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ScienceDirect
Procedia Economics and Finance 18 (2014) 320 – 326
Procedia Economics and Finance
www.elsevier.com/locate/procedia

4th International Conference on Building Resilience, 8-11 September 2014, Salford Quays, United Kingdom

Flood risk mapping for the city of Toronto

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Abstract

The city of Toronto has experienced many major floods over the past century: the flood following hurricane Hazel in October 15, 1954, the August 27, 1976 floods, the August 19, 2005, and the flooding of July 8, 2013. During the latest flooding, some parts of the City of Toronto received over 120mm of rain, while the monthly average for Toronto is 74.4mm. The impact was felt as 300,000 residents were affected by power outages. Other serious disruptions included flight cancellations, subway and other transportation closures. It was the most expensive disaster for the province of Ontario. According to the Insurance Bureau of Canada, the damage of the insured properties exceeded $850 million. This event renewed a debate on a number of issues, such as decaying infrastructure, insufficient flood management, and inadequate standards. Don River, the main river crossing the city, is wide but not deep enough, which together with sedimentation contributes to frequent flooding of surrounding areas. In addition, natural creeks have been buried in sewer pipes, thus losing the natural waterways towards the lake Ontario and forcing existing rivers and creeks to overflow their banks. While floodplain maps are generally available, the estimation of flood risk maps based on population, economic development, and critical infrastructure will enhance city's flood mitigation and preparedness planning. In this paper, we present an approach for determining spatial flood risk index map based on population vulnerabilities and terrain morphological characteristics using a geographic information system.

Selection and/or peer-reviewed under responsibility of the Centre for Disaster Resilience, School of the Built Environment, University of Salford.

Keywords: Flood risk, Mapping, Modelling, Vulnerability, Toronto

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Selection and/or peer-reviewed under responsibility of the Centre for Disaster Resilience, School of the Built Environment, University of Salford.
doi:10.1016/S2212-5671(14)00946-0

1. Introduction

Over the last 100 years, the city of Toronto has experienced four major floods: the flood following hurricane Hazel in October 15, 1954, the August 27, 1976 floods, the August 19, 2005, and the recent flooding of July 8, 2013 (PSC 2014; Nirupama et al. 2014). Toronto's population is about 2.5 million, concentrated in an area of 630 km2. The Greater Toronto Area (GTA) covers 7,100 km2 with about 5.5 million people. Toronto is socially and geographically the most vulnerable city in Canada because it is the most populated city (6th in North America), it is located at the shores of Lake Ontario of the Great Lakes, which is the largest surface fresh water system in the world, where numerous rivers, lakes and creeks that are part of the large watershed come together, and it is affected by air masses originating from the Gulf of Mexico, the Atlantic Ocean, and from the Arctic. Southern Ontario has experienced numerous tornadoes and impacts of passing hurricanes in the past several decades. For example, Hurricane Hazel in 1954, Hurricane Fran in 1996, and Hurricane Sandy in 2012 have caused damage in the city (City Report 2014; Coulson 2014; Global News 2013).

The flooding due to Hurricane Hazel in 1954 had significant impact on the city. It left 81 dead and 7,472 people were rendered homeless (GOC 2012; Bonnell and Fortin 2009). About 121 mm of rain fell in 12 hours in some areas totalling up to 210 mm over two days. The flooding was severe in low lying areas of the Don and Humber Rivers, as well as the Etobicoke and Mimico Creeks. It was the most severe flooding in the Toronto area in 200 years that triggered the establishment of the then Metropolitan Toronto and Region Conservation Authority (MTRCA), now known as Toronto and Region Conservation Authority (TRCA). Infrastructural damage was unprecedented at the time, including 20 bridges being destroyed or damaged beyond repair and full blocks of homes being swept away (PSC 2014; Toronto Star 2013). The August 1976 flooding event that lasted two days caused 75mm of rain by two large storms, causing over 1.3 million dollars damages (TRCA 1999). The August 19, 2005 flooding event recorded 153 mm of rain over 3 hours, which was only preceded by Hurricane Hazel in 1954 (D'Andrea 2010; TRCA 2009). It was a 100 year event north of the city, causing $500 million in insured damage. This storm was the province's most expensive natural disaster, and the second costliest ever nationwide.

The most recent flooding occurred late in the afternoon on July 8, 2013 (Nirupama et al. 2014). Some parts of the GTA received over 90mm of rain and in some cases, the total exceeded 100mm. At Pearson International Airport, more than 126mm of rain was recorded; while the monthly average for Toronto is 74.4mm (City Report 2014; The Star 2014; Young 2013). The power outages affected about 300,000 residents. Serious disruptions included flight cancellations, subway and other transportation closures, including the main train station of the city, Union station. Most of the public transit was not available until the next day. It was the most expensive disaster for the province of Ontario. According to the Insurance Bureau of Canada, the damage of the insured properties exceeded $850 million (Toronto Star, 2013; Kimbell 2013). For this event, rain gauge station locations and daily precipitation values for each of the rain gauge station are shown in Figures 1 and 2.

2. Data and method

Generally, risk is defined as the potential consequences of a hazard (EMO 2010; FEMA 1993; HIRA 2011; PEP 2004; ISDR 2004; Smith and Petley 2009; Wisner et al. 2004). Risk assessment is a process or application of a methodology for evaluating risk as defined by hazard and exposure of people to the event and impact (Armenakis and Nirupama 2013). Here, a combination of catchment characteristics, including terrain slope, drainage network, and land depression as well as people's vulnerability have been taken into account to evaluate flood risk. The flood hazard component has been calculated based on the assumption that flood inundation will occur at areas of low terrain slope and land depressions. The calculations are carried out on normalized spatial layers of low slope and land depression areas. The consequence component is based on vulnerability elements of the population per Census Tract. Flood risk map has been generated as a spatial overlay operation between the hazard and vulnerability layer components as shown in Figure 3.

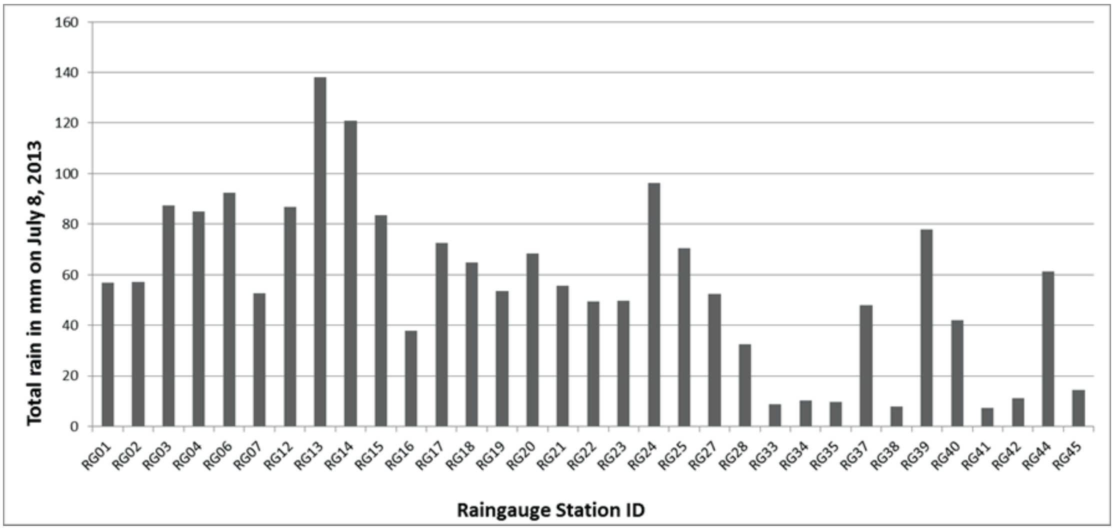

Fig. 1. Rainfall recorded at various rain gauge stations in the study area.

Fig. 2. Locations of rain gauges in the GTA.

2.1. Vulnerability Estimation

The 2006 Census data from Statistics Canada was used to extract demographic information in the study area. The 2006 Census Tracts, (CT), data has been used as the basis unit to extract demographic details on vulnerable groups (Table 1). In order to standardize various data, percentage values of each of the ten categories (Fig. 1) has been calculated based on total population in corresponding census tract. Total weighted vulnerability was calculated as Eq. 1:

$$V_{CT} = \sum_{i=1}^{10} \left[\left(\frac{\%C_i}{\sum \%C_i} \right) \times \left(\frac{C_i}{P} \right) \right] \quad (1)$$

where,

V_{CT} is total vulnerability per each CT
$\%C_i$ is the category population percentage in each CT
C_i is the category population in each CT
P is the total population in each CT

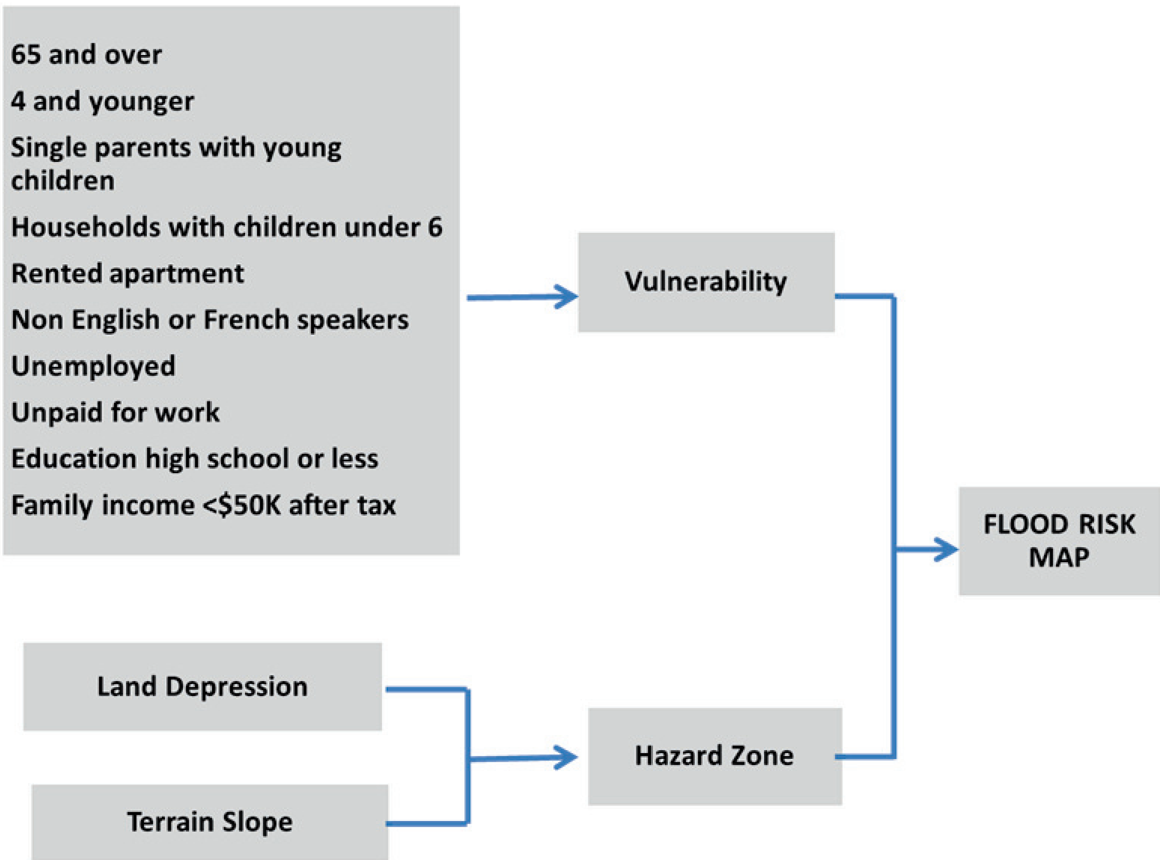

Fig. 3. Schematic of flood risk mapping.

Table 1. Excerpt from the 2006 Census Tract demographic data.

CT_ID	CT Population	65 and older	4 and younger	SingleParents with young children	Households with children under 6	Rented apartments	Non English or French speakers	Unemployed	Unpaid for work	Education high school or less	Family income <50K after tax
5350221.02	4240.00	670.00	235.00	335.00	290.00	1020.00	115.00	250.00	330.00	510.00	580.00
5350041.00	3394.00	500.00	125.00	190.00	150.00	530.00	675.00	260.00	295.00	1190.00	360.00
5350032.00	5469.00	590.00	175.00	290.00	175.00	2320.00	110.00	650.00	270.00	715.00	455.00
5350064.00	2448.00	310.00	40.00	60.00	40.00	1270.00	40.00	295.00	150.00	155.00	130.00
5350244.02	5917.00	435.00	520.00	880.00	650.00	990.00	235.00	530.00	635.00	1145.00	880.00
5350012.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5350357.02	5009.00	430.00	480.00	835.00	605.00	1135.00	110.00	570.00	500.00	1015.00	925.00
5350361.01	5771.00	815.00	185.00	335.00	260.00	120.00	40.00	515.00	585.00	730.00	305.00
5350161.00	6946.00	865.00	370.00	675.00	440.00	845.00	725.00	410.00	850.00	2335.00	845.00
5350247.01	7319.00	555.00	460.00	545.00	550.00	515.00	515.00	485.00	760.00	1320.00	600.00

2.2. Flood Hazard Estimation

The flood hazard risk map was generated using topographic data. They consist of a 10m Digital Elevation Model (DEM) and the river network covering the GTA (Fig. 4). Based on the DEM, a slope map of less than 2% and a land depression map were derived (Fig. 5 and 6). The latter was generated as the fill DEM minus the actual DEM localizing the sink type areas in the region.

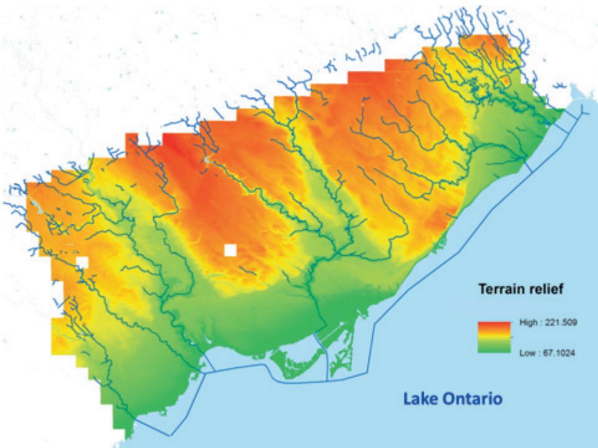

Fig. 4. Digital Elevation Model of the study area.

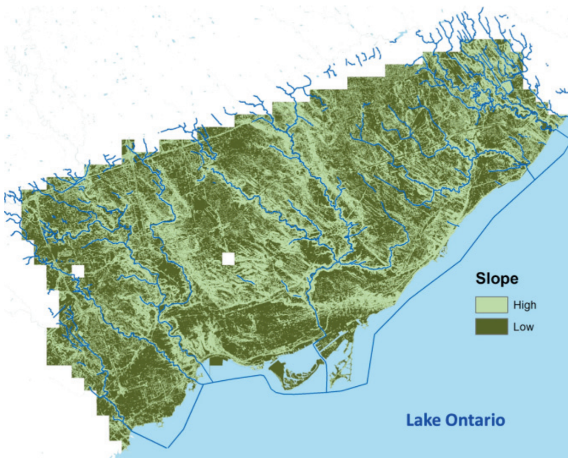

Fig. 5. Slope of the study area.

2.3. Flood Risk Estimation

Based on the conventional risk formula as given in Eq. 2 (Long and John 1993; PEP 2004; HIRA 2011; Martínez and López 2010), the flood hazard layer component H has been defined as the union of two spatial layers, the one being slope values of less than 2% and the second of land depressions (Fig. 7). The vulnerability has been defined as a combination of various vulnerable groups estimated by Eq. 1 using the elements shown in Table 1. The vulnerability has been calculated for the area of each Census Tract (Fig. 8). The final flood risk map R (Fig. 9) was generated by the integration of the two spatial layers H and V respectively as per Eq. 2,

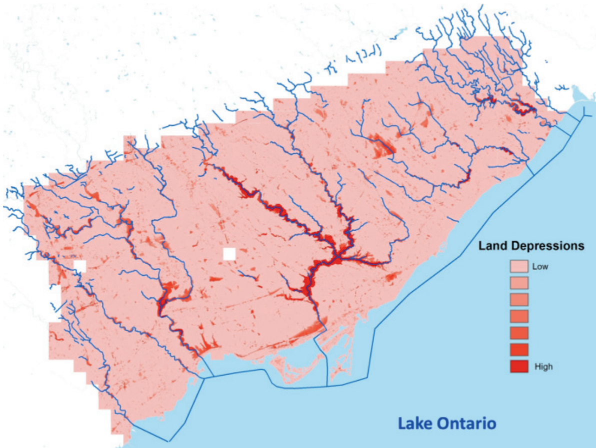

Fig. 6. Land depressions in the study area.

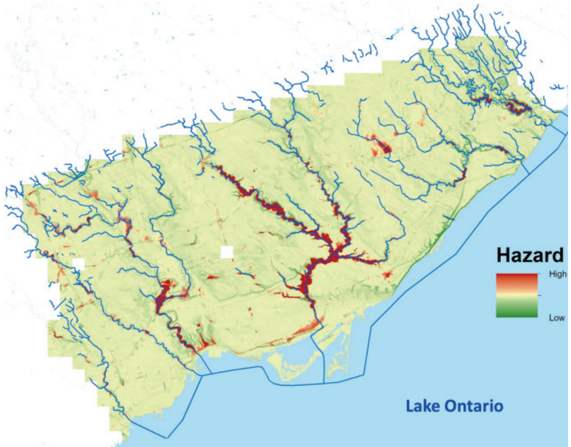

Fig. 7. Hazard map of the study area based on slope and land depressions.

$$R = H \times V \tag{2}$$

where, R = Flood Risk; H= hazard; and V = vulnerability.

Based on Figure 9 we observed that generally the flood risk is higher in the southern (downtown of the city of Toronto), north-western and the north-eastern areas of the GTA region. Central and south-western regions are exposed to lower flood risks.

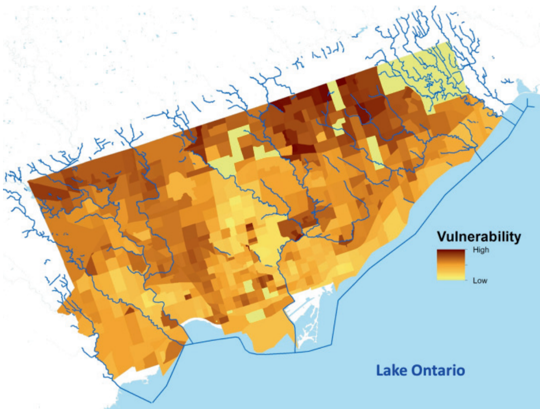

Fig. 8. Estimated vulnerability for each Census Tract in the study area.

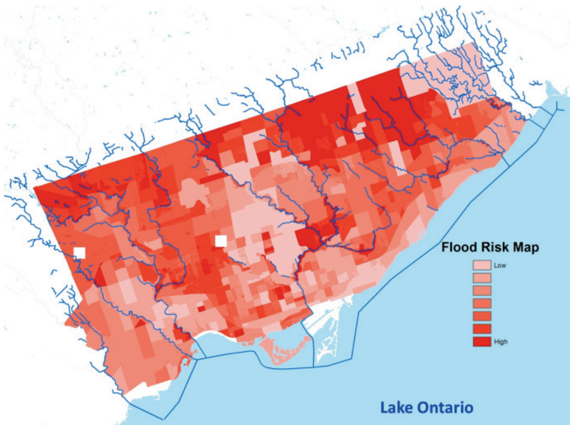

Fig. 9. Flood risk map.

3. Concluding remarks

Appropriate flood risk mapping is one of the best practices for flood mitigation and control management. In this study, a preliminary assessment of flood risk due to recent extreme flooding event has been carried out. The ArcGIS geographic information system was used for the spatial modelling and visualization of the results. The proposed method uses analytical tools to prioritize spatial flood risk areas and can assist with the development of disaster impact reduction strategies, and overall effectiveness of flood management. This study complements current efforts and initiatives taken by the City of Toronto in light of recent flooding events that caused tremendous damage in the city. It is worth noting that highly vulnerable areas that are located in low land areas and around rivers are exposed to higher risk of flooding. Effective mitigation and preparedness strategies are required to reduce future flood risk in the communities. In continuation to this study, floodplain mapping based on rainfall trends will be carried out supported by multicriteria spatial analysis. The various spatial relationships among assets data, land use information and flood risk maps will be also investigated.

Acknowledgements

We are thankful to Dr. Vicky Shi, Storm Water Management, City of Toronto for providing hydrologic data. Rosa Orlandini, Map Library, York University, is also thanked for her assistance in locating spatial data sets. The digital elevation data were provided by the Ontario Ministry of Natural Resources through the Ontario Geospatial Data Exchange (OGDE) program. The CanVec river data obtained through the GeoGratis geoportal, Natural Resources Canada. The 2006 demographic and area polygons of the census tracks were obtained from Statistics Canada.

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