Flood Exposure and Social Vulnerability for Prioritizing Local Adaptation of Urban Storm Water Systems

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Abstract Changes in rainfall patterns due to climate change are likely to increase weather-related hazards significantly, including floods and associated economic and social damage in urban areas. Adapting storm water systems to cope with these changes can be expensive, and often competes for resources with other priorities. Therefore, targeted adaptation of the infrastructure in a municipality, based on an assessment of both physical risks of flooding and socioeconomic vulnerability, can help decision-makers better allocate resources while developing adaptation plans. Conventional flood studies commissioned by municipal councils typically concentrate on geophysical aspects such as flooding frequency and areal extent. This paper goes beyond those and develops a Flood Social Vulnerability model (FSV) by combining hydrological and hydraulic analyses with social vulnerability analyses. The approach is illustrated by applying it to Marrickville, a local government area in Sydney's inner-west that is prone to flooding.

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1 Introduction

Global flood losses are increasing due to a number of factors, including changes in climate patterns as well as growing population and economic development in flood-prone areas [1, 2]. The reported average annual global losses between 1980 and 2012 exceeded $23 billion [3]. Climate change is likely to increase weather-related hazards significantly, including flood and associated economic and social damage [4] due to changes in rainfall patterns and increases in the frequency and intensity of extreme weather events [3]. A rich literature has helped us to understand the dynamics of floods and predict future flooding scenarios [5–8]. In addition, a number of studies have proposed and/or analysed flood management strategies aimed at reducing economic damage and assisting communities in adapting to flooding events [2, 9–11]. However, most flood studies are conducted at city or catchment scales that are important and useful for municipal governments, but not sufficient. Municipalities require locally-specific data and strategies that can identify populations at risk and develop specific measures to reduce vulnerability and increase resilience. Such strategies are typically inscribed within, and informed by, larger-scale strategies but are not entirely determined by them.

In some cases, local authorities have conducted their own flood studies. These studies typically concentrate on the geophysical aspects of flooding, by determining frequency and areal extent of floods, and by providing recommendations for improving drainage paths and upgrading storm water infrastructures (e.g. [12–14]). However, different communities and individuals may be at risk for different reasons (e.g., living in low-lying areas, poor mobility, poor access to financial resources in times of flood). Hence, for effective flood risk management and for better adaptation to floods, it is important to know not only how significant the aggregate flooding risk is, but who is at risk and what are the drivers of their vulnerability [15]. While the literature on flooding has recognized the importance of incorporating institutional and socio-economic factors in determining vulnerability to flooding, conducting such assessments at local scale remains limited.

This paper develops and applies a new methodology for assessing vulnerability to flooding in urban areas at local scale. The study aims to advance our understanding of the relative importance of geophysical, institutional and socio-economic factors within local communities that make them vulnerable to flooding. A hybrid approach, combining hydrological and hydraulic analyses with social vulnerability analyses, is adopted. The methods developed here are tested and illustrated by applying them to Marrickville, a local government area in Sydney's inner-west that is prone to flooding events.

2 Risk Assessment Framework

A number of different conceptual frameworks exist for analyzing flood risk and vulnerability. One such framework—used by a number of studies in the literature and adopted in this paper—defines flood risk as a pyramid in which the impact of floods is the outcome of the interaction between *hazard*, *exposure* and *social vulnerability* [16]. Hazard is typically characterized by its probability of occurrence and most commonly represented by the areal extent and depth of flooding in time and space under different scenarios [17, 18]. "Exposure" is the extent to which valued aspects of a community's life (e.g., health, prosperity, security) are likely to be affected by the flood [19]. On the other hand, social vulnerability (SV) refers to the intrinsic characteristics of the exposed elements which determine their potential to be harmed and their capacity to cope with, and adapt to, the hazard [20]. This helps explain why two communities equally exposed to the same hazard may experience its impacts in very different ways. In our adopted framework, the above three concepts are represented by the three dimensional risk pyramid shown in Fig. 1. Increasing the magnitude of any of these dimensions increases the volume of the pyramid, which in turn reflects a higher overall risk.

3 Development of Flood Social Vulnerability Model

In order to implement the above-mentioned risk framework in the context of local scale storm water management under climate change, a conceptual model of Flood Social Vulnerability (FSV) is developed here (Fig. 2). The three dimensions of the risk pyramid are operationalized by three sets of indices: (i) Flood Hazard Index (F_H); (ii) Flood Exposure Index (F_E); and (iii) Social Vulnerability Index (SoVI). Each of these indices are implemented within our framework using a set of indicators that capture major elements of an individual index. Each individual index is calculated as a weighted average of its indicators:

Fig. 1 Risk pyramid

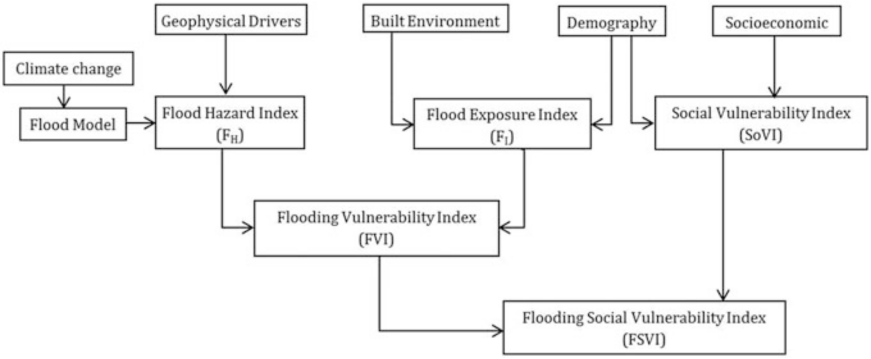


Fig. 2 Conceptual model for flood social vulnerability

$$F_m = \sum_{i=1}^{N_m} w_i I_i \tag{1}$$

Here F is the index of the dimension m (i.e., flood hazard, flood exposure, social vulnerability), w_i is the weight of indicator I_i. N_m is the number of indicators for dimension m.

The unit of analysis mostly depends on available data and can range from a single household to a large geographical area incorporating hundreds or thousands of households. F_H for a unit of analysis within a municipality is determined by certain characteristics of a flood event such as its aerial extent, flood depth, duration etc. Changes in rainfall patterns can influence these flood characteristics. On the other hand, F_E is captured by the demographic and built-environment characteristics of the unit of analysis. This can include population density, age and density of different types of built infrastructure such as residential, commercial and industrial properties, roads etc. Finally, SoVI is determined by the socioeconomic characteristics of the residents of the study unit, which may capture social capital, education, access to resources and technology, etc. A large number of socioeconomic indicators are available, that can be used to quantify social vulnerability. However often these indicators are highly correlated which can reduce the validity of the index since additive aggregation generally requires indicators to be algebraically independent of one another [21]. Therefore, a principal component analysis (PCA) is conducted to reduce an large initial set of selected social vulnerability indicators into a small set of principal components [22, 23]. SoVI is calculated by adding the principal components using equal weights. Finally, the three indices can be combined to calculate a Flood Social Vulnerability Index (FSVI) for each unit of analysis (Eq. 2).

$$FSVI_i = F_{Hi} \times F_{Ei} \times SoVI_i \tag{2}$$

The advantages of the multiplicative approach used in calculating the FSVI is that it magnifies cases in which more than one index is pointing to high vulnerability and yields a small value in cases in which any one of the indices indicates very low vulnerability.

4 Application of FSV in Marrickville Council

In order to test the applicability of FSVI, we applied the methodology to the suburb of Marrickville. Marrickville is a local government area (LGA) in Sydney's inner-west, which has experienced significant flooding as recently as 2012 [24]. It has medium-density residential and light-density industrial developments, as well as a number of major and minor roads. The storm water system of Marrickville valley sub-catchment drains its water through a curb/gutter system, to a pipe system, and finally into four major outfalls, including a tunnel, into the Cooks River. The Marrickville valley is divided into seven sub-catchments and the total drainage system consists of open channel and underground pipe systems [12]. According to the 2011 census data the total population of Marrickville LGA was 76,500, 65% of whom were engaged in full time employment with a median weekly household income of $1605. In addition, 34.6% of the population were enrolled in, or attended, tertiary education.

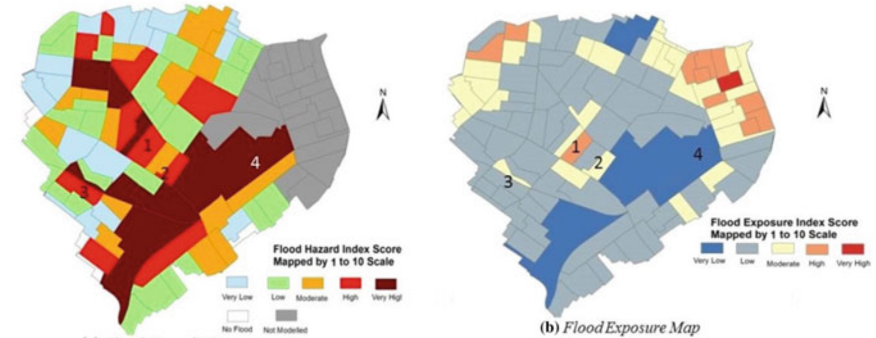
The unit of analysis for this study was adopted as Statistical Area Level 1 (SA1), which is designed by the Australian Bureau of Statistics (ABS) as the smallest unit for publicly available census data [25] typically including 200–800 residents. Table 1 shows the indicators used in the study. In order to generate indicators for F_H, an existing flood model was collected from the Inner West Council, which is the municipal authority responsible for the Marrickville area. Flood events were then simulated by means of a hydrological and a hydraulic modelling technique using TUFLOW and Drains software, respectively. The hydraulic model calculates flood levels and flow patterns, and simulates the complex effects of backwater, overtopping of embankments, waterway confluences, bridge constrictions and the effect of other hydraulic structures. Our analysis did not include the east-end catchment because data representing it were not available. The model was calibrated in a previous study against qualitative flooding hot spots, community questionnaire results and comparisons with earlier studies. No calibration based on the magnitude of past flood events was possible because of the lack of stream gauges in the catchment area. The model was used to generate a flood hazard index for an event equivalent to 100 year Annual Recurrence Interval (ARI) 2-h rainfall. In estimating F_H, the average flood depth was used (rather than the maximum depth) because of the large spatial variation of flood depth. The two indicators of F_H were normalized to a scale between 1 and 10. Figure 3a shows the spatial distribution of F_H.

Table 1 Indicators used for developing FSV for Marrickville council

Model	Indicators	Unit
Flood hazard	(i) Areal extent of flooding	As a % of total area
	(ii) Average flood depth	meter
Flood exposure	(i) Population density	count/km^2
	(ii) Building density	
	(iii) Old building density	
Social vulnerability[a]	(i) Number of children below 5 years of age	As a % of total population
	(ii) Number of people over 65 years of age	
	(iii) Number of people between 35 and 39 years of age	
	(iv) Number of people requiring special assistance	
	(v) Number of females	
	(vi) Number of non-citizens	
	(vii) Number of people moved residence in the last year	
	(viii) Number of people with low speaking proficiency in English	
	(ix) Number of people with weekly income less than $300	As a % of total population aged 15 years and over
	(x) Number of people with weekly negative or nil income	
	(xi) Number of people who never go to school	
	(xii) Number of single parent families with children under 15	As a % of total families
	(xiii) Number of couple families with more than 2 dependent children	
	(xiv) Number of unemployed families	
	(xv) Number of dwellings with no internet connection	As a % of total families
	(xvi) Number of dwellings with no motor vehicle	
	(xvii) Number of dwellings occupied by single individuals	
	(xviii) Number of dwellings occupied by 5 individuals or more	
	(xix) Number of dwellings owned with mortgage	
	(xx) Number of dwellings with median household income	

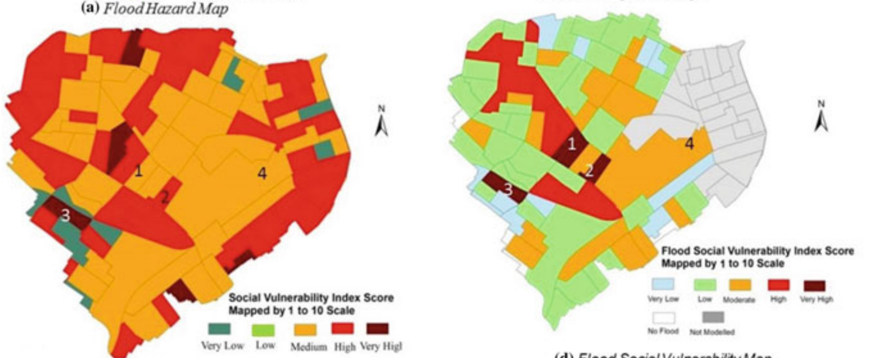
[a] This table shows 20 out of 31 indicators that satisfied the criteria for PCA

The National Exposure Information System (NEXIS) designed by Geoscience Australia provides aggregated information about residential, commercial and industrial structures. The aggregate information of population density, building density and old building density was extracted from the NEXIS database and used to generate an exposure index F_E. Figure 3b shows the spatial distribution of F_E. Socioeconomic data given by 31 indicators was collected from ABS (2011) and was next analysed with PCA to calculate SoVI for each SA1 (Fig. 3c). After a number of PCA iterations, 31 indicators were reduced to 20 that satisfied a number of criteria (e.g. multicollinearity, Kaiser-Meyer-Olkin measures, Bartlett's test of sphericity). A total of 5 components (each with 3–6 indicators) were produced, which explained 68% of all data variance. Components scores were then added using equal weights to determine SoVI. Next, F_H, F_E and SoVI were normalized between 1 and 10, where hazard, exposure and social vulnerability all increase with the increase of the index. Finally, F_H, F_E and SoVI were combined using Eq. 2 to calculate FSVI (Fig. 3d).



(a) *Flood Hazard Map*

(b) *Flood Exposure Map*



(c) *Social Vulnerability Map*

(d) *Flood Social Vulnerability Map*

Fig. 3 Vulnerability profile of each study unit

5 Discussion

Units of analysis marked as 1, 2 and 3 in Fig. 3 were found to have the highest FSVI. High flood hazard, high exposure and medium SoVI resulted in a very high FSV for unit 1. This SA1 is located in the lower-elevation area of the Marrickville valley catchment, thus leading to high water depth and extent of flooded area (37% area flooded). This area also included a large number of residential buildings which increased its exposure to flooding. In the case of unit 2, high FSV was caused by the interaction of high flood hazard and moderate exposure index and SoVI. In unit 3, though the exposure index was low, the hazard index and SoVI were high. This SA1 was characterised by a relatively large percentage of aged and disabled population and low average income. On the other hand, despite its very high flood hazard, unit 4 had a medium FSV, mainly because of very low exposure (low population density and relatively newer houses).

All impacts of flooding are experienced locally and preparedness requires detailed information at a local scale that can help local government planners to develop specific, differentiated mitigation plans, rather than simply adopting flood mitigation measures based on larger-scale studies. The method proposed here can be particularly useful if the information it generates is used by local government to identify sections of the urban drainage system that need increase in capacity or to conduct more focused qualitative and quantitative assessments of drivers of vulnerability in areas identified as highly vulnerable.

In terms of future work, the effectiveness of the existing storm water infrastructure under future climate change will be tested where F_H will be developed by re-running the flood models for different climate change scenarios using The NSW and ACT Regional Climate Modelling (NARCliM) projection scenarios.

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