

Vulnerability of flash flooding in Riyadh, Saudi Arabia

Muhammad Tauhidur Rahman¹ · Adel S. Aldosary¹ ·
Kh Md Nahiduzzaman¹ · Imran Reza²

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Abstract In recent years, hazardous flash flooding has caused human deaths and damages to urban infrastructures in Saudi Arabian cities. This study has computed, mapped, and analyzed the physical vulnerability, social vulnerability, and overall composite flash flood vulnerability (CFVI) indices using a simulated flood and 2006 census data on seven social variables for 153 neighborhoods of the City of Riyadh, the capital of the Kingdom of Saudi Arabia. The physical vulnerability index was computed by ranking a potential flood depth map created by simulating a 6 h of high-intense rainfall in the city. The social vulnerability index was constructed by standardizing the social data variables. Finally, the two indices were multiplied to create the CFVI. The CFVI map revealed that the low-lying central and southern half of the city is highly vulnerable; northern and northeastern peripheral neighborhoods are moderately to highly vulnerable; and the mountainous western neighborhoods are the least vulnerable to flash flooding. Low-income and unemployed expatriate families living in densely populated central, south, and southeastern neighborhoods are more vulnerable to flooding than rich Saudi families living in the sparsely populated northern half of the central city, western, northwestern, and southwestern neighborhoods. The CFVI map will help city planners to formulate effective flood control measures to protect the city residents and urban infrastructures from future flood damage. This flood vulnerability research can be expanded to other Saudi cities by incorporating more physical and social variables.

Keywords Vulnerability · Flash floods · Vulnerability assessment · Riyadh · Saudi Arabia

✉ Muhammad Tauhidur Rahman
mtr@kfupm.edu.sa

¹ Department of City and Regional Planning, King Fahd University of Petroleum and Minerals, KFUPM Box 5053, Dhahran 31261, Saudi Arabia

² Department of Civil and Environmental Engineering, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

1 Introduction

In the recent human-induced global climate change scenario, frequent flash floods have become a major natural disaster affecting various elements of physical, human, social, economic, and ecological systems of large cities in the Kingdom of Saudi Arabia. The desert city of Riyadh, the capital of the Kingdom and home to nearly 6.2 million people (2015), was hit by 12 hazardous flash floods since 1985. Nine of them occurred every year since 2009. These floods have resulted in 168 deaths and thousands of car accidents causing an unknown number of injuries and devastated the city's homes, business economy, and transportation infrastructures worth millions of dollars.¹

Flash floods are an unpredictable climatic hazard. Compared to riverine floods, which occur due to rise of water level overflowing river banks and inundating its floodplains, flash floods are more dangerous because of their sudden occurrences with violent water movements causing more deaths of unprepared people, especially at night (Montz and Gruntfest 2002; Ruin et al. 2008; Pollak 2009; Ruin et al. 2009; Calianno et al. 2013). A city's vulnerability to flash flooding depends on the degree of urbanization and development of built-up environment; demographic, social, cultural, political economic conditions of its people; and its political ecology and government action plan on climate governance, and strategies for coping, adaptation, and mitigation of hazards (Hewitt 1983; Liverman 1990; Blaikie et al. 1994; Bohle et al. 1994; Liverman 2015). Flash flooding of Riyadh is no exception to this scenario. In the absence of a river and drainage outlets to sea, rapid population growth, urbanization, and transformation of large areas of sandy desert into concrete built impervious surfaces that delay rainwater infiltration has greatly increased the risk of hazardous flash flooding occurrences in Riyadh for the next 25 years (Sharif et al. 2016). Hence, flash flood mitigation has now become a major challenge for the Riyadh's city planners (Nahiduzzaman et al. 2015). For planning successful flood mitigation strategies for the city, there is an urgent need to identify the city areas and residents vulnerable to flash floods (Ewea 2010; Alamri 2011; Saud 2012).

One of the most important aspects of urban planning is the study of physical and social vulnerabilities of a city and its residents to hazardous flooding. While the physical conditions of a city would determine the frequency, duration and depth of flooding, the demographic, social, cultural, and political economic conditions of its residents would define the degree of their exposure to it, and the challenge of mitigation, coping, and adaptation to the hazard depends partly on people's experience and perception and mostly on the political ecological parameters such as government's role in climate governance, urbanization, and development of the city built-up environment which make the city vulnerable to the hazard (Blaikie et al. 1994; Cutter et al. 2003; Liverman 2015). Utilization of remote sensing and geospatial technologies is important to identify the present land use and flash-flooded areas of a city. However, in the event of climatic warming, and uncertainty of future occurrence of flash floods, it may not be enough for flood mitigation planning as it overlooks the dynamics of changes in demographic, social, cultural, and political ecological factors which define the city's level of vulnerability to climate hazards (Hodgson and Cutter 2001; Preston et al. 2011). What would be a useful research tool for designing a viable flash flood mitigation action plan is the computation,

¹ Economic loss varies with the duration and severity of a flash flood event. The nature of loss includes car accidents, shut down of retail and whole sale businesses and financial transactions during and after an event; repairing of damaged buildings, cars, roads, highways and telecommunication networks amounting millions of dollars per event.

mapping, and analysis of a composite index of flash flood vulnerability combining selected physical, social, and political ecological indicators. It will allow city planners to understand the complexities of factors which make a city vulnerable and identify its areas and residents at risk of exposure to the hazard (Adger et al. 2004). Studies dealing with the physical and social vulnerabilities of flash floods in riverine urban areas of Tropical and Mediterranean climates are numerous (Clark et al. 1998; Rygel et al. 2006; Balica et al. 2012). However, those dealing with non-riverine desert cities are nonexistent.

The objective of this paper is to compute, map, and analyze a composite flash flood vulnerability index (CFVI) for the City of Riyadh. First, a flash flood event will be simulated using the GSSHA flood modeling and GIS. Using the data on flood depth and selected demographic, social, economic, political, economic, and urban land use characteristics of the city, separate physical, social, and composite vulnerability indices will then be computed, mapped, and analyzed to identify city areas and residents vulnerable to flash floods. A brief review of the literature and a conceptual framework underlying this study is presented in Sect. 2. The study area, data, and methodology are described in Sect. 3, while the results and analyses are presented in Sect. 4. Finally, Sect. 5 contains the conclusions and directions for future research. The study will fill the gap in the literature on flash flood vulnerability of desert cities.

2 Modeling vulnerability of flash floods

Theories explaining natural hazard vulnerability are multidimensional and built upon exposure and coping, disaster risk, global environmental change, political ecology, susceptibility, sustainable development, and hazard-of-place models (Cutter 1996; Birkmann 2006; Liverman 2015). The exposure and coping model of vulnerability that emerged from social geography and human ecology perspective of famine research views vulnerability as a product of interactions between the exposure to an external stressor, and the social and institutional capacities to respond and cope with it (Bohle 2001; Cannon et al. 2003; Birkmann 2006). The model emphasizes the social conditions of a group that determines its capacity to cope with stress and ignores the impact of biophysical conditions of the place that induce the stress.

The disaster risk model views hazard, exposure, vulnerability, and coping measures as determinants of risk. It contends that vulnerability itself has physical, social, economic, and environmental dimensions (Bolin and Bolton 1983; Davidson 1997). The physical vulnerability or the exposure model examines the impact of biophysical conditions such as proximity to source, frequency, duration, and magnitude of hazards on the degree of exposure and ignores the social elements of coping capacity (Hewitt and Burton 1971; Heyman et al. 1991; Haque and Blair 1992; Alexander 1993; Wu et al. 2002).

The political ecology model seeks to explain climate change-related drought and flood vulnerability from cultural ecology and political economy perspectives and focuses on the issues of mitigation and adaptation to those hazards (Liverman 2015). The model views climate governance by local and regional governments as a way of flood mitigation, and technological modification, strategic and structural adjustments of the environment to reduce vulnerability and increase resilience as possible means of adaptation (Liverman 2015). The cultural ecology approach of the political ecology model examines how climate change caused hazardous floods and how people adapted to them. On the other hand, its political economy perspective focuses on how people's socioeconomic inequalities make

them vulnerable to a climate hazard and defines their abilities to anticipate, cope with, resist, and recover from its impacts (Blaikie et al. 1994; Liverman 2015).

Precisely, the political economy model of vulnerability, known as the pressure and release model (PAR), contends that exposure to natural hazards is inherent of a place because of its proximity to sources of hazards. However, its vulnerability is determined by three root causes, such as political economic conditions which determine people's access to power and resources; dynamic pressures exerted by rapid population growth and unplanned urbanization that creates unsafe conditions; and unsafe conditions that make people vulnerable to natural disasters (Wisner et al. 2003). Similar in concept is the social vulnerability model which assumes that the degree of hazard damage varies among places based on social inequalities, the level of urbanization, and rate of economic growth that shape coping, resistance, and resilience capacities (Wisner et al. 2003). Measures of social inequalities include gender (Enarson and Morrow 1998; Alston and Whittenbury 2013; Sultana 2014), age (Bolin and Bolton 1983), family size (Drabek and Key 1986; Wu et al. 2002), race and ethnicity (Bolin and Bolton 1986; Fothergill et al. 1999), housing conditions (Bolin and Stanford 1991; Wu et al. 2002; Cutter et al. 2003), and household income, land ownership, and property value (Hewitt 1983; Watts 1983; Liverman 1990; Bolin and Stanford 1991; Haque and Blair 1992; Blaikie et al. 1994; Hewitt 1997; Wu et al. 2002).

The global environmental change model, emerged from the perspective of human–environmental relationship, argues that vulnerability is determined by exposure, coping responses, impact responses, and adaptation responses (Turner II et al. 2003). The model focuses on social response to cope with a hazard than its physical determinants. The holistic model of vulnerability contends that vulnerability depends on exposure and physical susceptibility, socioeconomic fragility, and lack of resilience (Cardona et al. 2003; Birkmann 2006). The sustainable development model of vulnerability claims that vulnerability reduction and sustainable development are interrelated and such relationship is modified by social, economic, and environmental conditions (Bogardi and Birkmann 2004).

The vulnerability literature suggests that vulnerability is a function of exposure and coping ability, both of which are influenced by physical and social conditions of a place. However, most empirical vulnerability studies focused either on biophysical or on social conditions and ignored the value of human experience and perception, and the context of place to cope with hazards (Cutter 1996; Cutter et al. 2003). Cutter (1996) and Cutter et al. (2003) proposed a merger of physical and social vulnerability indicators to formalize an overall hazard-of-place vulnerability model that accounts for human experience and perception of hazard as well as their ability to cope, recover, and adapt to the hazard. The model contends that the hazard potential is produced from an interaction between the risk of occurrence of a hazardous event and mitigation measures to reduce it; that the hazard potential is modified by various biophysical conditions which produce the physical vulnerability, and the demographic, social, economic, and housing conditions which produce the social vulnerability; and that the physical and social vulnerabilities jointly produce an overall place vulnerability (Cutter et al. 2003). Cutter introduced the concept of social fabric to include “community experience with hazard and community ability to respond to, cope with, recover from, and adapt to hazards” which is influenced by demographic, social, economic, and housing conditions representing the built-up environment (Cutter et al. 2003; Cutter and Finch 2008). From the climate hazard perspective, however, Cutter's overall hazard-of-place vulnerability index suffers from two limitations. First, it does not include political ecology indicators such as social-political power relations influencing

the climate governance and development of built-up environment that make a city vulnerable to hazard. Second, it relies on census data that do not account for changes in vulnerability indicators (Liverman 2015).

Numerous studies have examined the human vulnerability of flash floods in riverine humid subtropical, Mediterranean, and semi-arid climates in the USA, Mexico, France, and Italy and identified several key physical and social factors affecting the flash flood vulnerability. Montz and Gruntfest (2002) reported that flash flood vulnerability is influenced by hydrometeorological conditions, unregulated urban development, and early warning systems and preparations. Intensity and timing of rainfall, catchment size, river discharge, and soil moisture are key physical factors influencing flash flood vulnerability in the USA and Southern France (Kelsch et al. 2001; Ruin et al. 2008, 2009). Demographic factors such as population growth, age and gender, economic growth and need for urban expansion, and behavioral factors such as travel pattern, activity at time of flood occurrence, knowledge and understanding of the warning systems also influence social vulnerability (Gruntfest and Handmer 2001; Ruin et al. 2008; Pollak 2009; Špitalar et al. 2014). Population density, stream locations, elevation, vegetation, road networks, urban land use, and degree of imperviousness are classified as major anthropogenic factors increasing the probability of exposure to flash flood hazards (Calianno et al. 2013; Hong et al. 2013). Among Mexican ethnic communities, differences in cultural belief, knowledge, and understanding of warning systems influence their coping strategies with flash floods (Valverde 2011).

Based on the review of the literature on the vulnerability of flash floods in rural riverine humid and semi-arid climates, it is revealed that the vulnerability of flash flood is determined by exposure and coping capacity, which are physically and socially constructed. Hence, for desert cities, the vulnerability of flash floods should also be examined in the context of physical, social, and behavioral perspective. In the present study, we chose Cutter's hazard-of-place model as a theoretical framework to examine the physical, social, and composite vulnerability of flash floods for the City of Riyadh for its accountability of physical and social conditions of place as well as experience and perception of its people.

From the review of the literature, we carefully selected two physical variables such as the duration and intensity of rainfall, and surface elevation which determines the depth of flash flood, a key indicator of physical vulnerability. We also selected two demographic variables such as population density and age (% of total population <7 years and >65 years); two ethnicity variables (% of population non-Saudi Arabs and % of population Asian origin); two economic condition variables (household average annual income and % of population unemployed); and one built-up environment variable (% of city land under urban use) as indicators of social vulnerability. These variables correspond to those used in Cutter et al. (2003) hazard-of-place model of vulnerability.

Due to the lack of neighborhood data, we could not include a political ecology indicator representing government political power and climate governance initiatives in our overall index of flash flood vulnerability—an issue central to the climate hazard political ecology model proposed by Liverman (2015) and ignored by Cutter et al. (2003). However, in our discussion, we have incorporated an aggregate data on government spending in the construction of housing and road network in Riyadh to evaluate the role of political power relations on the development of city built-up environment that poses risks to flash flood hazards (see Sect. 4.2.4).

A flash flood vulnerability model is proposed here accounting for the above-selected variables with the following assumptions. First, the risk of flash flood occurs in the event of sudden continuous high-intensive rainfall for more than 6 h, and such risk interacts with

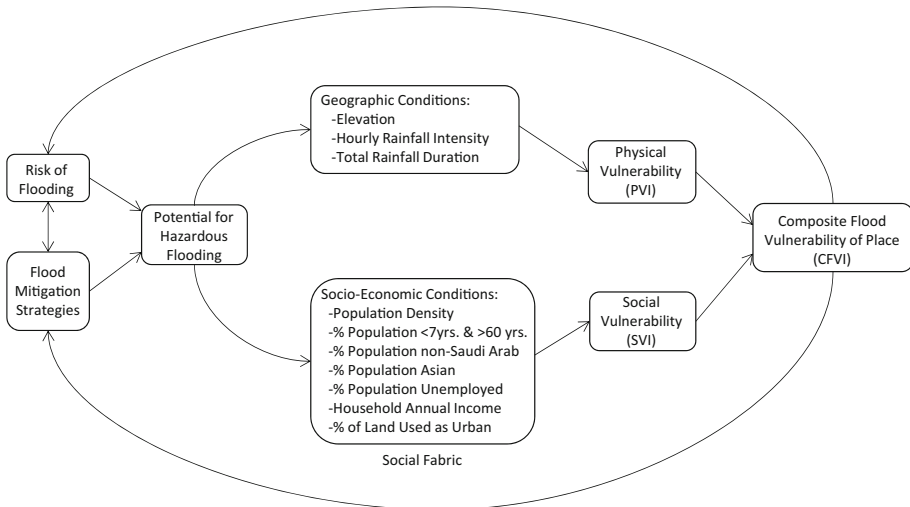


Fig. 1 Place-of-hazard model of flash flood vulnerability of Riyadh, Saudi Arabia (modified from Cutter et al. (2003))

the city's flood mitigation strategies and preparedness to create the potential for exposure. Second, the degree of exposure is modified (reduced or enhanced) by such physical indicators as the city's land elevation that determines the flood depth, and demographic, social, economic, and built-up environment indicators including population density, age, differences in ethnicity, average household income, degree of unemployment, and urban land use patterns. Finally, the physical and social vulnerability indicators interact to produce a composite flash flood vulnerability index representing an overall place vulnerability of the city (Fig. 1). In the proposed model, it is hypothesized that densely populated urban neighborhoods with high percentages of impervious concrete surfaces (i.e., residential and commercial buildings, roads, highways, tunnels, and bridges) will be more vulnerable to flash floods. Families with large number of young children (<7 years) and older (>65 years) people, and high percentage of non-Saudi and Asian expatriate residents with low household income and high degree of unemployment (both of which will force them to live in poor housing conditions) will be more vulnerable to flash floods than those Saudi residents with high household income living in better housing conditions. Variables such as age, ethnicity, household income, the rate of unemployment influence the community experience, and perception of flash flood hazards would represent the social fabric in the proposed model.

3 Study area, data, and methodology

3.1 Study area

Located at the center of the Arabian Peninsula, Riyadh Metropolitan area, the largest city in the Kingdom of Saudi Arabia, occupies an area of 5384 km² (including 1781 km² of urbanized area) subdivided into 209 administrative neighborhoods housing nearly 6.2 million people (General Authority for Statistics 2016). The present study area accounted

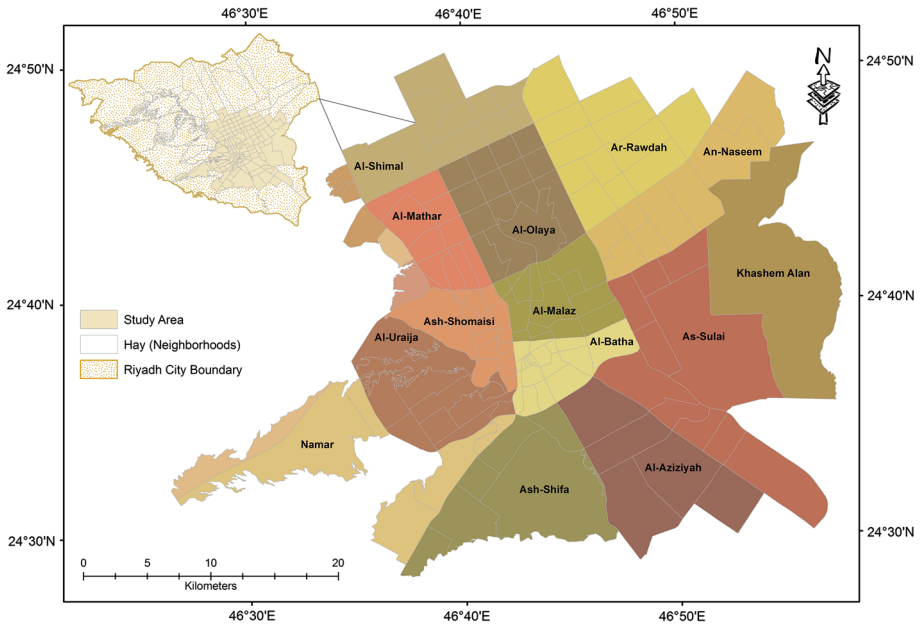


Fig. 2 Study area with the neighborhoods and municipalities (shown in *different colors*)

for 153 neighborhoods with an area of 1241 km² forming the core of the city inhabited by 98 % of the city’s population (Fig. 2). These neighborhoods were severely affected by all the recent flash floods. The remaining 56 neighborhoods are newly settled urban built-up areas housing nearly 2 % of the city population. They were excluded from this study owing to lack of demographic and socioeconomic data used in this study. The selected neighborhoods vary from each other in terms of population density, demography, socioeconomic conditions, housing and urban infrastructures. The city’s population is comprised of 60 % Saudi and 40 % non-Saudi Arab, African, and South and Southeast Asian expatriate population representing 50 languages and cultures (Qhtani and Al Fassam 2011; General Authority for Statistics 2016). Hot dry summer (22–43 °C) and cool moist winter (8–22 °C) with mean annual rainfall of 92 mm characterize the city’s desert (BWh) climate (Qhtani and Al Fassam 2011). The city is divided into the western hills, a northwest to southeast running 120-km-long central valley of the Wadi Hanifa, and the eastern lowland plain. The Wadi has divided the city into the western highlands with southeastward slope and the eastern lowlands. In the past, the wadi used to get flooded once in every 5 to 10 years and the flood water had benefitted the local agriculture. However, urban encroachment and filling of Wadi channel beds over the past three decades have drastically reduced their drainage capabilities. The city’s uniform aridisol soil is sparingly occupied by irrigated date palm gardens and ornamental plants.

3.2 Population pressure, urbanization, climatic change, and flash floods

Riyadh’s population staggeringly grew from 80,000 in 1951 to 662,000 in 1974; to 2.8 million in 1992; to 4.5 million in 2004; to 5.4 in 2010; and to 6.2 million in 2015 (Al-Ahmadi et al. 2009; Middleton 2009; General Authority for Statistics 2016), making

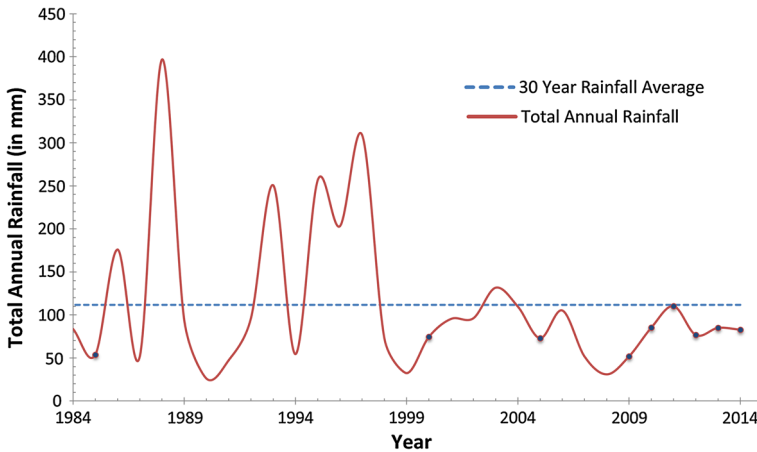


Fig. 3 Total annual rainfall between 1984 and 2014 for the City of Riyadh with blue markers indicating years of flooding *Source:* Presidency of Meteorology and Environment

Riyadh one of the fastest growing cities in the world (Ashwan et al. 2012; Sharif et al. 2016). At the same time, the city urban area also grew in pace with increasing population from 35 km² in 1952 to 300 km² in 1971, to 632 km² in 1995, to 1781 km² in 2014 (Arriyadh Development Authority 2003).

Over the past 30 years, Riyadh's annual mean temperature increased by 0.0521 °C; mean maximum temperature by 0.038 °C; and mean minimum temperature by 0.0562 °C, while its diurnal temperature range (DTR) has declined by −0.0236 °C per year—all indicating climatic warming (Almazroui et al. 2012; Krishna 2014). During the same period, the city received an average annual rainfall of 112 mm which has shown a linear declining trend (Fig. 3) (Presidency of Meteorology and Environment 2016). In recent years, a large percentage of annual precipitation occurred in a single event as torrential rain with an intensity >8 mm/h for several hours yielding a large volume of surface runoff that moved violently from the mountains inundating the city roads, highways, tunnels, and underpasses creating flash floods. Interestingly, most recent nine flash floods affecting Riyadh occurred in the years when the annual rainfalls were below the annual average, indicating that the amount of annual precipitation is not the cause of flash flood; it is rather the amount and intensity of rainfall per event, and the imperviousness of surface condition that delays the infiltration (Fig. 3; Table 1).

3.3 Data

In this study, we used the data on land elevation, soil, vegetation, and urban land use and simulated a uniform high-intensive rainfall (60 mm per hour) for 6 h starting at midnight (to avoid solar evapotranspiration) with a total run-time of 9 h (last 3 h were added to monitor after-rain effects) using the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) of Watershed Modeling Systems (WMS v. 9.1). The model is chosen over traditional HEC-1 and TR-20 lumped conceptual rainfall runoff models for its various advantages including scientific and technological supremacy, more accurate simulation of urban hydrologic processes, mapping and analysis of hydrologic response of a watershed to given hydrometeorological inputs, monitoring the effects of land use and soil types on

Table 1 Dates and rainfall amounts during the occurrences of flash floods in Riyadh between 1985 and 2016. Sources: National Centers for Environmental Prediction (NCEP) (2016) and Presidency of Meteorology and Environment (2016)

Year	Date(s)	Amount of rainfall per event		Total annual rainfall (in mm)
		(In mm)	(% of total annual)	
1985	December 24	0.75	2 %	53.8
2000	November 15	16.00	21 %	74.6
2005	January 21 and February 15	59.11	81 %	73
2009	November 24	7.70	15 %	51.9
2010	May 3	6.00	7 %	85.3
2011	January 18	41.50	38 %	110.3
2012	April 14	33.70	44 %	76.7
2013	May 1	23.24	27 %	85
2013	November 18	16.00	19 %	85
2014	April 16	10.20	12 %	82.9
2015	November 25	Data not available	–	Data not available
2016	April 14, 2016	Data not available	–	Data not available

surface runoff, retention, infiltration, and vegetation interception, and channel routing of surface and groundwater flow among others at moderate grid cell level applying minimal calibration of data from multiple drain outlet locations on stream intersections (Niedzialek and Ogden 2003; Erturk et al. 2006; Downer et al. 2008; Sadrolashrafi et al. 2008; Ewea 2010; Paudel 2010). Input data given to run the model included a 30-m resolution DEM, a 30-m resolution gridded land use data, and the streets and road networks of the study area. At the onset of GSSHA modeling, all watershed contours and stream branches were transferred into “generic” streams with no overland flow as expected of the desert climate of the study area. All stream elevations, irregular slopes, and holes on the study area terrain were interpolated and smoothed to obtain a constant upstream to downstream slopes. A 30-m cell sized 2D GSSHA grid was then created, and all model parameters were assigned at the grid level.

The model used the following assumptions. The DEM was used to delineate basins, create stream networks, and detect flow directions and water accumulations using TOPAZ function which identified all watersheds on higher slopes found in the northwest and western parts of the study area. Since the study area is very large (1241 km²), multiple outlet locations on stream intersections were created and the minimum flow accumulation threshold was set to 100 km² to see all watersheds and to identify the major tributaries flowing directly into the city. The surface water routing was computed using the Gauckler–Strickler formula (Manning’s equation). Since the simulation was continuous, the alternate direction explicit and the Hortonian Green and Ampt infiltration with redistribution methods were selected to compute the overland flow and infiltration for the basin. A land use index map was created from a 30-m land use map. In this map, four land use/land cover classes were identified, and Manning’s roughness coefficients were assigned to each land use class as follows: urban (0.011), soil (0.025), vegetation (0.10), and water (0). A uniform index map was created to assign the values of initial soil moisture (0.2), and infiltration parameters such as hydraulic conductivity (23.56 cm/h), capillary head (4.95 cm), porosity (0.437), pore distribution index (0.694), residual saturation (0.02), field

Table 2 Indicators of social vulnerability identified by Cutter et al. (2003) and the relevant indicators used in this study

Indicators of social vulnerability identified by Cutter et al. (2003) for the USA	Relevant indicators of social vulnerability selected for the study	Increases or decreases in social vulnerability
Wealth (per capita income)	Average income per neighborhood	Decreases with increasing income
Age	Percentage of children (<7) and elders (>65) per neighborhood	Increases with increasing percentage of children and elders in community
Density of built-up environment	Population density per neighborhood	Increases with increasing population density
Single-sector economic dependence	Percentage of built-up area per neighborhood	Increases with increasing built-up area. Lowest in vacant areas
Housing stock and tendency	Data not available	
Race (African-American)	Not applicable	
Ethnicity (Hispanic)	Not applicable	
Ethnicity (Native American)	Percentage of Arabs (non-Saudi) per neighborhood	Increases with increasing percentage of Arabs
Race (Asian)	Percentage of Asians per neighborhood	Increases with increasing percentage of Asians
Occupation	Percentage of people unemployed	Increases with increasing percentage of unemployed
Infrastructure dependence	Data not available	

capacity (0.091), and wilting point (0.033) for sand covering the entire study area. A final index map showing a continuous grid map representing the DEM was created. The model produced a hydrograph along with a flood depth map showing the Hortonian runoff and volume of water that may accumulate within the study area. The flood depth map was then converted into a 30-m ArcGIS v.9.3 raster grid layer in which each cell value represented the flood depth value.

Neighborhood-level data on population density, age, ethnicity, household income, unemployment, and principal urban land use of the city were collected from 2006 census and updated in 2013 through field surveys (Table 2).

3.4 Methods

The study involved the construction of the physical, social, and overall flash flood vulnerability indices for the study area neighborhood districts. The physical vulnerability index (PVI) is generally computed by dividing the square root of the product of ranked physical variables by the total number of variables. Index values range between 0 and 1 with quartiles representing low to high level of vulnerability (Gornitz and Kanciruk 1989; Gornitz et al. 1992; McLaughlin and Cooper 2010). In the present study, the flood water depth values obtained from GSSHA simulation model were regrouped from 1 to 5 at an equal range interval to create the PVI value for each grid cell. Cell value of 1 indicated the lowest vulnerability, while that of five indicated the highest vulnerability to flash floods.

To construct the social vulnerability index (SVI), neighborhood census data on population density, percentage of population <7 years and >65 years of age, percentage of

population non-Saudi Arab, percentage of population Asian, percent of population unemployed and/or not in the labor force, and percent of land under urban residential and road transport network use variables were transformed into a standardized score by dividing the value of that variable in each census neighborhood (V_n) by the maximum value (V_{\max}) for the variable in the entire study area as follows (Wu et al. 2002):

$$I_n = \frac{V_n}{V_{\max}} \quad (1)$$

The value of standardized score for each variable ranged from 0 to 1, representing lowest to highest vulnerability. For the average household income, which exerts inverse impact on vulnerability (high-income family will be less vulnerable), standardized score computed as above was subtracted from unity as follows (Wu et al. 2002):

$$I_n = 1 - \frac{V_n}{V_{\max}} \quad (2)$$

This will also yield scores from 0 to 1, and neighborhoods with high average annual income will score low, while those with low income will score high, indicating that high-income neighborhoods are less vulnerable than low-income neighborhoods. Finally, the standardized scores of all seven variables were averaged to compute the SVI. Again, the SVI scores ranged from 0 to 1, indicating lowest to highest social vulnerability. The SVI was then converted into 30-m ArcGIS raster layer, mapped, and analyzed.

The physical and social vulnerability indices can be multiplied or averaged to compute an overall vulnerability index (Wu et al. 2002; Zhang and You 2014). Since there was only one physical vulnerability index and seven social vulnerability indices, it would not be rational to take a weighted average of all nine variables to merge and create an overall composite flood vulnerability index (CFVI). In reality, spatially any neighborhood with 0 physical vulnerability score would have the lowest vulnerability of flash floods regardless of its high value of social vulnerability indices. Hence, we took the multiplicative approach to computing the CFVI as follows:

$$\text{CFVI} = \text{PVI} \times \text{SVI} \quad (3)$$

Since the PVI scores ranged from 1 to 5, and SVI scores ranged from 0 to 1, the CFVI scores would range from 0 to 5. In this scale, 0 would indicate not vulnerable and 5 would represent the highest vulnerability. The CFVI was mapped and analyzed to evaluate the overall vulnerability of the city to flash floods.

4 Results

4.1 Physical vulnerability index (PVI) of flash flooding

The simulated 6 h of high-intensive rainfall will result in 772,729,876 m³ of surface runoff creating flash floods attaining to a maximum height of 5.8 m and inundating large sections of central and southern neighborhoods of the study area. Based on slope gradient, the flood water will tend to flow from the northwest to southeast to drain into the Wadi Hanifa channels and inundate its surrounding areas (Fig. 4a). Since the Wadi channel beds are now filled with urban wastes, construction debris, and eroded soil materials, their depth varies from 0.5 m in the northwestern neighborhoods to 4–5 m in the southern Ash-Shifa,

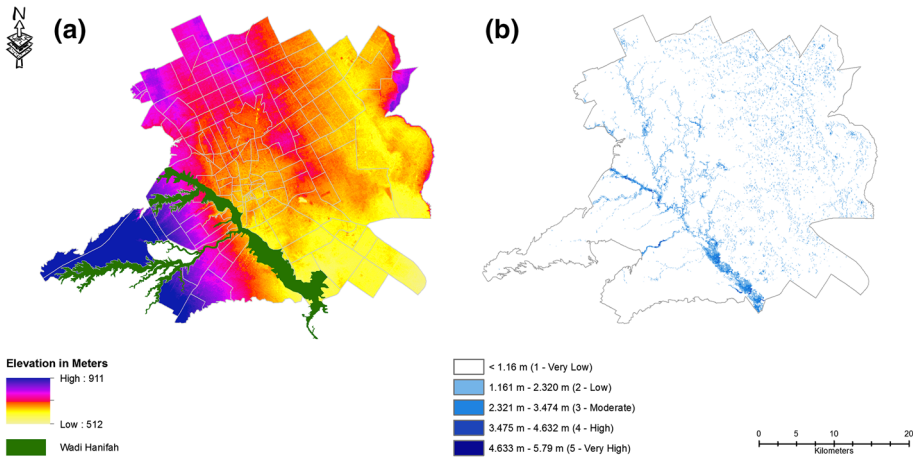


Fig. 4 Neighborhoods, Wadi Hanifa, and the topographic profile of the study area (a) and the distribution of the physical vulnerability scores (PVI) along with the flood depths across the study area (b)

Al-Bat'ha, and Al-Aziziyah neighborhoods where steep slopes increase the vulnerability of floods (PVI score 3–5) (Fig. 4b). After each rain, numerous existing ditches, highway tunnels, and underpasses in Al-Olaya, Al-Naseem, As-Sulai, and Khasem Alan neighborhoods transform into small basins with 1- to 2-m-deep flood water which makes them low to moderately (PVI score of 2–3) vulnerable (Fig. 4b). Elsewhere in the study area including the mountainous northern and western Al-Mathar and Al-Shimal neighborhoods, less than 1-m water accumulation creates low vulnerability (PVI score <2).

4.2 Social vulnerability indicators of flash flooding

4.2.1 Demographic indicators

4.2.1.1 Population density High population density increases the disaster vulnerability by impeding rescue and evacuation operations (Cova and Church 1997; Cutter et al. 2000). In Riyadh, the highest population density ($>20,000$ people/km²) was found in the downtown/central Al-Malaz, Ash-Shomaisi, and Al-Batha municipal neighborhoods inhabited by large number of emigrant laborers, service workers, low-income small business owners, and their employees. Population density decreases to <1000 people/km² in the high-class residential neighborhoods in peripheral suburbs of the city where professional expatriates, diplomats, businessmen, and elite governmental employees live. Based on population density, highest vulnerability of flash flood (index score 0.6–1) was found in densely populated downtown central Al-Malaz, Ash-Shomaisi, and Al-Batha municipal neighborhoods; low vulnerability (0.2–0.4) in the moderately populated western and northern neighborhoods of Ar-Rawdah, Al-Urajja, Al-Olaya, Al-Mathar, and An-Naseem municipalities; and very low vulnerability (<0.2) in the very thinly populated outskirts of the city (Fig. 5a). About 9 % of city's total population are highly vulnerable (>0.6), 7 % are moderately vulnerable, and remaining 84 % are least vulnerable to flash flooding (Table 3).



Fig. 5 Distribution of vulnerability index scores for population density (a), percentage of children and elders (b), percentage of non-Saudi Arabs (c), and percentage of Asians (d) in the study neighborhoods

4.2.1.2 Age Human experience and perception of natural hazards change with age. Middle-aged educated adults have better understanding and perception of the flash flood warnings than younger and older people, and they have a better idea how to escape and save their family members from a flash flood. In any flooding situation, young children (<7 years) and older adults (>65 years) always suffer the most due to their physically restricted mobility (Bolin and Bolton 1983). Considering this phenomenon, Ar-Rawdah, Al-Shimal, and An-Naseem in the north, Namar, Ash-Shifa, and Al-Aziziyah in south, and a narrow band of central neighborhoods, where large number of families with young children (<7 years) and senior citizens (>65 years) live, were found to be moderately (0.3–0.6) vulnerable (Fig. 5b). Elsewhere, the eastern neighborhoods inhabited by single Asian expatriates, and small families without children or older parents were found to be the least vulnerable (<0.2) to flash floods.

4.2.2 Social indicators

4.2.2.1 Ethnicity Ethnic composition was found to be an important social indicator of vulnerability in general (Bolin and Bolton 1986; Fothergill et al. 1999), and flash flood vulnerability, in particular, as ethnic differences affect the strategies of coping with a flash flood (Valverde 2011). In Riyadh, most of non-Saudi Arabs live in Al-Malaz, Al-Olaya, Ash-Shomaisi, and Al-Batha, while most Asians reside in As-Sulai, Al-Batha, and Al-Aziziyah neighborhoods (Fig. 5c, d). The majority of these minority groups live in low-cost apartments in and around the city center near their workplace. During 2009 and 2013

Table 3 Percentage of population allocated for each index value for the seven indicators of social vulnerability

Indicators of social vulnerability	Index value ranges													
	0–0.2		0.21–0.40		0.41–0.60		0.61–0.80		0.81–1					
	Population	%	Population	%	Population	%	Population	%	Population	%	Population	%	Population	%
Population density per neighborhood	2,152,781	53.47	1,259,994	31.29	263,740	6.55	195,167	4.85	154,805	3.84				
% of children (<7) and elders (>65) per neighborhood	2,384,747	59.23	1,626,333	40.39	10,483	0.26	3900	0.10	1024	0.03				
Average income per neighborhood	89,814	2.23	133,626	3.32	384,662	9.55	1,133,573	28.15	2,284,812	56.74				
Percentage of Arabs (non-Saudi) per neighborhood	3,214,487	79.83	404,016	10.03	310,832	7.72	70,345	1.75	26,807	0.67				
Percentage of Asians per neighborhood	3,234,603	80.33	488,504	12.13	224,702	5.58	76,793	1.91	1885	0.05				
Percentage of people unemployed per neighborhood	1,438,544	35.73	170,192	4.23	787,542	19.56	1,376,634	34.19	253,575	6.30				
Percent of urban built-up area per neighborhood	0	0.00	54,705	1.36	145,992	3.63	189,061	4.70	3,636,729	90.32				

flash floods, these people were severely affected as their homes and businesses were submerged under 1–2 m of water for several days. Both downtown and south and eastern neighborhoods were found to be moderate to highly vulnerable (index values >0.35) to flash flooding. In the northern Al-Olaya, and Al-Mathar, the Saudi residents employ Filipino, Indian, Pakistani, and Bangladeshi expatriate drivers and housemaids who live in the Saudi family residences and experience very low vulnerability (<0.2). The non-Saudi Arabs, who have no experiences with flash floods, are more vulnerable to the hazard than the experienced Asians.

4.2.3 Economic indicators

4.2.3.1 Average annual income and unemployment Unemployment contributes to low household income among expatriate and Saudi families living in As-Shifa, Al-Batha, Al-Malaz, and Al-Olaya neighborhoods. Few neighborhoods in the immediate northern vicinity of the central downtown showed high annual household income as well as high rate of unemployment among rich Saudi families. These family members earn high income from their businesses, and their adult family members simply do not work and are not in the labor force. This phenomenon resulted in the vulnerability index scores of ≤ 0.4 for household income, while scores ≥ 0.5 for unemployment (Fig. 6a, b). From the average-income perspective, 85 % of low-income residents are highly vulnerable to flash flooding. Similarly, 60 % of unemployed residents are moderate to highly vulnerable to flash floods, while 40 % residents who are members of wealthy Saudi families and not in the labor force are least vulnerable to it (Table 3).

4.2.4 Built-up environment indicator

4.2.4.1 Urban land use and development of built-up environment Over the past 45 years, the City of Riyadh has grown as the national capital and the headquarter for political power and decision makers of an oil-rich Kingdom. The Saudi Government has established the High Commission for the Development of Arriyadh (HCDA) in 1974 to plan and supervise the city's socioeconomic development and environmental management. The present urban land use of 18.8 % residential, 11.2 % agricultural, 37.1 % roads, 1.8 % industrial, 2 % commercial activities reflects government's political decisions on the capital's development (Arriyadh.com 2014). Since 1971, the Saudi Government had approved, modified, and updated the Riyadh City Master Plans to expand and improve the built-up

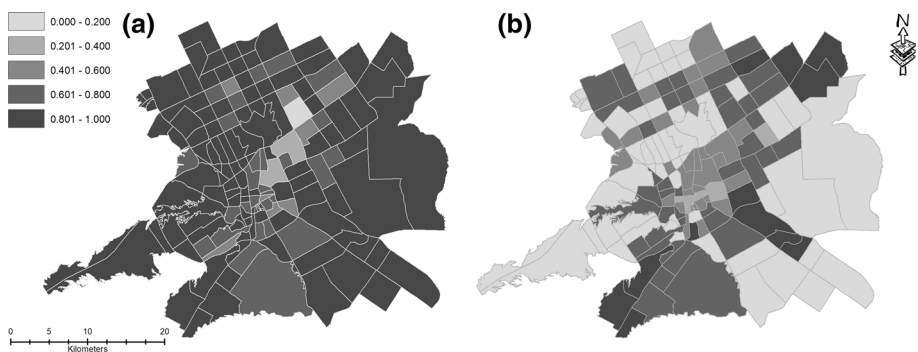


Fig. 6 Distribution of vulnerability index scores for average income (a) and percentage of people unemployed (b) in the study neighborhoods

environment. They have spent huge sum of money to build new residential buildings and to construct 446 km of new road and highways, 70 tunnels, 79 bridges, and 175-km metro rail line in addition to the improvement of the existing roads and highways (Table 4). However, in the wake of oil-based economic boom and staggeringly faster population growth, implementation of those Master Plans was not fully successful and the city's built-up environment continued to grow somewhat unplanned way, increasing its vulnerability of flash flood in several ways (Arriyadh Development Authority 2003). First, urban construction has increased the imperviousness of sandy soils, which in turn accelerated the accumulation of rain water to cause flash floods. Second, filling of Wadi Hanifa channels by construction debris has greatly reduced its water holding, infiltration, and drainage capacity. Meanwhile, an expansion of city sewage system coverage from 14 % in 1982 to 53 % in 2014 has increased the sewage runoff into the Wadi from 500,000 m³ to 800,000 m³ daily (Arriyadh Development Authority 2003, 2013). Although 37 % of the sewage runoff is recycled, the remaining untreated water raises the ground water table and pushes solid wastes back to septic tanks, causing architectural damages to building foundations and structures, and roads and tunnels along the Wadi (Arriyadh Development Authority 2003). All of these have increased the city's risk of flash flood hazards even with short torrential rain for 45 min as observed on May 3, 2010 (Alamri 2011). Spatially, the highest vulnerability of flash floods (>0.85) was found in 129 high-density residential neighborhoods in the city, along the banks of Wadi Hanifa, and areas along the highways running through the city, especially near the tunnels and underpasses (Fig. 7).

4.2.5 Social vulnerability index (SVI) of flash flooding

We categorized the SVI scores into quantiles and identified very low (bottom 20 % quantile) to very high (top 20 % quantile) with middle three quantiles representing low, moderate, and high levels of social vulnerability in the study area (Fig. 8a). The densely populated central, south, and eastern neighborhoods, where large number of low- to moderate-income non-Saudi Arab and Asian ethnic minority families with large number of children and older members live, are moderately to highly vulnerable. The sparsely populated western and northern peripheral neighborhoods, where high-income Saudis and ethnic minority professional families live, show very low to low vulnerability to flash floods. It was observed that age, ethnicity, household income, degree of unemployment, and urban land use patterns influenced the community experience and perception of flash flood hazards. Older Asian population with low annual income, living in highly urbanized central downtown areas, would be the most vulnerable people who have experienced flash floods in the past and have better perception of its impacts. Their perception and experience will help them to recover from and cope with future flash flood hazards.

4.3 Composite flood vulnerability index (CFVI) of flash flooding

The CFVI scores ranged between 0.202 and 2.09. They were categorized into quantiles to identify very low–low–moderate–high–very high levels of vulnerability in the study area (Fig. 8b). About 13 % of city area was found to be very highly vulnerable; 23.7 % high; 22.6 % moderate; 21.2 % low; and 19.5 % to be least vulnerable to flash floods. Mapping CFVI scores suggest that the low-lying southern half of the central city, southeastern, and several northernmost neighborhoods, where flood water accumulates to a higher depth after each rain, are moderately to very highly vulnerable to flash floods. These neighborhoods are densely settled by large number of low-income and labor families who work in the

Table 4 Population growth, urbanization, and flash flood events in Riyadh from 1971 to 2016. *Sources:* Al-Mubarak (1999), Arriyadh Development Authority (2003), Middleton (2009)

Phase	Years	Population (in millions)	Urbanized area (in km ²)	Number of residential units	New constructions of roads in km	Government spending on roads (in billions of USD)	Runoff from Wadi Hanifa (m ³)	Number of flash floods
1	1971–1985	0.66 (1974)	300	151,963	199	NA	500,000	1
2	1986–1995	2.80 (1992)	632	297,859	71	2.96	Data not available	0
3	1996–2005	4.50 (2004)	1785	543,357	58	2.74	Data not available	2
4	>2006	6.20 (2015)	1800	900,000	118 for roads 176 for metro	4.90 for roads 22.0 for metro	800,000	9

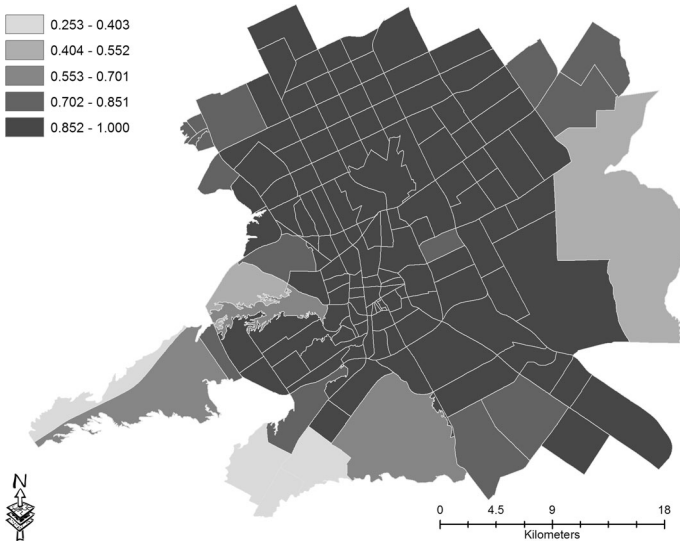


Fig. 7 Distribution of vulnerability index scores for the percentage of urban built-up area of each neighborhood

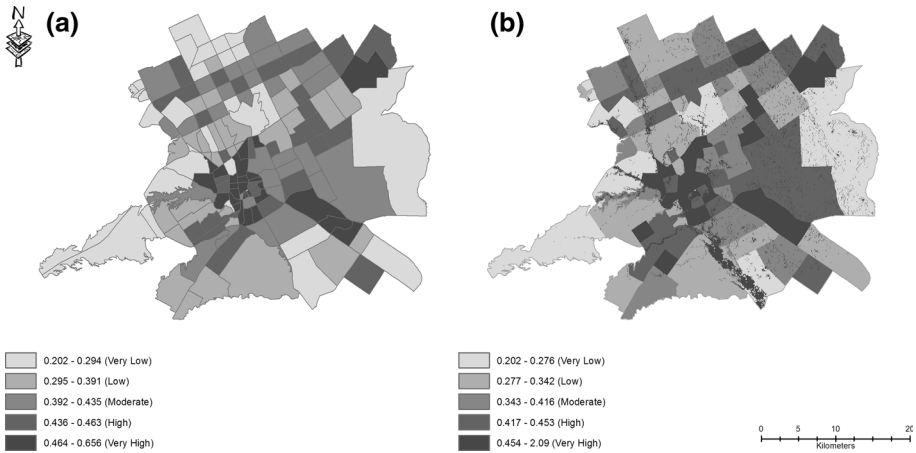


Fig. 8 Distribution of the social vulnerability index (SVI) scores (a) and composite flood vulnerability index (CFVI) scores (b) across the study area neighborhoods. Muhammad Tauhidur Rahman

surrounding urban and industrial areas. In contrast, the northern half of the central city, western, northwestern, and southwestern neighborhoods were found to be the least (very low to low) vulnerable. These sparsely populated mountainous lands are occupied by residential buildings of high-income Saudis and Asian expatriates.

4.4 Discussion

The study results have several comparative methodological, theoretical, empirical, and policy implications. First, the study has made significant contributions to the methodology

of flash flood vulnerability study by applying a sophisticated GSSHA flood simulation model to map the flood vulnerable areas and then integrated it with key indicators of social vulnerability to compute a composite vulnerability index (CFVI). While several existing studies focused mostly on analysis of physical aspect of flash floods (e.g., Ruin et al. 2008, 2009), others emphasized more on the human, economic, and behavioral issues and ignored the physical aspects of the hazard (Gruntfest and Handmer 2001; Ruin et al. 2008; Pollak 2009; Ruin et al. 2009; Valverde 2011; Špitalar et al. 2014), and the present study significantly differs from them on the ground that it has analyzed the physical, social, economic, and built-up environmental factors affecting the flash flood vulnerability of a desert city through reexamining the theoretical premises of Cutter's hazard-of-place model. The study results suggest that rapid population growth and unplanned urbanization, increased surface imperviousness, increased sewage runoff, and inadequate drainage capacity of the Wadi Hanifa jointly contributed to frequent flash floods in Riyadh in the event of a torrential rain. These conditions have also increased the risk of more frequent hazardous flash floods in the next 25 years (Arriyadh Development Authority 2003; Sharif et al. 2016). The flash flood map simulated and analyzed here has initially identified the city areas at very high risk of future flash flood exposure. This map along with other government initiatives will help to plan flood mitigation and adaptation strategies.

Second, the present study has met the existing gap in the global flash flood vulnerability research concerning a highly urbanized rapidly growing non-riverine desert city. As mentioned earlier, high-intensive rainfall on impervious concrete surfaces has increased the flash flood vulnerability of the study area. Most of the 168 victims who died of flash flood over the past 7 years were young children, women, and very old people who were either walking on streets or trapped inside their car while traveling and drowned in violently moving flood water (BBC, Al-Jazeera TV, Arab News, and YouTube videos). These findings are comparable to numerous case studies on smaller rural watersheds in riverine humid and semi-arid regions in the USA, Mexico (Gruntfest and Handmer 2001; Montz and Gruntfest 2002), and Southern France (Ruin et al. 2008) where urbanization and age were found as factors increasing the vulnerability of flash flood hazards.

Third, people's experience with and perception of flash flood varied with ethnicity. We observed from the video footages that victims of flash floods in Riyadh were Saudi and non-Saudi Arab residents who had no previous exposure to flash floods. They suffered while travelling under heavy rain in the flooded roads, highways, tunnels, and underpasses. Although the weather service of Riyadh had issued early warnings of intensive rainfall, many Saudis were not knowledgeable and did not understand the severity of the warning system and became vulnerable. Interestingly, none of the victims were Asians who had previous exposure to flash floods. This finding provides support to studies reported by Ruin et al. (2008, 2009); Pollak (2009); and Špitalar et al. (2014).

Fourth, the study results suggest that Riyadh's rapid population growth and unplanned urbanization have created unsafe conditions particularly in the low-lying central neighborhoods. Unemployed or low-income Saudi and non-Saudi expatriate families living in such unsafe conditions were exposed to hazardous flash floods, and their children, women, and older people were the most vulnerable to these floods. This finding provides strong support to the political economy model of vulnerability (Hewitt 1983; Watts 1983; Liverman 1990; Bolin and Stanford 1991; Haque and Blair 1992; Blaikie et al. 1994; Hewitt 1997; Wu et al. 2002; Wisner et al. 2003).

Fifth, from the analysis of physical and social vulnerability indices and their maps, it became apparent that population growth, surface elevation, and rapid urbanization increasing surface imperviousness are major anthropogenic exposure factors increasing the

vulnerability of flash flooding of Riyadh. People's age, ethnicity, income, rate of employment, and deteriorating living conditions in the urban built-up environment are social and economic factors that influence people's experience with and perception of flash floods. They act as the social fabric that influenced the flash flood vulnerability of the city. This finding supports Cutter's place-of-hazard model as well as other flash flood vulnerability case studies in the USA reported by Calianno et al. (2013) and Hong et al. (2013).

Sixth, the study has revealed that Riyadh's urban development was shaped by the Saudi Government's political and economic power relations, national capital development plans, and monetary spending on building residential units and transport networks, which, in turn, had increased the city's vulnerability to flash floods. The lack of neighborhood-level data prevented us from inclusion of a political ecology indicator in the composite flash flood vulnerability index (CFVI) to examine the effect of government's role on climate governance and mitigation of flash flood vulnerability of the city. However, our analysis of aggregate data on government spending on urbanization and their impact on increased flash flood vulnerability of the city lends us at least a minimal support to Liverman's (2015) political ecological framework of climate vulnerability research.

Finally, flash floods are new climatic hazards affecting the economy, residential and transport infrastructures, and public health and safety of the residents of Riyadh. The Riyadh City government has formalized Master Plans for public safety and evacuation regulations, and the Civil Defense Corps and Riyadh City Police Department are responsible for the emergency evacuation and flood disaster management. However, neither their effectiveness has been adequately tested, nor the flash flood forecasting and warning systems were updated with advanced technologies (Alamri 2010; Al-Qahtani 2014). The level of city's preparedness, people's capacity to respond to and cope with, challenges of mitigation, adaptation, and resilience to hazardous flash floods are grossly inadequate due to lack of previous experiences. Higher training and frequent simulation exercises on flash flood management for both city residents and government officials are needed to improve the city's preparedness for managing the disaster.

5 Conclusions

The present study has constructed, mapped, and analyzed the physical, social, and composite flash flood vulnerability indices of 153 neighborhoods of the City of Riyadh, the capital of the Kingdom of Saudi Arabia. While the physical vulnerability of the city to flash flooding was assessed by simulating 6 h of intensive rainfall and measuring the depth of flood water, its social vulnerability was assessed by standardized ranking of census data on seven demographic, social, economic, and urban built-up environment variables. The physical vulnerability map revealed that most of the city's central and southern low-lying floodplain lands occupying high-density residential, commercial, industrial buildings, roads, highways, tunnels, bridges, and underpasses are highly vulnerable to flash floods compared to the western highlands. The SVI revealed that densely populated areas inhabited by low-income unemployed families are more vulnerable to flash floods than sparsely populated areas inhabited by high-income families. It is to be noted here that despite the occurrence of nine flash floods in the City of Riyadh over the past 7 years, there were no maps or recorded flood data identifying the flood-affected areas. There were also no post-flood research data and interviews of families of victims about the situation in which they died. This has made the present vulnerability study a very difficult task. Also,

we could not incorporate political ecological indicators of climate vulnerability due to lack of sufficient data. However, we recognized that under the evident climatic warming, the city has increased risk of exposure to frequent flash floods in the next 25 years. Although the study has identified city areas and residents vulnerable to flash floods, Saudi Government's political decisions on climate governance, as well as improved preparedness through constant training, would play an important role in planning strategies toward flash flood mitigation and adaptation. This research can be further expanded to include more social, political economic, and political ecological indicators that may make the city more vulnerable to future flash floods.

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Author Contributions As the first author, Muhammad Tauhidur Rahman planned and developed the research framework, performed the GIS and data analyses, created and mapped the vulnerability indices, and prepared and edited the manuscript. Adel Aldosary and Kh Md Nahiduzzaman collected the socio-economic data and edited the manuscript. Imran Reza simulated and produced the flash flooding results and maps.

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