A spatial analysis approach to evacuation management: shelter assignment and routing

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Abstract

Evacuation planning requires an integrated analysis of heterogeneous spatial datasets including population, road network and facilities. It is a complex and challenging task to delineate evacuation circumstances and make reasonable connections among the datasets which evacuation management of emergency situations will be based on. An evacuation management system requires an easy configuration by evacuation managers who do not necessarily have full knowledge of Geographic Information Systems (GIS) but need to understand the situation promptly and provide decisive instructions that can be fulfilled only when they can manage datasets and develop new workflows in various scenarios. A spatial analysis platform provides toolkits for spatial data acquisition and processing, analysis, and visualisation from/to online open sources. Such toolkits built in typical GIS software are utilised in this paper to show the feasibility of enabling users to manage spatial data and customise their analysis by combining common data analysis tools to meet their requirements in evacuation planning. Case studies are provided to demonstrate the usability of these toolkits in Brisbane flood evacuation management.

1 Introduction

Natural hazards are damaging events that may potentially cause casualties, loss or damage of assets, social and economic disruption or environmental degradation. They can be single, sequential or combined in their origins and effects, and different in terms of location, magnitude/intensity, frequency and probability (Alexander, 1991; Thywissen, 2006). Although methods exist for assessing the risks associated with natural hazards and control structures, less effort has been devoted to developing response activities such as evacuation (Johnstone et al., 2009). Evacuation describes the withdraw actions of people from a specific area because of a real or anticipated threat or hazard (Vogt et al., 1992). It is a positive response to disasters and also one of the most beneficial ways to reduce further damage.

Natural hazards threat thousands of lives and a large amount of valuable assets each year. As Australian cities expand due to the increase in population, buildings and infrastructure, disaster events in Australia tend to be more costly (Crompton et al., 2008). Moreover, global climate change has been predicted to be a significant impact on

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sea level rise and severe storms in Australia (Middelmann, 2007), which increase the possibility of substantial losses of lives and properties. To minimise the negative consequences associated with these potential disasters, policy administrators need to ensure that appropriate emergency plans are in place.

Queensland has a long tradition in dealing with floods. Current work includes academic and government's efforts being conducted in understanding the physical parameters that describe floods' specific characteristics. These parameters determine floods' starts and spreads. Based on the parameters, flood simulation models are built to capture the flood behaviour over the floodplain (Gouldby et al., 2008; Van Der Knijff et al., 2008). More recent researches have been conducted to understand the causes, impacts and lessons learned from severe floods happened in Brisbane (Carter, 2012; van den Honert et al., 2011).

With all the preparation in flood behaviour and impact study, it is time to further investigate into the strategies for evacuation management and address the need for evacuation maps from previous Australian researches. Making the evacuation strategy more convincing and understandable is raised as one of the concerns when less than ten percent of the population living in the flood-prone communities in Grafton responded to the official evacuation warnings (Pfister, 2002). However, more recently, an evaluation of the usefulness of tsunami evacuation maps which specifies inundated zones and potential exits/vertical evacuation buildings was undertaken by interviewing 500 permanent residents, and the results show that it can benefit not only evacuees but also emergency service officers (Dall'Osso et al., 2010).

From the emergency manager's perspective, it is beneficial to preserve an evacuation map showing the arrangement of accommodating potential evacuees. Also, including the official evacuation buildings into the analysis can help evaluate the spatial coverage and effectiveness of existing shelters. To achieve these aims, evacuation managers need to have the skills of acquiring, processing, analysing and visualizing spatial data even though they are not required to understand Geographic Information Systems (GIS) fully. In this case, powerful toolkits for manipulating datasets in GIS software are required.

Spatial analysis is typically defined as a subset of analytic techniques whose results depend on the geographical frame, or will change if the frame changes, or if objects are repositioned within it (Goodchild et al., 1999). These analytic methods for processing data have the objective of solving some scientific or decision-making problem based on the understanding of spatial relationships and patterns in our world. GIS was initially developed as tools for the storage, retrieval and display of geographic information. Capabilities for the geographic analysis of spatial data were either poor or lacking in these early systems (Fotheringham et al., 1994). Revolution in spatial data representation and statistical methodology provide the opportunity for spatial data analysis and GIS coming into contact (Goodchild et al., 2004). Nowadays, at the very heart of GIS technology, spatial analysis is addressing the problems ranging from computational analysis of geographic patterns to finding optimum routes, site selection, and advanced predictive modelling. GIS software is a powerful platform for integrating the databases and hosting the different computational models (Ahola et al., 2007; Church et al., 2000; Taylor et al., 2010). It provides numerous means to process and visualize spatial data. The input for a GIS platform can be a single or combination of data on physical characteristics, demographics and land use, infrastructure and facilities. The quality of output information is largely dependent on the comprehensiveness and accuracy of input datasets.

This paper takes a first step in a spatial analysis approach to assist evacuation management especially in relation to the routing and shelter assignment process. It aims to address three main problems: (1) what is the nearest achievable shelter for a given community in the inundation zone during a flood evacuation? And what are the corresponding detailed instructions for evacuating by car? (2) What is the possible congestion condition given residential locations? (3) How do the existing shelters serve the evacuees? And what is the potential location for new shelters to achieve better supply coverage? To respond to these questions, a case study in 2011 Brisbane River flood scenario is examined. There are 1,186 mesh blocks along the river with a population of around 100,000. This case will be examined through two open-source extensions in ArcGIS, which assist to analyse the situation with real network distances and floodwater impacts on such an inundation emergency.

This paper describes a spatial analysis method for evacuation management in Brisbane River inundation scenario using GIS software. The first section of the paper provides an introduction of floods in Australia, followed by the background of shelter assignment. The next section presents a method for dataset collection and for decision-making in shelter assignment and evacuation routing, including a case study for Brisbane flood. The third section provides an analysis of the results. The paper concludes with a discussion of the applicable scenarios and limitations of this approach.

2 Floods in Australia

Floods occur when water covers land which is normally dry. There are two categories of floods in Australia: localised flash flooding as a result of thunderstorms and more widespread flooding following heavy rain over the catchment areas of river systems. Seasonal flooding occurs in Northern Australia regularly. Since 1990, historic major flood events happened in the states of Queensland, New South Wales, Victoria and Tasmania. Recent floods with high magnitude recurred in Queensland (2011), Victoria (2011) and Queensland and New South Wales (2013). Among these three floods, the 2011 Queensland flooding caused the severest damage; it affected over 200,000 people across the state and leaded to an estimated reduction in Australia's gross domestic product (GDP) at about $30 billion.

Town councils and shires have started mapping the 100-year flood areas. However, they still leave the evacuation-related options to residents. People are assumed to know their vulnerability and take the responsibility for their own information acquisition and evacuation preparation (Astill et al., 2014; Bohensky et al., 2014). Therefore, in case residents do not seek evacuation information actively, greater operations from local governments to assist communities exposed to flood threats are required.

Official shelters are places (e.g. showgrounds, churches, clubs…) that are authorized to provide accommodation in an emergency. In a flood scenario, shelters can be located near/in the inundation boundary; yet they have higher elevations to avoid damage. In an inundation emergency, sheltering in vertical evacuation buildings is more feasible and efficient than escaping the whole area during an evacuation (Mas et al., 2013). One main objective of evacuation planning is to match the urgent needs with appropriate resources in the most efficient and timely manner (Alexander, 2005). Shelter assignment in this context refers to giving instructions for evacuees on which shelter to choose, and detailed routes they should take to reach destinations. Assigning evacuees with appropriate shelters is one of the three most discussed topics lying in the approach of sheltering as an evacuation strategy; the other two are evaluating capacity of existing shelters and proposing locations for new shelters (Lämmel, 2011). In Australia, emergency management places reliance on individuals to get alerted and informed before they take self-help approach to protect themselves against risks from natural hazards (Astill et al., 2014; Bohensky et al., 2014; EMA, 2004). However, it might not be efficient to rely on people's initiatives to be aware of their situations, and choose their own shelters and routes in the evacuation process; as this could potentially result in overcrowded shelters and/or severe traffic disruptions. In order to provide residents with information on where and how to escape, shelter assignment strategies need to be fixed early during the evacuation or even before the disasters' occurrences, especially for the scenarios in which the dangerous area can be largely defined according to previous events (e.g. floods).

3 Methodology

3.1 Case study in Brisbane

Brisbane is the capital city of Queensland; it locates in south east of the state and has a population of around 2,100,000 inhabitants. Brisbane River, flowing across the city from west to east, is the longest river in Queensland. The river catchment has an area of around 13,570 km^2, with the Great Dividing Range as the western boundary and various smaller coastal ranges to the north. Most part of the catchment is covered by forestry and grazing land while Brisbane and Ipswich metropolitan areas are also within the range. Flood inundation in this river has been observed since 1823, followed by extensive floods happening during the years before 1990. The second largest flood since the 20th century occurred in 2011 (Figure 1).

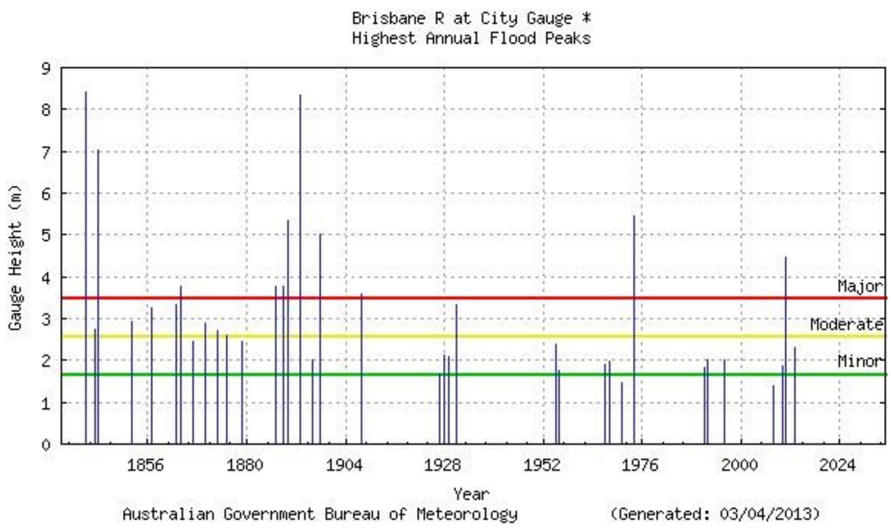


Figure 1: Floods in Brisbane (BoM, 2013)

During the 2011 flood event, Brisbane city experienced a major flood (defined as having a gauge height of 3.5 m or higher) from 10:00 am on 12th January until 6:00 pm on 13th January, accounting for a period of 32 hours. The flood peaked at 5:00 pm on 12th and again at 3:00 am on 13th with a gauge height of 4.25 m and 4.46 m respectively. As a result, in metropolitan Brisbane, over 15,000 properties were inundated and approximately 3,600 households evacuated (van den Honert et al., 2011).

Flood lines which descript the flood extent in years 1974 and 2011 are available from Queensland government. A comparison of these two flood boundaries shows that they are very similar in most areas of Brisbane city (van den Honert et al., 2011). Therefore, although the Annual Return Interval of flooding is uncertain, the boundary of inundation is largely predictable. In this paper, a case study is conducted. The study area covers the majority of Brisbane (north, west, inner city, south and part of Brisbane east), and the affected area is based on 2011 flood lines (Figure 2).

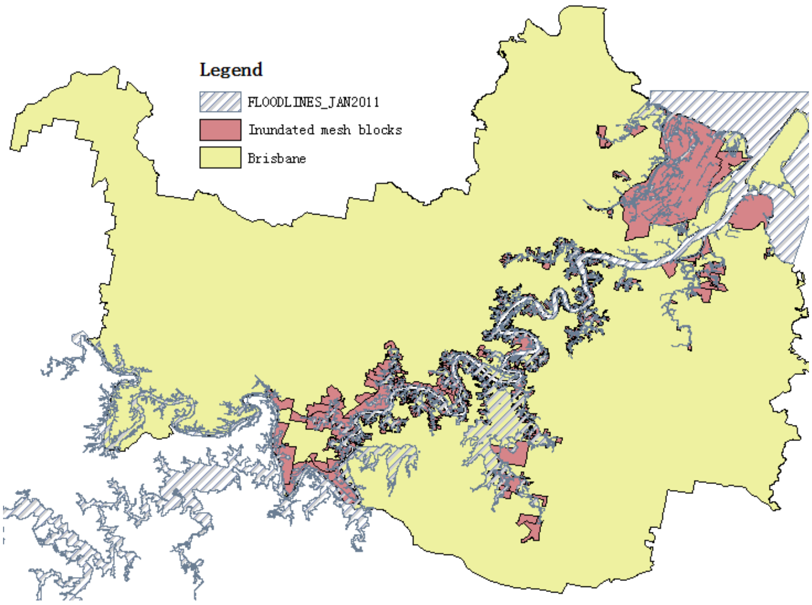


Figure 2: 2011 Brisbane flood lines and affected mesh blocks

3.2 Dataset collection and scenario assumption

Datasets (Table 1) have been collected and pre-processed to conduct a simple analysis to generate shelter assignment and routing instructions. Flood extent of 2011 event is downloaded from Queensland Government public database. Mesh block (the smallest census unit) boundaries are acquired from Australian Bureau of Statistics (ABS). Road networks covering the whole Brisbane city can be exported from open data source such as Open Street Map. In particular, five types of roads: trunk, motorway, primary road, secondary road and tertiary are extracted because of people's preference in choosing familiar, wider streets for evacuation (Tomsen et al., 2014). One evacuation centre can be identified from a news report on 11th January 2011. On 12th January, another news report, with the title "More evacuation centres set up", delivered the massage of setting up five more evacuation centres. Therefore, altogether six shelters are considered in this analysis.

Table 1: Datasets participating in the analysis and their sources

Datasets	Sources
2011 QLD floodlines	Queensland (QLD) Government
Road network for Brisbane city	Open Street Map (OSM)
Official shelters	News report during the event
2011 QLD mesh blocks extent	Australian Bureau of Statistics (ABS)
2011 Australian mesh blocks census counts	Australian Bureau of Statistics (ABS)

Flood lines and mesh block files are integrated to generate locations that are affected by floodwater. There were 100,649 people residing in 1,186 affected mesh blocks, which were confirmed by the news report that "100,000 customers are expected to lose electricity" on 12th January, 2011 (first flood peak). Apparently, six shelters cannot accommodate all those people for evacuation. In reality, most residents experienced low flood inundation and they chose stay-in-place until the water decreased; a good portion of evacuees sought accommodation from family or friends; others turned to official evacuation buildings. Evacuees were approximately 3,600 households in metropolitan Brisbane, which is expected to be more than 8,000 people according to the average household size (namely 2.3 persons per household) in 2011 census data for Brisbane inner city. However, their distribution can be across the 1,186 affected mesh blocks; therefore, shelter assignment analysis within this area is performed.

Prior to developing the shelter assignment strategy for this study, several assumptions had to be made for the emergency scenarios. Firstly, it was assumed that evacuees are distributed across all the inundation areas. Secondly, the whole routing strategy was car-based, with an evacuation speed of 30 km/h (Mas et al., 2013). Thirdly, each evacuee moves to its closest shelter, using the shortest possible route on the road network (this is a feasible choice in a small community well-known by its inhabitants). Lastly, we chose 30 minutes as the maximum time that evacuees would be willing to travel to shelters by car.

3.3 Analysis approach in GIS software

This case study is conducted under two criteria. The first criterion is that the approach is based on real network distances in place of straight-line distances. Therefore, more realistic travel time is captured. The second criterion is that the bridges across Brisbane River are assumed to be unusable or too risky to use during an evacuation; shortest paths passing these bridges are not accounted as solutions.

This analysis is conducted using Network Analyst built in ArcGIS and Urban Network Analysis toolbox developed by the City Form Lab (Sevtsuk et al., 2012; Sevtsuk et al., 2013). Network Analyst extension aims at creating, editing and analysing network datasets. It provides eight solvers to address routing related problems. Four solvers are used in this analysis: route, nearest facility, origin-destination (OD) cost matrix and service area. Service area solver returns polygons which show the service areas generated according to specified search radius or given cost limits. It stores the geometry of the road network into a triangulated irregular network (TIN) data structure. The distance along the road line serves as the height of the locations inside the TIN if the road is usable; otherwise the height is assigned a much larger value. Dijkstra's algorithm (Dijkstra, 1959) is applied to calculate the shortest network distance. The service area polygons are formed by carving out regions covering areas in between the specified break values. Optionally, an origin–destination cost matrix for evacuation from the resident locations to each shelter can be calculated. The results of this matrix can be used to identify residential areas that will be serviced by each shelter within a given drive time.

Urban Network Analysis toolbox contains two sets of tools: centrality tool and redundancy tool. The centrality tool is designed for studying the spatial configurations of cities, and their related social, economic, and environmental processes (Sevtsuk et al., 2013). While the redundancy tool calculates second shortest paths, and the redundant value is to be set by the users. Both of the nearest facility solver in the Network Analyst toolbox and the centrality tool in the Urban Network Analysis toolbox can offer solution for searching the nearest buildings within a given distance. The later one allows weights to be assigned to the destinations, which changes destinations' attractiveness to the origins. However, in this analysis, the weight is difficult to quantify because there is a lack of data describing the capacity and condition of shelters. The centrality tool also offers a "Betweenness" solver. The "Betweenness" of a building is defined as the fraction of shortest paths between pairs of other buildings in the network that pass by building i (Freeman, 1979); the formula is as follows:

$$Betweenness[i]^r = \sum_{j,k \in G-\{i\},\ d[j,k] \leq r} \frac{n_{jk}[i]}{n_{jk}} * w[j]$$

Where

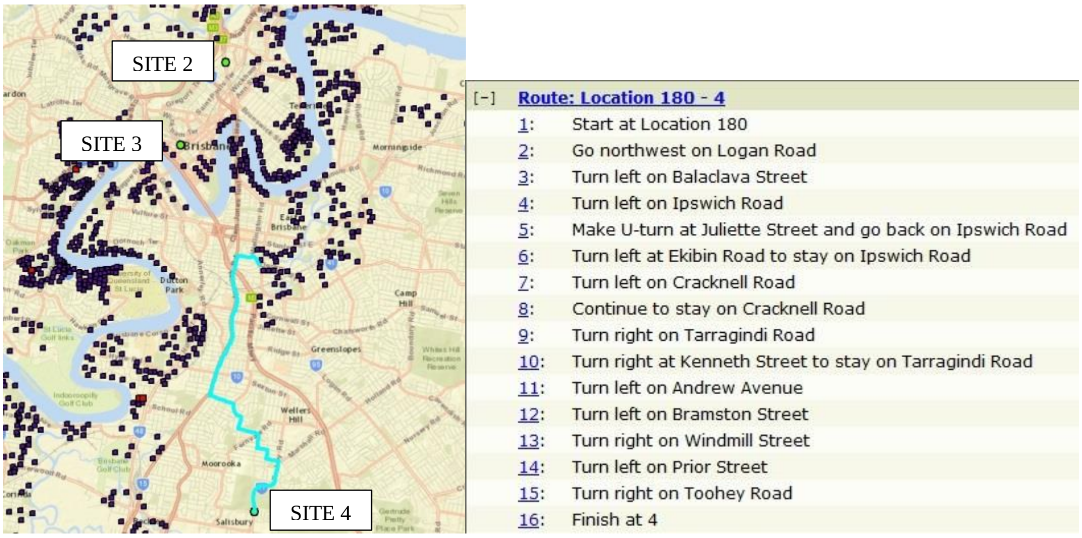
- r is the search radius, G is the graph, $d[j,k]$ is the distance from node j to node k
- n_{jk} is the number of the shortest path from node j to node k
- $n_{jk}[i]$ is the number of the shortest path from node j to node k and pass by node i
- $w[j]$ is the weight of each origin j

If the w[j] is assigned by demographics for example population, the "Betweenness" can estimate the potential of passersby at different buildings on the network.

4 Results

The main target for an evacuation strategy is to specify a certain shelter and detailed route for each mesh block. Figure 3(a) shows one example of how residents from a given mesh block (black dot) can evacuate to the nearest shelter (green dot) following the highlighted path in the graph. Additionally, the criterion of ruling bridges out of the analysis is illustrated as well because the farther shelter was chosen (Site 4) instead of taking the risk of approaching nearer shelters (Sites 2 and 3) across Brisbane River. From Figure 3(b), the evacuees can understand exactly where to turn and which road to choose until they arrive at the shelter.

Based on the assumption that people take the shortest path to evacuate, the possible congested segments can be predicted by calculating "Betweenness" value for each mesh block. The "Betweenness" method estimates how many times each mesh block is passed by evacuees on their way from their locations to shelters along the shortest paths. Figure 4 illustrates the passer-by frequency of each mesh block when residents choose shortest paths for an evacuation with the distance less than 15 km. This can help point out the possible congested road segments. People will need to try avoiding those areas and choose their second shortest routes as alternatives. From the legends in Figure 4, it is clear that the major and medium crowed locations are gathering around the middle part of Brisbane. In particular, these places are either neighbourhoods that are surrounded by Brisbane River on two/three sides or mesh blocks that have dense population (e.g. central business district). Furthermore, from the busiest points, one can tell that Sites 2, 3 and 4 will be expected for more accommodation than Sites 1, 5 and 6. The congestion condition can be estimated at any location where an observation point is established (in this analysis, the locations of 1,186 mesh blocks).



(a) (b)

Figure 3: Evacuation route (a) and instructions (b)

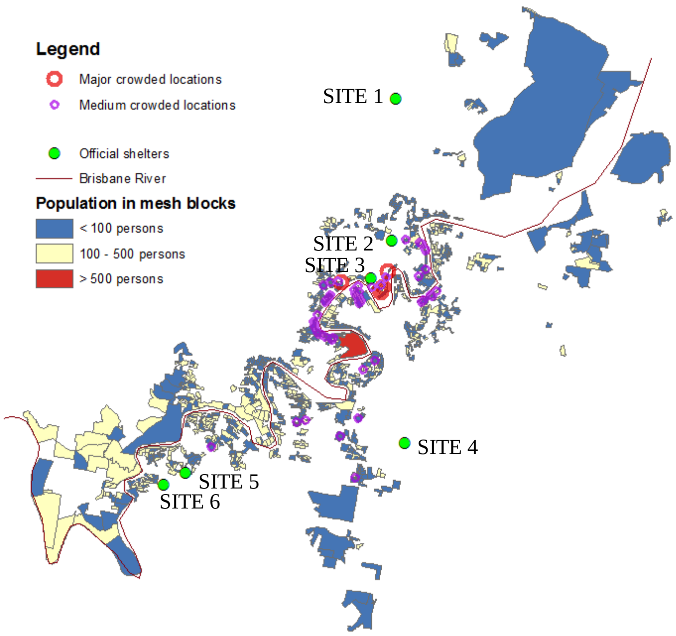


Figure 4: Locations congestion may occur

From the perspective of shelter management, the service areas for each shelter need to be defined and evaluated. In Figure 5, three polygons surrounding each of the six evacuation buildings represent service areas within three different ranges. Mesh blocks located in each of the three polygons from inside out can reach the corresponding shelter during an evacuation in 10 min, 20 min and 30 min respectively. These polygons are calculated based on two criteria: distance along available roads and the exclusion of flooded bridges in the analysis (as they are considered to be risky in an inundation emergency). We notice that some service areas illustrated in the graph do cross a bridge; this is because the algorithm for generating polygons will connect sequential points to form boundary lines, ignoring all the details between adjacent points. As 30 minutes are considered to be the longest time people accept when evacuating, any mesh block that cannot be covered by shelters within 30-minute driving distance reveal problems in the distribution or/and number of shelters. There are 190 mesh blocks locating in the eastern and western parts of Brisbane which have no shelter accommodation in that sense. Although this number can be exaggerative because of the imprecise presence of road networks (especially in terms of segment connectivity), the analysis results imply that more shelters should be established in the east and west of Brisbane in the future.

Table 2 shows that Sites 2 and 3 provide shelter services to the largest number of mesh blocks. Most of the mesh blocks assigned to these two shelters are located within 10 km. Site 4 will accommodate the second largest number of mesh blocks; the majority of the evacuees escaping to this shelter will travel more than 10 km. Sites 5 and 6 have similar total number of mesh blocks to serve; the reason could be that they are close to each other. The service area of Site 1 only covers 5 mesh blocks, which indicates that it is far for evacuating by car and it may aim to accommodate residents rescued by helicopters.

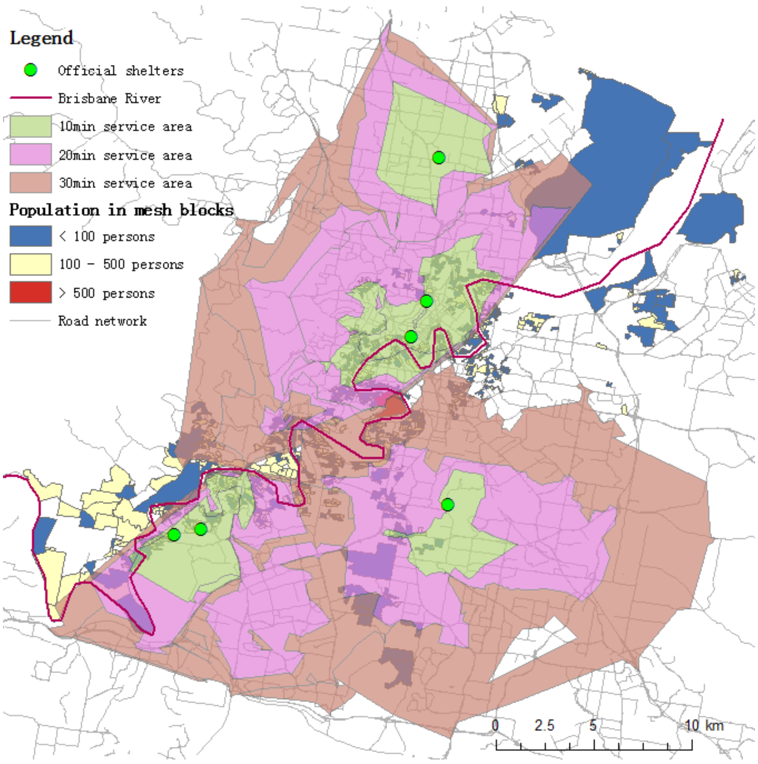


Figure 5: Shelter service areas

Table 2: Number of mesh blocks each shelter covered

	Name	Number of mesh blocks covered			
		Total	**Within 0 - 5 km**	**Within 5 - 10 km**	**Within 10 - 15 km**
Site 1	Kedron Wavell Services Club	5	0	5	0
Site 2	RNA showgrounds at Bowen Hills	314	149	145	20
Site 3	Salvation Army	328	184	120	24
Site 4	Nathan	249	10	58	181
Site 5	Good News Lutheran Church	130	99	1	30
Site 6	St Catherine Anglican Church	106	60	40	6

5 Discussion and limitations

The results in the previous section indicate that spatial analysis is an effective tool for evacuation management, especially for shelter assignment and routing. The results show that spatial analysis can provide evacuees with detailed information on shelter selection and possible routes. Congestion conditions at the mesh blocks' locations can also be predicted on the basis of individual choice of shortest paths for evacuation. Furthermore, evaluation on existing shelters and locations is performed in order to establish new shelters. This study has shown the capability and effectiveness of spatial analysis to address evacuation management problems which need to be accurately resolved by emergency managers.

The applicable scenario mainly involves large-scale evacuation management under flood disasters. Evacuation strategies for the residents exposed to floods are developed. This study focuses on car-based evacuation which requires that the road network is well developed so that the approach applies especially when the study area includes or is close to a central business district. Additionally, a dense population is considered. In a case where only a few people are surrounded by an undeveloped road network, the most suitable solution must be helicopter rescuing. Lastly, the applicability of this study relies on evacuees' familiarity with official shelters.

The results from the Network Analyst toolbox are sensitive to the relative location of residents and nearby road segments. For example, only the mesh block that is reasonably near to the network is considered to be reachable. Furthermore, a service area is illustrated as a polygon which connects adjacent points at the cut-off location along a road segment. This may lead to an unnecessary misunderstanding that some service areas include unreachable segments between adjacent roads. Tools in Urban Network Analysis do not support barriers. Constraints on bridges need to be set up manually in the analysis.

Nevertheless, the analysis tools are beneficial for emergency managers to gain a better understanding of the whole picture of large-scale evacuation and provide a feasible and organised way to manage the evacuation situation. Improvement of the analysis results requires further refinement of the algorithm and models used in the two toolboxes and integration with other useful modules such as the flood planning module and the real time traffic module built in GIS software.

6 Concluding Remarks

This paper presents a first step in the flood evacuation management analysis of Brisbane River in a large-scale scenario. The evacuation boundaries are defined based on two major historic flood events. This case study utilised the spatial analysis approach. The results show that the shelters established during 2011 Brisbane flood evacuation are inadequate and new shelter locations are proposed in case of future flood events. The proposed approach is feasible and suitable for emergency managers who do not necessarily have expertise in GIS. Limitations of the conventional GIS toolboxes used in this study are discussed. Further study can be conducted to utilise other analysis modules which manage the floodwater as well as the real traffic condition because the real evacuation situation demands for such temporal information, hence a dynamic analysis is required.

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