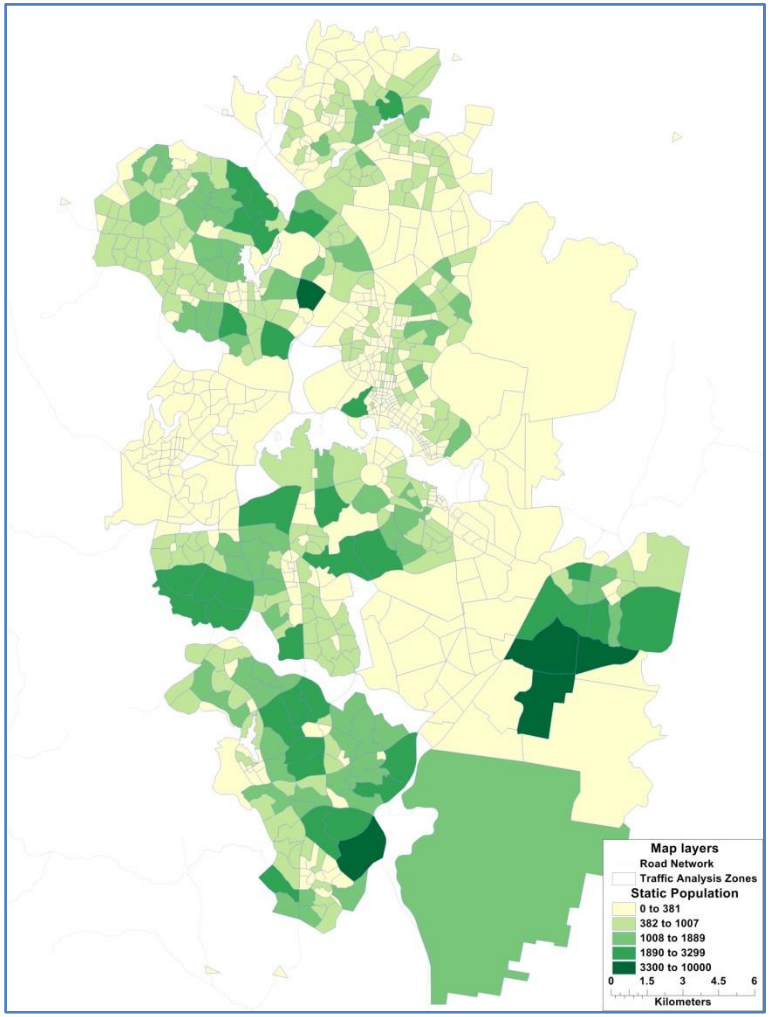


Figure 8: ACT - Queanbeyan 2011 Static Population Distribution 7:00 AM

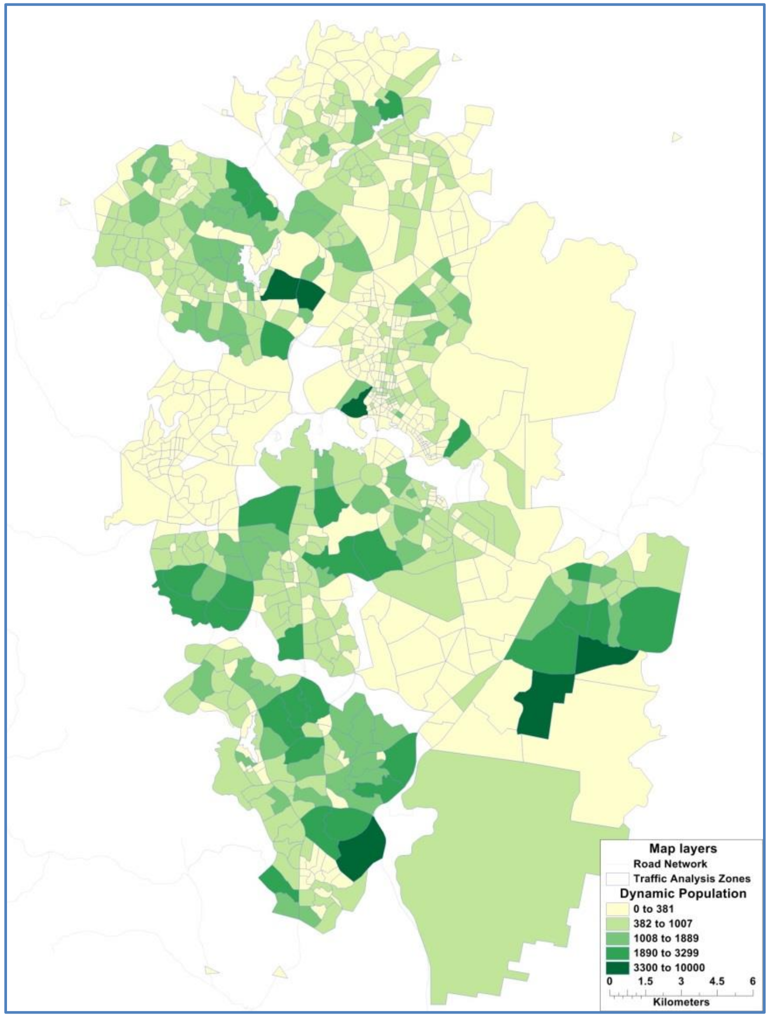
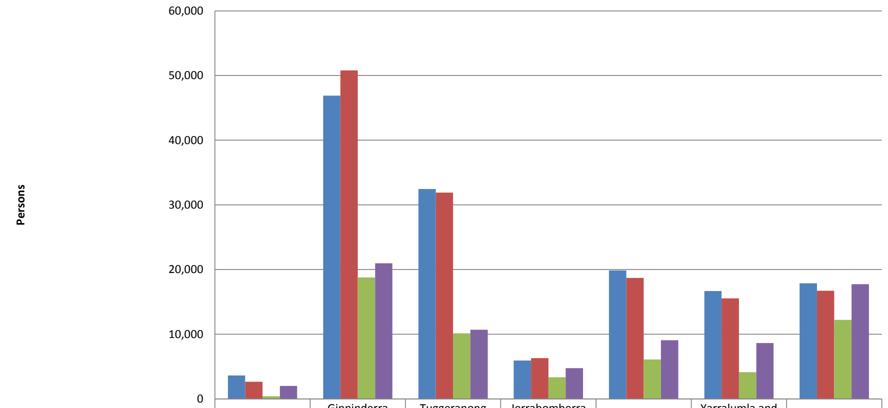


Figure 9: ACT - Queanbeyan 2011 Dynamic Population Distribution 9:00 AM

Estimating the Riverine Flood-Affected Dynamic Population

FEPZ-TAZs allow the estimation of populations at flood risk: i.e. the populations that need to be evacuated. The total maximum static affected population of flood-affected areas of ACT - Queanbeyan reaches 55,164 people, while the total maximum dynamic population reaches 73,962 people, a difference of 18,798 extra people, as summarised in Figure 10. Therefore, without estimating the dynamic population, the evacuation plan might under-allocate resources. Figure 11 and Figure 12 compare the locations of estimated static and dynamic populations in flood-affected TAZs.



	Lake Griffin	Ginninderra Creek	Tuggeranong Creek	Jerrabomberra Creek	Queanbeyan	Yarralumla and Long Gully	Sullivans Creek
TAZ Population	3627	46892	32456	5953	19876	16685	17896
2011 Census Population	2666	50800	31912	6310	18706	15551	16730
Flood Affected Census Population	420	18781	10148	3348	6106	4139	12222
Flood Affected Dynamic Population	2023	20971	10712	4778	9078	8644	17757

Figure 10: ACT and Queanbeyan Potential Flooded Areas Estimated Static and Dynamic Populations by Riverine Area

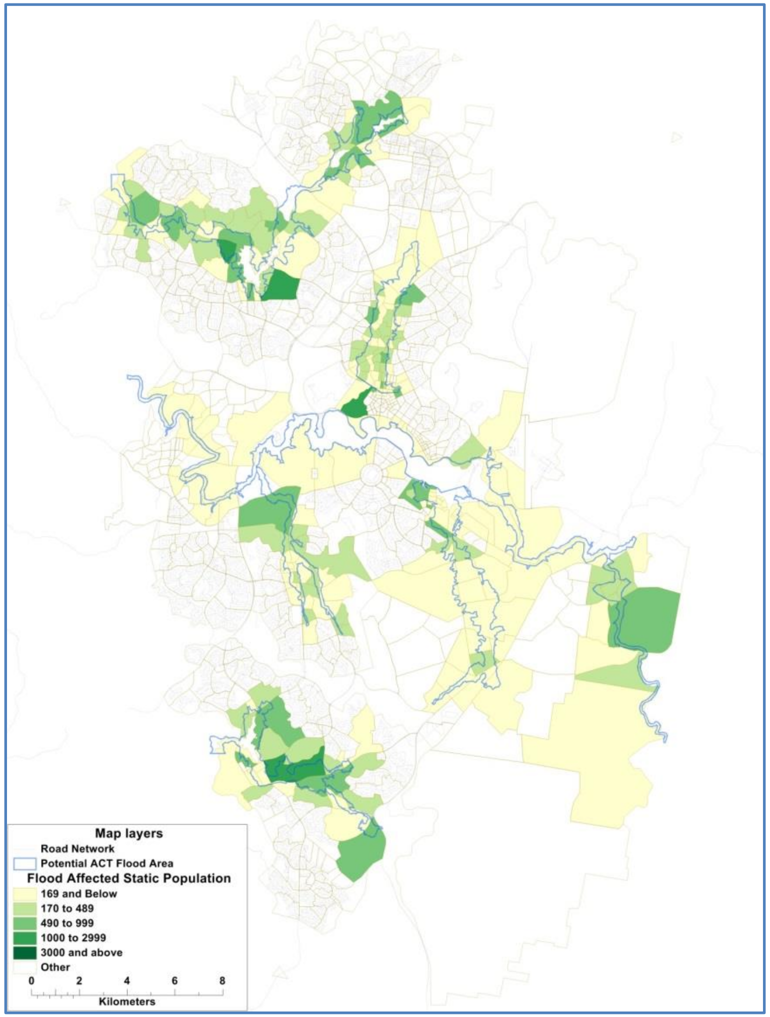


Figure 11: Flood-affected FEPZ-TAZs Static Population Distribution 7:00 AM

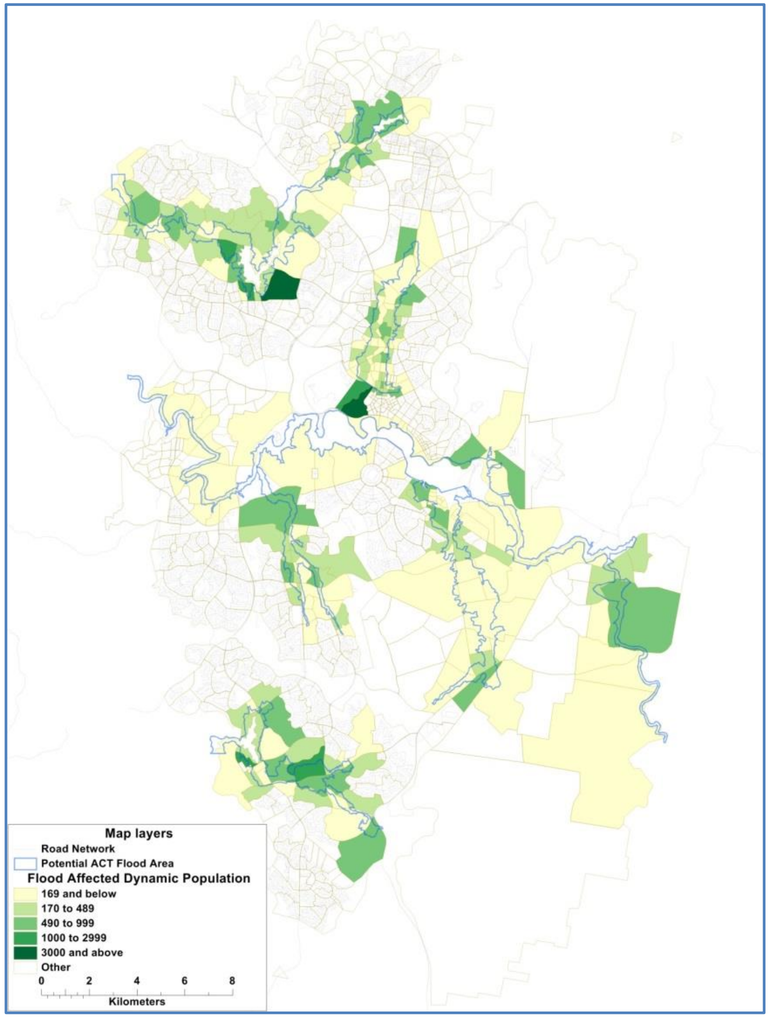


Figure 12: Flood-affected FEPZ-TAZs Dynamic Population Distribution 9:00 AM

Method for Calibration of Estimated Static Flood-Affected Populations

Because residential blocks are smaller than the census MBs and they therefore fit the FEPZ boundary better, a residential block-based method was also used to estimate the flood-affected population to verify the estimated flood static population based on the census MBs for the same FEPZ.

Australian Bureau of Statistics (2012) indicates in the fact sheet from the 2011 census that the household size of ACT is 2.6 people per household.

Figure 13 shows the ACT residential block layer that was used to estimate the flood-affected population. The spatial join tool was used to identify flood-affected residential blocks that are located inside the MB layer.

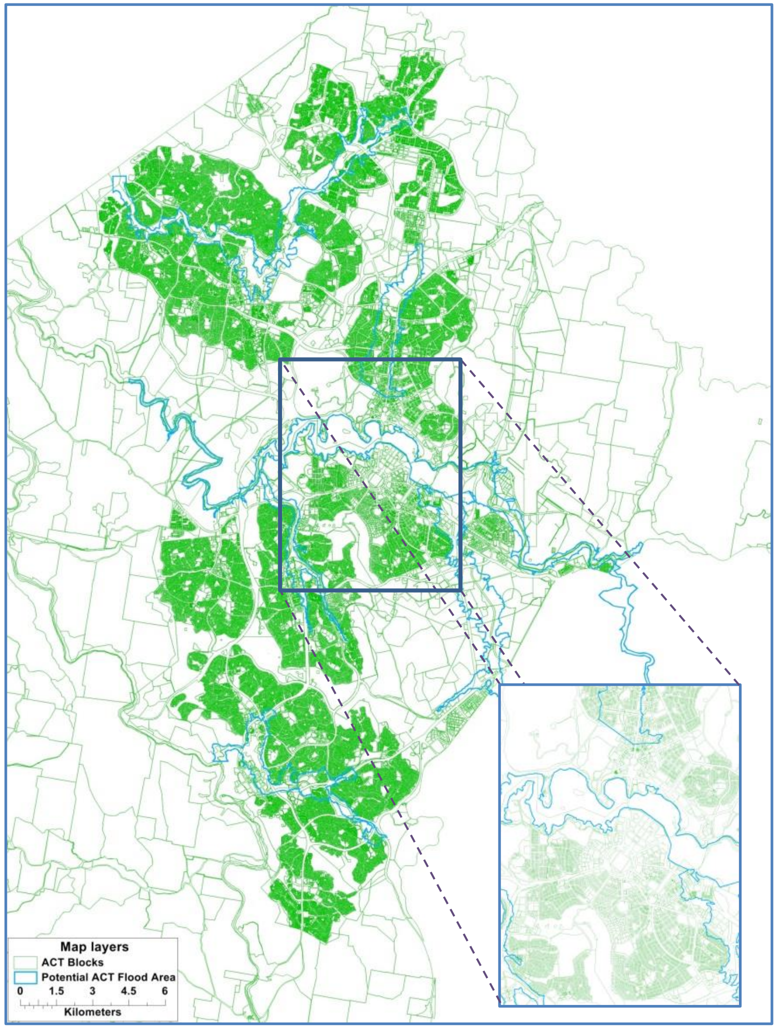


Figure 13: ACT Blocks Geographical Layer

We used both a statistical correlation test and a two sample t-test for equality of population means to examine the statistical relationships between the means of the two estimated flood-affected populations at different scales. As shown in Figure 14, there is significant statistical correlation (R^2 = 0.93) between the two population estimates for the six FEPZs. The t-test shows they are significantly dependent at a 95% confidence level (t = 1.18, p = 0.15). Hence at the FEPZ scale, both methods produce similar estimates of flood-affected population.

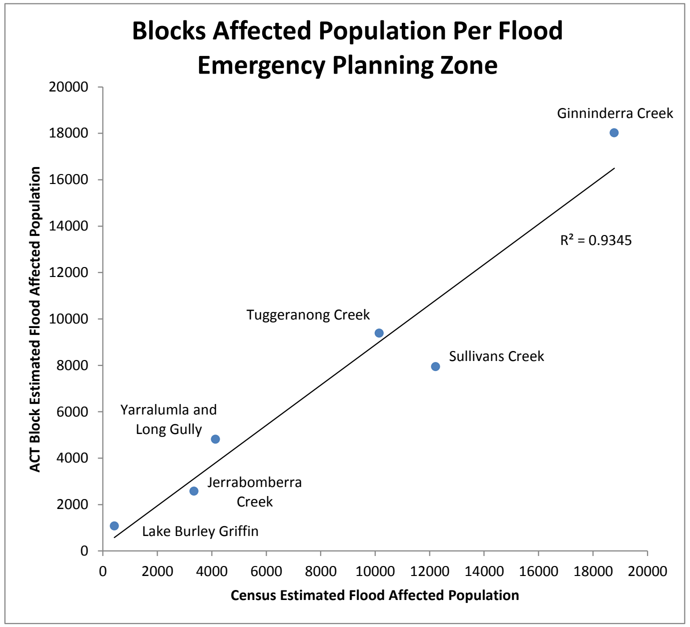


Figure 14: ACT Census Mesh Block and Residential Block Affected FEPZ Population

At the disaggregated level of TAZs, the correlation test between the two sets of projected populations showed only moderate correlation (R^2 = 0.42). The t-test for shows they are not significantly dependent at a 95% confidence level (t = 1.48, .p = 0.07).

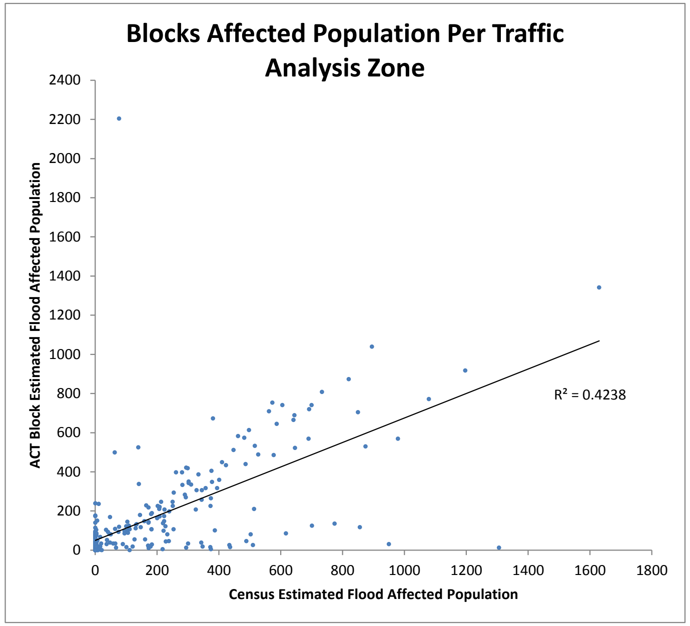


Figure 15: Residential Block and Census Mesh Block Affected TAZ Populations

While the census MB population is overestimating the population at risk (Figure 15) for many TAZs, likely because the geographical fit between residential blocks and TAZ boundaries is better than that of census MBs and TAZ boundaries, MB population counts are available nationwide, while residential block population information may not be. Moreover, from an evacuation standpoint, it would be better to slightly overestimate the population-at-risk than underestimate it.

EVACUATION MODEL OUTPUT PHASE

A final step produces the evacuation travel time matrix, and incorporates State Emergency Services (SES) information in the warning time matrix. These two matrices are then combined to generate the main output of the model, the riverine flood evacuation time matrix that needs to be minimised or optimized when producing an operational evacuation plan.

Extracting the Evacuation Travel Time Matrix

The riverine flood evacuation congested travel time matrix was extracted from STPM travel time matrix, resulting in 277 (of 798) origins (FEPZ-TAZs) and 22 (of 298) destination zones (DRS-TAZs). Table 1 compares statistical indicators for the STPM congested travel time matrix and the riverine flood evacuation model.

Model	No. of Origins	No. of Destinations	Average Travel Time Minutes	Maximum Travel Time Minutes
ACT-Queanbeyan STPM	798	798	17	103
Riverine Flood Evacuation Model	277	14	14.8	39

Table 1: Travel Time Matrices Statistical Indicators

SES Flood Evacuation Model Time Component Integration

We also integrated the SES timeline for flood evacuation operations into our model, to ensure that our model could be used in actual operational planning. This is done by incorporating the time needed for evacuation (En) for each flood-affected area as a constraint that needs to be satisfied. The warning time (W) for each flood-affected area is also a variable in the objective function to optimise the evacuation operation. Converting the constant warning time per each evacuation flood area to a variable that depends on the evacuation destinations might reduce potential transport network congestion by avoiding starting evacuation operations at the same time in each flood-affected zone. Including En and W in the evacuation operations planning model consists of two steps: 1) calculating the minimised evacuation travel time TP, considering the time needed for evacuation for each flood-affected area En_i as a constraint that the optimised evacuation travel time should not exceed; 2) calculating the variable warning time for each evacuation trip destination by converting the constant flood-affected area W_i to W_{ij}.

Calculating the Total Evacuation Travel Time Considering E_{ni} as a constraint

$$\text{Minimise (TP)} = \sum_{i=1}^{i}\sum_{j=1}^{j} TT_{ij} \times AP_{ij}$$

Subject to the constraints:

$$\sum_{j} AP_{ij} = AP_{i}$$

$$\sum_{i} AP_{ij} <= RS_{j}$$

$$\sum_{j} TT_{ij} <= En_{i}$$

$$AP_{ij} \geq 0$$

Where:

TP : is the total evacuation travel time.

TTij : is the travel time between flood-affected area i and relocation shelter j

APij : is the affected population that needs to be evacuated from source zone i to destination zone j,

APi : is the constraint of evacuation of all affected population from flood-affected zone i,

RSj : is the constraint of not exceeding the capacity of the relocation shelter in zone j,

En_i : is the constraint of not exceeding the total time needed (provided by the SES model) to evacuate the flood-affected area i.

Calculating the variable warning time for each evacuation trip destination

$$W_{ij} = W_{i} \times \frac{MTT_{ij}}{\text{Max } MTT_{i}}$$

Where:

Wij : is the warning time between a flood-affected area i and relocation shelter j

Wi : is the provided SES constant warning for zone i,

MTTij : is the model travel time between flood-affected area i and relocation shelter j

Max MTTi : is the maximum evacuation model travel time of zone i,

Incorporating the SES model time as a constraint avoids the situation where the transport network closes before the evacuation is completed.

Discussion and Conclusion

This paper describes the development of a GIS for the evacuation operations planning for riverine flood disaster scenarios for the ACT and neighboring Queanbeyan City. It demonstrates how to deal with different sources of geographical and demographic data to estimate the potentially affected riverine flood areas and populations. As well, it estimates the evacuation times including the travel time between flood-affected areas and relocation shelters, warning times, and time needed for evacuation. A method was developed to estimate the dynamic potential affected population, using both the static population of affected areas and the produced and attracted trips, which are provided by the government's strategic transport model. This MB based estimation method was cross-checked using larger-scale data (residential blocks). While the MB based method has the advantage that MB population counts are available countrywide, they systematically overestimate the population at risk. While the residential block estimates are spatially more precise, they rely on estimates of household size, which are only measured in the five-yearly census. The two population estimation methods provide more similar population estimates for larger regions than they do for smaller regions. The extracted evacuation times, the potential dynamic population and the relocation shelters' capacities can now be used as transportation-problem variables (Ford & Fulkerson 1956) to optimize the evacuation trip distribution between riverine flood-affected areas and the relocation shelters, leading to a final evacuation operation plan.

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