

Population evacuation: evaluating spatial distribution of flood shelters and vulnerable residential units in Dhaka with geographic information systems

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Abstract The objective of this study was to evaluate the spatial distribution of flood shelters in relation to flood hazards in a resource-poor country. Flood hazard estimates were developed from multi-temporal flood-affected frequency and floodwater depth maps. It is intended that the results could support non-structural flood management. In addition, the location of vulnerable housing units was mapped and their accessibility to shelters was computed with the aid of spatial techniques using a geographic information system. A subset of the Dhaka Metropolitan Development Plan zone and Dhaka megacity, covering an area of 878 km², was used as a case study since this area is likely to experience more frequent and intense flooding in coming years as a result of rapid urbanisation and climatic change. Using three different criteria, the study identified that a total of 5537 buildings, out of 6342 candidate structures, can be used as emergency shelters during floods, and approximately 145,000 dwellings (19.3 % of total residential units) of various types were located in places that are prone to flood. Further, many (3500 of 5537) of the identified shelters were not sufficiently close to vulnerable dwellings to protect approximately 496,000 potential flood victims during an emergency. There were 26.4 % of the total residents living in vulnerable housing units. In addition, 1098 flood shelters were distributed over five catchments in the study area, although in close proximity to vulnerable residents, do not have the capacity to house the number of people who could potentially seek refuge there. This study, the first of its kind in Dhaka, can assist urban planners and emergency managers in developing an effective evacuation plan for an imminent flood disaster as the city currently lacks any disaster management plan.

Keywords Dhaka · Flood shelter · Population evacuation · Geospatial modelling · Flood hazards · GIS

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1 Introduction

One of the most important negative consequences of climate change would be an increase in the frequency and intensity of weather-related hazards (Easterling et al. 2000). Studies have demonstrated that among hydro-meteorological hazards, floods are the most pervasive and their impact in terms of economic loss is intensifying with time (Jha et al. 2012; Ferreira et al. 2011). For example, floods occurring between 2000 and 2011 around the world resulted in an estimated loss of more than US\$ 285 billion which can be compared to loss of only US\$ 1.8 billion during the 1950s (Dewan 2013; EM-DAT 2012). From this statistics, one can perceive that the economic loss from floods has increased considerably despite the fact that there has been inflation in the value of the dollar as well as increases in the price of commodities. Although developed countries are not immune to flood-related hazards, loss of life is significantly higher in developing countries (Ferreira et al. 2011). Of the deaths attributed to flood between 1950 and 2011, 96 % occurred in Asia, 2.6 % in the Americas, 0.9 % in Africa, 0.4 % in Europe and 0.02 % in Oceania (Dewan 2013; EM-DAT 2012). An examination of the total number of deaths from floods between 1975 and 2000 around the world showed that the highest number of deaths (50 %) occurred in the low-income group and the middle-income group ranked second (49 %), whilst the high-income group accounted for only about 1 % of the total fatalities (UN 2003). Various modelling studies suggest that floods could bring significant level of suffering to people in the days ahead as a result of climate change (Whitfield 2012; Pall et al. 2011; IPCC 2007). For instance, Kleinen and Petschel-Held (2007) have predicted that up to 20 % of the world's population is at risk of increased flood activity due to climate change. This number, however, is likely to increase with a further rise of global temperatures (Hirabayashi and Kanai 2009).

Bangladesh, which is one of the most low-income countries in the world, frequently attracts the attention of the world community because of its high prevalence of various types of natural hazards, including floods. It is estimated that Bangladesh loses around US\$ 175 million in a normal year because of water-related hazards, particularly floods, which is restraining its economic progress (Mirza 2011). Despite the implementation of massive flood control works since the 1960s, predominantly those built under the Flood Action Plan (FAP) of the 1990s, flood remains an inordinate threat to people which is evidenced by the increasing damage to life and property (Hoque et al. 2011; DMB 2007; Mallick et al. 2005). For instance, the estimated loss due to the moderate flood event of 2004 was higher than loss for the 1998 flood, although the 1998 flood was the worst on record in terms of intensity and severity (DMB 2007; Choudhury 2006). Paradoxically, a significant increase in the extent of flood hazard areas across the country is reported by the Water Resources Planning Organization as being clearly linked with an increase in flood control works such as embankments (WARPO 2000). This is due to poor performance, and maintenance of engineering structures and the continual encroachment of urban areas onto floodplains in protected areas, which have caused pluvial flooding to become severe in many parts of the country (Bala et al. 2009). This is particularly the case in large cities such as Dhaka (Islam 2006). Even though fewer lives have been lost during the recent flood events, studies suggest that floods will continue to be a major concern for Bangladesh as a 23–29 % increase in flooded areas is forecasted with the rise in global temperatures of 2 °C (Mirza et al. 2003).

The overall objective of this paper is to assess the spatial distribution of flood shelters and vulnerable residential units in Dhaka with respect to flood hazards. Specifically, the study attempts: (1) to map the vulnerability of housing units to flood; (2) to identify

potential flood shelters based on flood hazards and evaluate their distribution in relation to vulnerable housing units; and (3) to estimate the potential population served by each shelter.

2 Background

Dhaka, the capital of Bangladesh, has experienced many disastrous floods in the last four decades. Though fluvial flooding was the dominant process during the 1988 and 1998 floods (Faisal et al. 2003), pluvial flooding was a major concern for the city during the 2004 and 2007 floods (Stalenberg and Vrijling 2009). This pluvial flooding caused a number of problems, including scarcity of drinking water, severe disruption to economic activities and an increase in the prevalence of waterborne diseases (Bala et al. 2009; Alam and Rabbani 2007; Khan 2006). Despite the embanked part of the city suffering relatively less damage from fluvial flooding during the 2004 and 2007 floods, it has been shown that the embankment itself was responsible for pluvial flooding in the city which caused considerable monetary loss in three sectors (infrastructure, telecommunications and ready-made garments) (Alam and Rabbani 2007). Similarly, a total of 43,250 diarrhoea cases were admitted to the International Center for Diarrhoeal Disease Research, Bangladesh (ICDDR, B) hospital during the 2007 flood (Harris et al. 2008). This was considerably higher than the number during the 2004 flood (IEDCR 2004). Studies have suggested that a number of factors are gradually diminishing Dhaka's ability to deal with flood hazard. These include: high dependency on structural solutions (Sultana 2010; Stalenberg and Vrijling 2009), very poor maintenance of flood control works (Bala et al. 2009; Chowdhury et al. 1998), continuous encroachment of urban areas onto surface waterbodies (Dewan et al. 2012a, b; Hossain and Rahman 2011; Dewan and Yamaguchi 2008; Alam and Rabbani 2007), dilapidated drainage infrastructure (Hossain and Rahman 2011; Khan 2006), high population density and extreme level of poverty (Sanderson 2012; Braun and Aßheuer 2011; Jabeen et al. 2010; Rashid et al. 2007; Islam 2005), an inadequate governance system (Barua and van Ast 2011), poor flood preparedness (Dewan 2006; Mallick et al. 2005) and inappropriate physical planning (Roy 2009). Together these factors increasingly place more people and properties at risk since the adaptive capacity of the city of Dhaka to climatic extremes is extremely poor compared to many large cities in the world (Senga 2004). The problem is expected to worsen with the on-going effects of climate change (Balica et al. 2012).

Despite the considerable level of resources that have been put in place to ameliorate flood damage, the city's vulnerability to flood has clearly increased with time (Dewan 2013) being exacerbated by piecemeal and unplanned urban growth (Dewan et al. 2012b; Sarker and Sivertun 2011). In order to safeguard life and property from future floods, a number of adaptation measures to water-related hazards have recently been proposed (GoB 2005). However, the success of flood management initiatives depends on a number of factors which can be placed in three categories: population factors, adaptability and future climatic prediction.

In the first case, due to a widespread misgovernance in urban and development sectors and an ever-growing population together with extreme inequality in resource distribution constantly compels thousands of people to settle in dangerous locations that are highly prone to flood. Using geospatial and census data at the community level within a geographic information system (GIS) framework, Dewan (2013) demonstrated that in 2001,

18 % of the population of Dhaka were living in high and very high flood risk areas. By 2011, this had increased to 22 % (Masuya 2014). Taking this in a context of a growth in the city population during the same decade indicates very large increase in the number of people at risk.

Secondly, Dhaka megacity (DM) currently has an ‘adaptation deficit’ (Burton 2005/2006) as non-climatic factors such as unplanned urbanisation are persistently increasing the exposure of urban infrastructure and properties to flood (Roy 2009). For example, the percentage of houses within the high and very high flood risk zones that are of *katcha* type (made from fragile materials) has increased from 43 % in 2001 to 70 % in 2011 (Masuya 2014). Since *katcha* houses are occupied by people from low socioeconomic groups, potential damage to life and property from future flood remains high.

Thirdly, existing flood control structures in the city were designed on the assumption of a stationary climate. With increased climatic dynamism, these structures are no longer relevant or valid (Milly et al. 2008). The traditional concept of ‘flood return period’ has been rendered meaningless by climatic non-stationarity (Kundzewich et al. 2010). Bangladesh is a resource-poor country and is not well placed to construct additional flood control structures, with their associated maintenance costs (Brammer 2010) or to incorporate new design codes into the existing structures (Kundzewich et al. 2010). The construction of engineering structures is further constrained by very high population density and limited available land. Taking all these factors into consideration, a new approach, based on non-structural measures, is required for effective preparedness planning to lessen the increasing flood vulnerability of Dhaka (Maniruzzaman and Alam 2002).

A disaster management cycle (Alexander 2000) or an emergency management system (Godschalk 1991) includes four distinct phases: mitigation, preparedness, response and recovery. Geospatial techniques can be effectively used in any of these phases for the successful management of natural disasters (Ebert et al. 2009) such as floods (Cutter 2003; Gunes and Koval 2000). Even though these techniques have shown immense potential in identifying hazard and risk areas with respect to flooding in various settings (Dewan 2013; Gillespie et al. 2007; Sanyal and Lu 2004), relatively little work has been done in the areas of flood disaster preparedness and the formulation of response strategies such as emergency evacuation planning (Kar and Hodgson 2008). Whilst Kar and Hodgson (2008) used GIS techniques in a study of shelter locations in Florida and a review by Banks et al. (2014) looks at the use of spatial tools for flood planning in a US context, developing countries have received less attention although Patel and Srivastava (2013) have used geospatial techniques for disaster management planning in Surat district (India). As emphasised by Hunt and Watkiss (2011), emergency preparedness and spatial planning will have an increasing role to play in reducing the risks associated with floodplain development in cities.

Non-structural solutions such as evacuation planning are becoming an emerging issue due to their effectiveness in reducing disaster risk and vulnerability (Yusoff et al. 2008; Cova 1999). Various methods, including macro-simulation, meso-simulation and micro-simulation models, have been applied to a range of hazards. For example, microscopic traffic simulation linked with a GIS was used to test the neighbourhood evacuation plan in the urban–rural interface in Salt Lake City, Utah (Cova and Johnson 2002). Kongsomsakul et al. (2005) used a location-allocation model to demonstrate optimal siting of shelters for flood evacuation planning. They combined the locations and capacities of shelters with available traffic networks to minimise the evacuation time through a bi-level programming model. Dunn (1992) used network algorithms within a GIS to identify alternative evacuation routes in an emergency. Similarly, Cova and Church (1997) developed a

method to examine potential evacuation difficulties in the transportation network during a simulated disaster in Santa Barbara, California. In another study, Cova et al. (2005) described a technique to estimate population at risk from wildfire. Using the concept of an ‘evacuation trigger point’, they delineate the time required to evacuate in the event of a wildfire in California. An agent-based model was used by Chen et al. (2006) to develop a procedure to determine potential evacuees and clearance times needed for evacuation during hurricane hazards in the Florida Keys. A similar type of method has been employed by Chen and Zhan (2008) to demonstrate simultaneous and staged evacuation strategies in the city of San Marcos, Texas. That study further remarks that, although certain staged evacuation strategies do help to reduce the total evacuation time, traffic congestion during a mass evacuation could be a serious issue. It should be noted that the majority of the micro-simulation work is based on a network data model, usually in a small area, to determine the total clearance time needed for evacuees to leave during an approaching disaster. Additionally, agent-based models could be difficult to implement in densely populated areas (Fang et al. 2003). Because Dhaka is densely populated and there is no up-to-date road network data, agent-based modelling or flood evacuation planning is very difficult task to carry out.

Apart from the simulation studies described above which require high-resolution geographic data (Cova and Johnson 2002) and advanced algorithmic skills (Yusoff et al. 2008), a few studies have utilised the spatial analytical tools embedded in a GIS to determine the site suitability of emergency shelters (Sanyal and Lu 2009; Kar and Hodgson 2008; Gall 2004) and to perform evacuation needs assessment (Chakraborty et al. 2005). Kar and Hodgson (2008) used a range of physical and social variables and the location of critical facilities in a weighted linear combination (WLC) approach with a Pass/Fail technique to identify the suitability of emergency evacuation shelters in Florida. Ironically, the study revealed that 48 % of existing shelters are located in physically unsuitable areas. Based on field survey, Gall (2004) employed spatial analysis to determine the location of vulnerable communities in Mozambique. The study further incorporates land cover, local infrastructures, and location of accommodation and human settlements to evaluate the suitability of emergency shelter sites. A study in Hillsborough County, Florida, used two different indexes (geophysical risk index and social vulnerability index) to assess the spatial variability of evacuation needs in relation to hurricane hazards (Chakraborty et al. 2005). A flood time image from European Remote Sensing Satellite-2 (ERS-2) with the location of rural settlements, derived from topographic maps, has been used to identify optimal sites for flood shelters in India (Sanyal and Lu 2009). In addition to these, a system dynamics approach was developed by Simonovic and Ahmad (2005) to estimate the number of evacuees and capture human behaviour in the Red River Basin, Canada. That study attempts to examine human decision-making processes in response to disaster warning using psychological, social and policy parameters.

Unfortunately, despite Bangladesh being prone to frequent large floods, studies of the kind described above are rare. Work based on a questionnaire survey in relation to the 1998 flood reported that emergency shelters are established on an *ad hoc* basis and only people from low-income groups took refuge during that flood (Maniruzzaman and Alam 2002). Unlike rural Bangladesh where designated flood shelters exist and are governed by the local administration, flood shelters in Dhaka were mainly initiated by local politicians. Hence, they were poorly coordinated, severely overcrowded and extremely unhygienic (Maniruzzaman and Alam 2002). Flood victims from better socioeconomic backgrounds preferred not to seek refuge in those shelters due to psychological barriers and lifestyle differences (Maniruzzaman and Alam 2002). In short, such types of ad hoc shelters are

incapable of reducing the societal/or community vulnerability to flood since affected people are often cut off from any kind of humanitarian assistance (Gall 2004) as was evident during the 1998 and 2004 floods in Dhaka (Hasnat 2006; Sarker et al. 1998).

Since emergency evacuation planning in relation to natural hazards requires a great deal of geographic data, a lack of spatial information can hinder the development of spatially explicit models, particularly in developing countries. For instance, Cova (1999) stated that high-resolution road networks, spatially referenced population datasets and accurate location of critical services greatly facilitated evacuation planning in the USA. Data of this quality are simply not available in low-income countries (Sanyal and Lu 2009; Gall 2004) which limits the construction of spatially explicit models for emergency preparedness and/or response strategies in such countries. Whilst it is true that some volunteered geographic information sources such as Open Street Map may eventually improve on this situation, it is the authors' experience that in developing countries that data currently suffer from an unacceptable level of errors of omission. Although the study by Sanyal and Lu (2009), for example, contributed to the understanding of the use of geospatial techniques in non-structural planning in a data-poor country, it does have a number of limitations. For example, they use only one flood event to identify hazard areas which seems an inadequate representation of flood hazards in an area (Hoque et al. 2011). Besides, lack of information on the population of the affected settlements or of other parameters such as building material type further weakened that study. Our study attempts to fill a gap by considering multi-temporal flood events with other spatially referenced information (e.g. population, location of shelters and housing characteristics) within a GIS framework.

A study of potential flood shelter accessibility in Dhaka has a number of special features. Firstly, it is a low-lying city with flat topography and dense overcrowding, rendering flood onset rapid and flood duration extended, both of which mean that evacuation out of the flooded area is very difficult. Secondly, it suffers from a lack of solid (*pucca*) multi-storey buildings capable of acting as shelters. Thirdly, its great socioeconomic disparity, layered social structures, chaotic civil administration and reliance on ineffective poorly maintained flood prevention structures mean that it has no organised shelter system, such as that present in rural Bangladesh.

3 Materials and methods

3.1 Study area

The study area encompasses a subset of the Dhaka Metropolitan Development Plan (DMDP) zone and DM that includes the historic city core and adjoining areas (Fig. 1). The area is located between 23.61° and 23.97°N latitudes and 90.22° and 90.59°E longitudes, and has an area of 878 km². Topographically, most of the area is flat with land elevation ranging between 0 and 16 metres above mean sea level (MSL) (FAP 8A 1991). It experiences a subtropical monsoonal climate with an average annual rainfall of 2000 mm, of which more than 75 % occurs during the monsoon season. There are five major rivers flowing across the study area: the Buriganga to the south, Turag to the west, Tongi Khal to the north and the Lakhya and Balu to the east and southeast. The major geomorphic units of the area are the highlands (or the Dhaka Terrace), the lowlands or floodplains, depressions and abandoned channels (Miah and Bazlee 1968). Geomorphologically, the

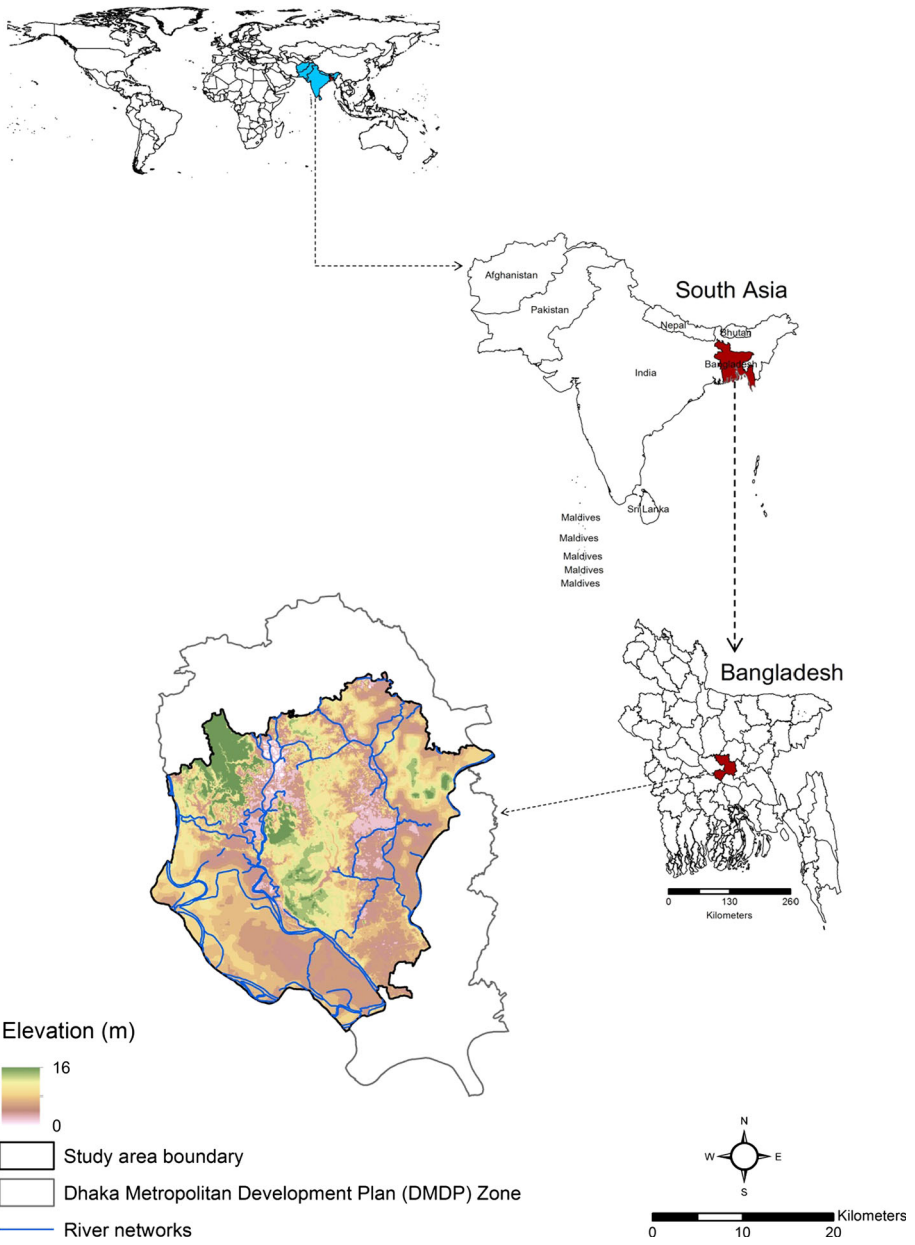


Fig. 1 Location of study area

dominant landform is a relatively young floodplain followed by higher terraces of the Pleistocene period (Kamal and Midorikawa 2004).

This study extent was chosen for several reasons. Firstly, the area is undergoing rapid urban development which has resulted in the rapid depletion of natural landscapes such as floodplains, cultivated areas and vegetation (Dewan and Corner 2012; Dewan and

Yamaguchi 2009a, b). For example, the current urban extent is predicted to grow from 19,556 ha in 2011 to 22,723 ha in 2022 at the expense of precious wetlands and agricultural lands, if the current rate of urban development continues (Corner et al. 2014). Effects of this include increased risk and vulnerability to flood in the coming years (Dewan 2013; Gain and Hoque 2012; Masood and Takeuchi 2012). On the other hand, the city's economy contributes at least 17 % of the national gross domestic product (GDP) (Islam 2005); so, high-magnitude floods caused by climatic extremes have a significant impact on both the local and national economies. As a result of rural–urban migration (Sanderson 2012; Islam 2005), the population of the city is increasing very fast, having increased from 5.4 million in 1991 to 11.6 million in 2011 (BBS 1998, 2012). This combined with a lack of residential space in existing urban areas forces many people to settle, often informally, in dangerous locations (Maniruzzaman and Alam 2002). As a result of increased exposure to flood and other water-related hazards, they are becoming the most vulnerable group. The mean population density of the study area according to the 2011 population and housing census is 39,277 persons per km². Understandably, this rapid very high density and population growth pose a big challenge to the relevant authorities in the development of effective spatial planning for reducing flood vulnerability (Stalenberg and Vrijling 2009). There is also tremendous inequality between the rich and poor in Dhaka (Siddiqui et al. 2010; Begum 2007), with the lowest per capita income being US\$ 550 per annum (Islam 2005). According to Hossain (2006), rich people constitute only 3 % of the total population who enjoy a high standard of living. It is the large number of people who are living below the poverty line, who are at highest risk of flood disaster (Jabeen and Johnson 2013; Rana 2011) and who predominantly seek refuge in the closest flood shelter during an emergency.

Even though non-structural solutions to flood, such as flood forecasting and warning systems, have improved significantly under the FAP (Bhuiyan 2006; Islam and Sado 2000), it has been shown that competent technical forecasting expertise, especially in estimating rainfall and flow, appears to be lacking (Chowdhury 2000). Nevertheless, flood forecasting and warnings based on advanced technologies could be used with some degree of certainty but precise warnings might be difficult to implement. One of the greatest deficiencies of the existing flood warning system is that warning messages are not easy for people to interpret effectively in order to respond to an approaching flood. To an illiterate person who lives at some distance from a particular river, a warning that the water level in that river will rise by six metres is essentially meaningless (Chowdhury 2005). In Dhaka, flood warnings are issued for major rivers such as the Buriganga, Balu and Lakhya but without any spatial detail (Hasnat 2006). In such a situation, it is very challenging for most of the inhabitants of the megacity to understand the danger level (DL) and to prepare themselves for evacuation (Dewan 2006).

Whilst some disaster planning does exist for Bangladesh as a whole (GoB 2010), the megacity of Dhaka presently lacks a specific disaster management plan (Hasnat 2006; Maniruzzaman and Alam 2002), which makes it impossible for the relevant authority to manage future large-scale hydrological events. It is, therefore, imperative to map out the locations of potential emergency shelters and their capacity based on flood hazards (Maniruzzaman and Alam 2002), which could assist effective flood preparedness planning. In addition, mapping of vulnerable housing units could support local communities to adapt with climate-induced extreme hydrological events, whilst measuring the accessibility of flood shelters for potential evacuees may reduce the degree of flood vulnerability to a larger extent (Gall 2004).

3.2 Data

The data used in this analysis comprised both spatial and aspatial data, collected from a number of sources. The spatial extent of floods, representing the four biggest flood events of 1988, 1998, 2004 and 2007, was extracted from multi-date remote sensing images, whilst floodwater depth maps were computed from a digital elevation model and peak water level data for the five major rivers in the study area. Details of the generation of these raster datasets can be found in Dewan (2013). Geographic data at the lowest level of census geography were obtained from the Bangladesh Bureau of Statistics (BBS 2012). This geographic database comprises a total of 1463 polygon features, which includes 967 urban communities (*mahalla*) and 496 rural communities (*mauzal*/villages). A building footprint dataset for 2005, including the location of administrative, residential, commercial, cultural and other structures, was sourced from the Detailed Area Plan (DAP) of the Capital Development Authority (RAJUK). That building database contains a number of attributes such as the number of stories, types of use and construction materials. A road network database of the major roads of the study area was obtained from the Center for Environmental and Geographic Information Services (CEGIS). A catchment feature dataset with detailed stream network data was collected from the Water Resources Planning Organization (WARPO).

Demographic attributes were obtained from the BBS community series (BBS 2012), which were prepared from the population and housing census of 2011. The portable document format (PDF) version of the data was encoded into a spreadsheet and then linked with the census tract boundary using a unique ID (BBS 2012).

3.3 Analytical techniques

3.3.1 Construction of the flood hazard map

Prior to the identification of potential flood shelters and vulnerable housing units, a map was constructed to delimit the spatial distribution of flood hazards in the study area, based on the four major flood events of 1988, 1998, 2004 and 2007. Although several hydrological parameters such as the depth of flooding, rate of water level rise, flood frequency, physical exposure of land, water velocity and sediment loads influence the flood hazard of a particular site (WMO 1999), this study uses only two parameters to delineate flood hazard. They are flood-affected frequency and floodwater depth because other variables were unavailable. A flowchart that depicts the logical flow of the work, including flood hazard assessment, is shown in Fig. 2.

The concept of flood-affected frequency was developed by Islam and Sado (2000) to produce a flood hazard map of Bangladesh for the 1988 flood. We built on this concept and used it to estimate flood-affected frequency by superimposing multi-temporal flood extent maps for major flood events (representing flooded and non-flooded areas). The flood-affected frequency raster was derived by reclassifying the frequency of flooding in each cell into four classes (high, medium, low and no flooding). The floodwater depth rasters for each of the 4 years were also classified into four depth categories (no water, shallow, medium and deep). The four classified floodwater depth rasters were then superimposed with the flood extent data to estimate the flood depth of flooded cells and then reclassify the area according to the intersections of the depth categories at each location. Details of the reclassification of the superimposed flood-affected frequency and floodwater depth maps can be found elsewhere (Dewan 2013; Islam and Sado 2000).

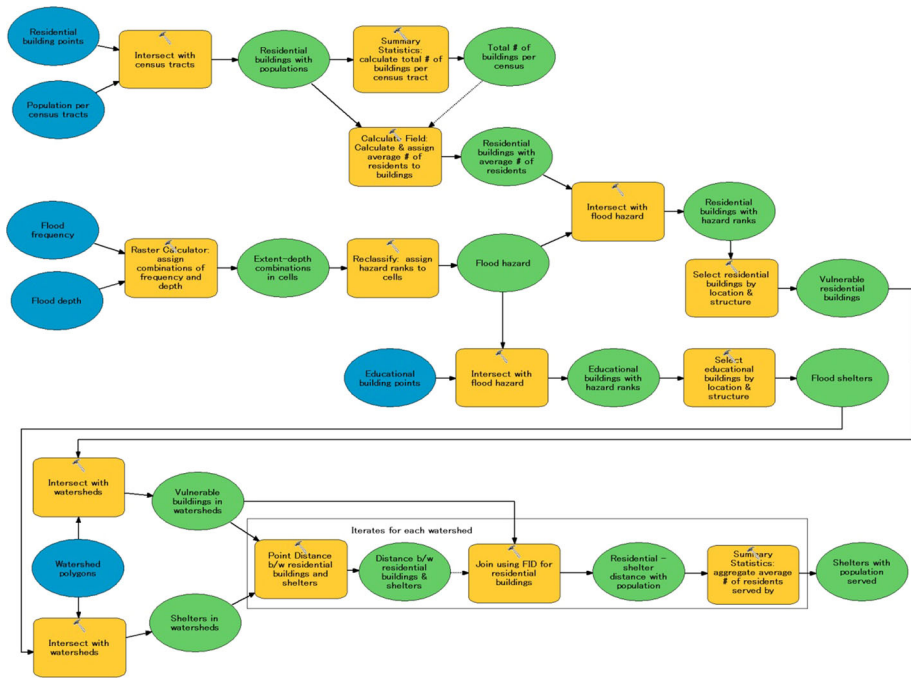


Fig. 2 Schematic representation of the analytical model

The flood hazard map was constructed by assigning a hazard rank to each cell in raster dataset according to the combinations of the classes on the flood-affected frequency and floodwater depth maps (Table 1). A 2D multiplication-ranking matrix suggested by Ochi et al. (1991) was used for flood hazard ranking. The guiding principle of this technique was that flood hazards for a particular cell increase in a nonlinear manner, which depends on both flood occurrence and depth. Each cell classified as ‘no hazard’ on the flood-affected frequency map is assigned to the ‘very low’ category on the hazard map. Cells classified as ‘shallow’ on the floodwater depth map and as ‘low’, ‘medium’ or ‘high’ on the flood-affected frequency map are assigned to the ‘low’ category on the hazard map. Cells classified as ‘medium’ or ‘deep’ on the floodwater depth and as ‘medium’ or ‘high’ on the flood-affected frequency map are assigned to the ‘high’ category on the hazard map. The ranks of 1, 2, 3 and 4 in Table 1 represent very low, low, medium and high, respectively.

3.3.2 Identification of flood shelters and vulnerable settlements

Unlike coastal areas of Bangladesh where a considerable number of multi-purpose cyclone shelters were constructed after the 1991 cyclone (Shamsuddoha and Chowdhury 2007), shelters in the study area are generally ‘dual-use’ facilities that are established on an ad hoc basis during floods (Maniruzzaman and Alam 2002). However, the location of these shelters as well as their capacity is generally unknown, but even when known, is not accessible to other groups such as to the non-government organisations (NGOs) and volunteer groups for relief operation. This leads to extremely poor coordination in relief distribution (Hasnat 2006; Sarker et al. 1998). As these facilities have been built other than

Table 1 Combinations of classes from maps of flood-affected frequency and floodwater depth, with assigned hazard ranks

	Flood-affected frequency	Floodwater depth	Rank
0	No hazard	No water	1
1	No hazard	Shallow	1
2	No hazard	Medium	1
3	No hazard	Deep	1
4	Low	No water	2
5	Low	Shallow	2
6	Low	Medium	3
7	Low	Deep	3
8	Medium	No water	2
9	Medium	Shallow	2
10	Medium	Medium	3
11	Medium	Deep	4
12	High	No water	2
13	High	Shallow	3
14	High	Medium	4
15	High	Deep	4

the purpose of emergency shelters, it is very difficult for emergency managers to guide potential evacuees to suitable refuges during floods, particularly in areas that lack any sort of flood protection (Alam and Ali 2002). It is also unclear whether these shelters are located in safer places as some may not be optimally located (Kar and Hodgson 2008). Since the performance of an evacuation plan depends on knowing the spatial distribution of shelters (Sherali et al. 1991), mapping of shelters with respect to hazard zones will be of significant assistance in mitigating flood vulnerability in Dhaka.

In this study, potential flood shelters were selected on the basis of two criteria. Firstly, the type of building and number of stories have been considered, and secondly, its location with regard to flood hazards. Buildings considered in this study as potential shelters include educational institutes (schools, colleges, mosque, madrasha), cultural facilities, civic centres and community centres. For the second criterion, buildings located in the ‘very low’ hazard zone, and buildings of *pucca*¹ construction more than two-stories high and located in low to medium hazard zones were deemed suitable as potential flood shelters.

Vulnerable residential units whose residents may have to evacuate during floods were identified as follows: any type of structure located in the high flood hazard zone, *katcha* settlements located in low to medium hazard zones and single-storey *pucca* or *semi-pucca* buildings that are located in medium hazard zones. *Katcha* houses, including *jhupri* settlements, are considered to be highly vulnerable to flood in this analysis since they are built with fragile materials such as mud, wood, bamboo with corrugated iron roofs (Hossain 2008; UN-HABITAT 2010). *Jhupri* are normally built entirely of thatched materials. In the 1998 flood, around 68 % of the damaged housing units were *katcha* and *jhupri* types (Alam and Rabbani 2007), and majority of people who took refuge in the flood shelters were residents of these types of house (Maniruzzaman and Alam 2002). *Semi-pucca* houses built with masonry walls similar to those for *pucca* with galvanised iron roofs are assumed to be

¹ *Pucca* is a type of structure made with solid material such as bricks and concrete. Some are reinforced with beams and columns, therefore, considered relatively less vulnerable (UN-HABITAT 2010).

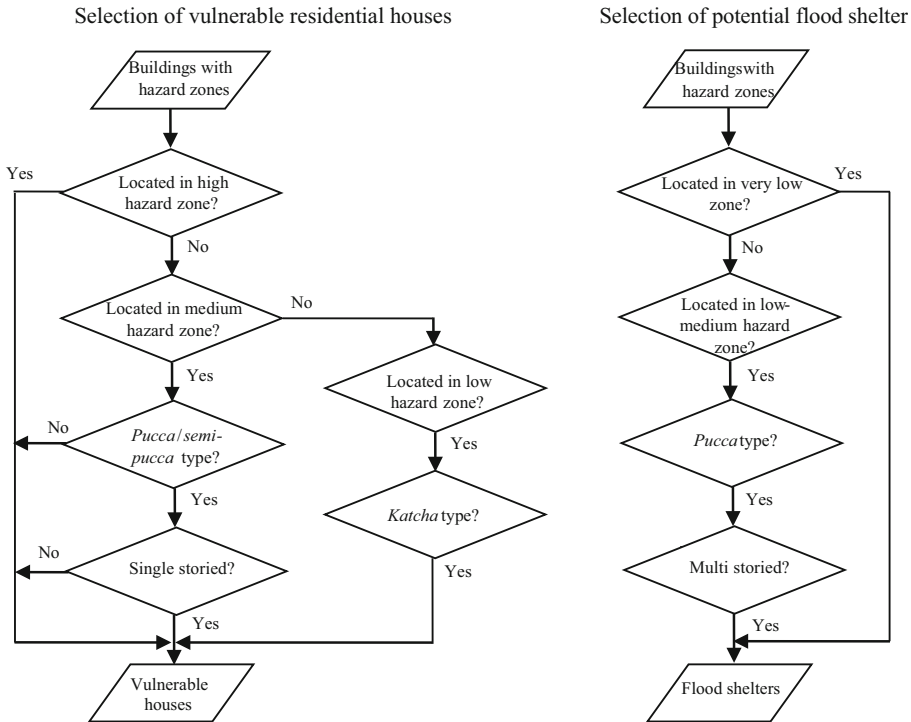


Fig. 3 Procedure of selecting vulnerable residential houses and potential flood shelters

able to withstand a low level of flood hazard but people have to evacuate during a serious emergency.

Structures suitable as flood shelters, and vulnerable residential buildings, were identified from the relevant spatial database using structured query language (SQL) and extracted as two separate layers in ArcGIS (version 10.1). These polygon features were then converted to points in order to minimise computation time for the intersection with the derived flood hazard rasters. Figure 3 shows the full selection procedures.

3.3.3 Distance between flood shelter and vulnerable houses

Once the distribution of potential flood shelters and vulnerable residential units was determined, the next task was to measure the accessibility to shelters through spatial modelling. Drawing on information from a previous study conducted in a similar socio-environmental settings (Sanyal and Lu 2009), this work aimed to compute the distance from vulnerable houses to the potential flood shelters, identified in the previous section. It was assumed that walking is the primary method of access to the closest shelter since the majority of the people in the study area do not have access to vehicles (Dewan 2006). A one-kilometre search radius was deemed appropriate for accessibility measurement. This is the maximum distance for evacuees of all ages to travel to the nearest shelter on foot and was decided on the basis of previous work in the cyclone-affected areas in Bangladesh (Paul 2009).

Since it is extremely difficult and dangerous to cross inundated waterbodies during a flood, the location of flooded rivers was taken into account. As each of the five major rivers has a number of tributaries/distributaries, only the rivers which appeared to overflow and heavily inundated the surrounding areas during the four major floods were chosen to split the study area into several regions by visually investigating flood extent/hazard maps with stream network data. The calculation of distances between the vulnerable residential houses and identified flood shelters was then performed separately for each region.

In order to identify vulnerable houses within one kilometre of a flood shelter, the straight-line distance between points representing residential units and shelters was computed using the point distance tool. The output from this operation is a table containing the distance between each shelter and all residential buildings located within a specified search radius together with the shelter ID and residential building feature IDs (Table 2). This table links housing units with their closest shelter facility. It is possible that there will be multiple flood shelters within the search range of any residential unit. This redundancy was removed by applying a rule that a housing unit may only be served by the single flood shelter that is closest. This follows the same logic as suggested by Sanyal and Lu (2009). This led to a database that was free from duplication (Table 2).

3.3.4 Calculation of population served by the shelters

To compute the number of people linked to each flood shelter, the average number of residents per residential unit was calculated. The total population of each community, from the 2011 population and housing census, was spatially intersected with the residential building dataset in order to derive the number of residential houses in each community. From the community population and the derived number of residential building features in each community, the average number of residents per building was calculated. A table, containing the populations that would need to be supported by a nearest flood shelter, was then derived by joining the post-processed distance table with the vulnerable residential housing dataset using the residential feature ID and aggregating the numbers of residents assigned to the residential unit(s) by each shelter ID (Table 3).

Table 2 An example of post-processed distance table and the vulnerable residential units

Vulnerable residential unit ID	Flood shelter ID	Distance (m)
1	1	469
2	1	404
3	2	400
4	2	395
5	3	728

Table 3 An example of the output table showing the number of populations that each shelter could support during emergency

Flood shelter ID	Number of residents serve
1	873
2	795
3	728

4 Results and discussion

Figure 4 shows the spatial distribution of flood hazard in the study area. The highly hazardous zones located mainly in the eastern part of the study area, close to the Balu river, in the mid- to northern part of the Buriganga river and in the southwest of the study area, between the Buriganga and the Dhaleshwari rivers. The medium and low hazard zones were mostly located along the fringes of the highly hazardous zone.

More than 60 % of the study area was affected by floods (low to high hazard zones), and approximately 45 % was estimated to be highly hazardous. The medium and low hazard zones comprised approximately 3–16 % of the study area (Table 4).

A spatial intersection of the flood hazard map with the 2011 population data showed that 24.8 % of the total population were exposed to some level of flood hazard. Although most of them were located in the low hazard zone, over 7 % of the population were within the highly hazardous zone (Table 4).

A total of 5537 buildings of various types, including multi-storied *pucca* structures, located in the low to medium hazard zones were identified as potential flood shelters out of 6342 candidate shelters which satisfied the previously mentioned criteria (Fig. 5). This figure also shows the location of flood shelters according to the number of neighbouring

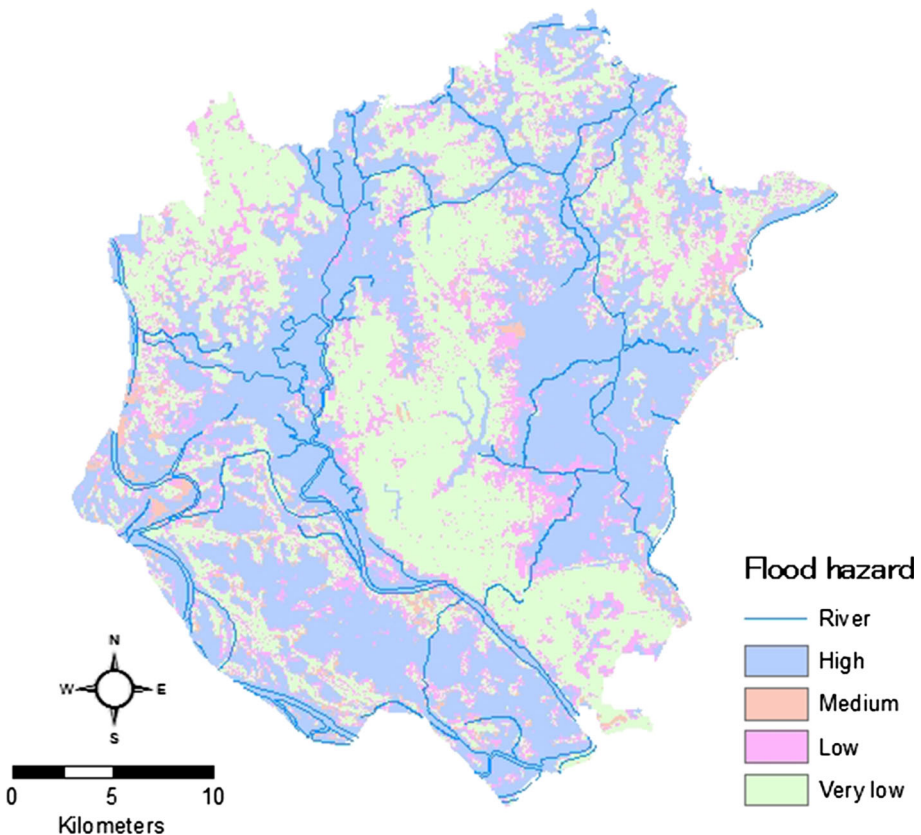


Fig. 4 Distribution of flood hazard in the study area

Table 4 Area and percentages of population in each flood hazard zone

Hazard zone	Area in hectares (%)	Population (%)
Very low	32,252.5 (36.8)	75.5
Low	13,812.9 (15.7)	15.6
Medium	2426.5 (2.8)	1.9
High	39,275.7 (44.7)	7.3

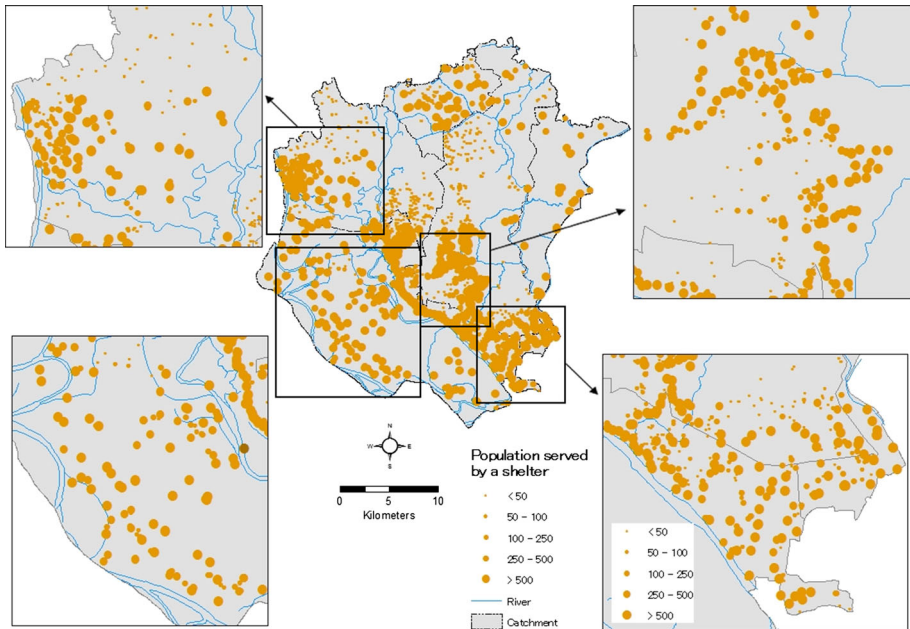


Fig. 5 Distribution of the identified flood shelters with numbers of residents served by the shelters

residents that they would have to serve. The shelter features in the smallest graduated symbol represent a requirement to serve <50 people. As the number of population to be served by a shelter increases, the symbol becomes bigger. Some shelters would need to serve >500 people during emergency (Fig. 5), which may exceed their capacity.

In order to evaluate the number of people who could not be served by these shelters, the capacity of each flood shelter was estimated by using the total floor size of its polygon feature and the number of stories. It was assumed that each evacuee would require a minimum area of 3.5 m² in a shelter since flood events may require long-term evacuation for a period of month or more (Sphere Project 2011). This was then compared with the population requiring refuge at that location. This result indicated that a total of 1098 flood shelters, distributed over five catchments in the study area, had insufficient capacity to accommodate all their closest vulnerable residents.

Approximately 145,000 residential housing units (19.3 % of total housing units) were identified as vulnerable to flood because they were either located in the high hazard zone, or are single-storey *pucca* or *semi-pucca* types located in the medium hazard zone, or *katcha* type that were located in low to medium hazard zones. Figure 6 shows the

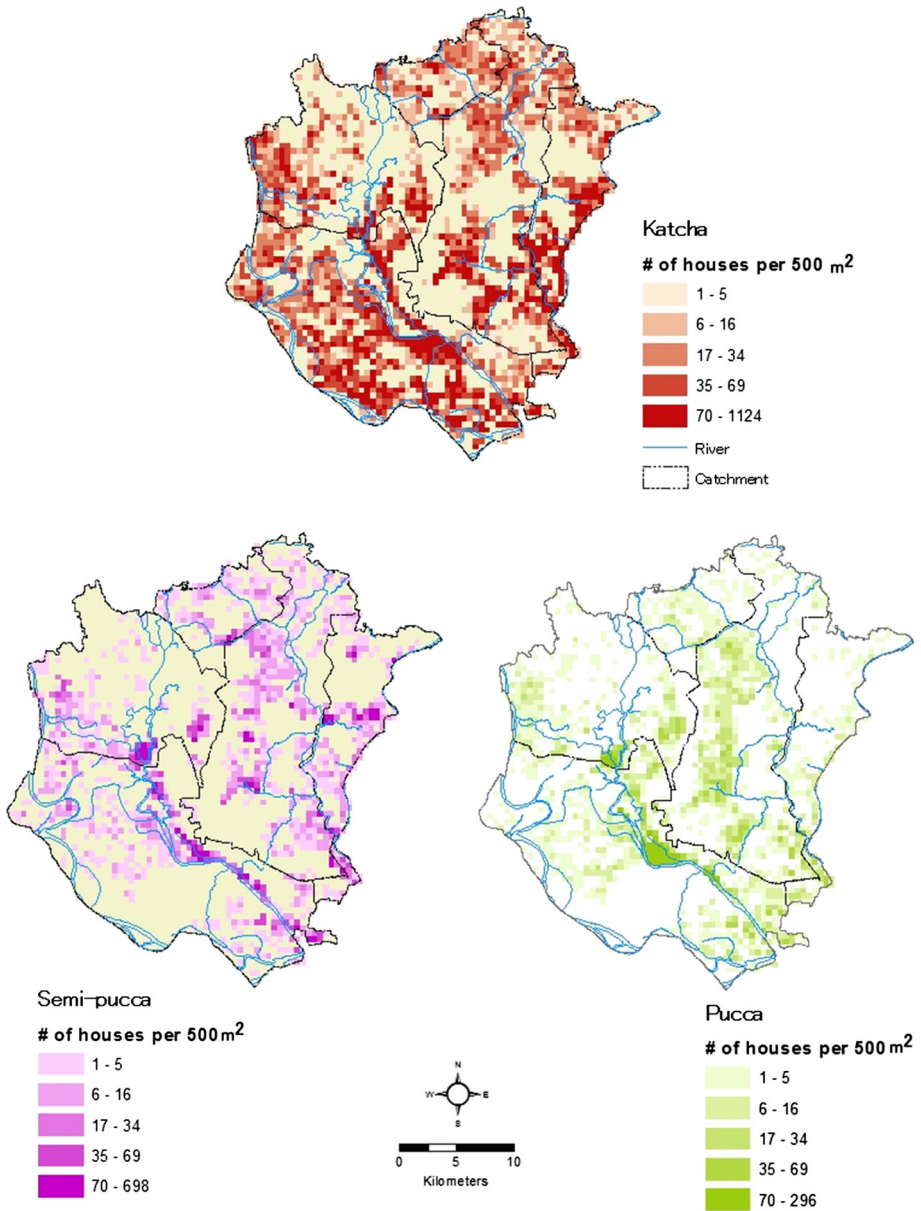


Fig. 6 Spatial distributions of the vulnerable residential units, by housing type

distribution of vulnerable residential units (e.g. *katcha*, *pucca* and *semi-pucca*) in the study area. Interestingly, a large number of *katcha* houses are distributed in the outskirts of the present urban core and may face severe damage in the event of large fluvial flood as there is little or no flood protection. Some *katcha* houses located in the urban core where flood protection is available may also be susceptible to damage in the event of pluvial flooding (Alam and Rabbani 2007).

Figure 7 shows a detailed view of part of the study area with flood shelters and the neighbouring residential houses identified within one kilometre of the shelters. The houses whose residents could be served by the closest flood shelter are represented using the same colour. This figure also includes the road networks of the area to give an idea of potential routes to the flood shelters. The lines in red are Thiessen polygons whose centroids are the identified flood shelters. This assists in understanding the locational relationship between a shelter and a vulnerable house and may also be used to validate our claim that people living within each polygon would find the corresponding flood shelter the nearest to travel to (Sanyal and Lu 2009).

The number of shelters, their neighbouring vulnerable houses and the populations that they would be required to serve were examined at the catchment level. This can be valuable for the management of flood risk at the catchment scale in the study area since local authorities appear to operate at this scale during emergency. Tables 5 and 6 show the estimated number of shelters identified, more than one kilometre from vulnerable units, the number of shelters that may exceed their capacity in supporting evacuees during emergency and the number of vulnerable houses according to the five catchments. It may be noted that the vulnerable residents that a flood shelter, in a particular catchment, has to serve may not necessarily be within that catchment because our analysis to link vulnerable residents to nearby flood shelters was carried out on the basis of inter-fluvial zones.

These results show that the Tongi Khal catchment has a total of 211 potential shelters, of which 73 are more than one kilometre away from vulnerable houses and hence are of no use to those vulnerable residents. In addition, 92 of them would exceed their capacity in terms of accommodating evacuees during an emergency. The number of vulnerable housing units in this catchment was 6529 with a total of 82,264 residents. Of these

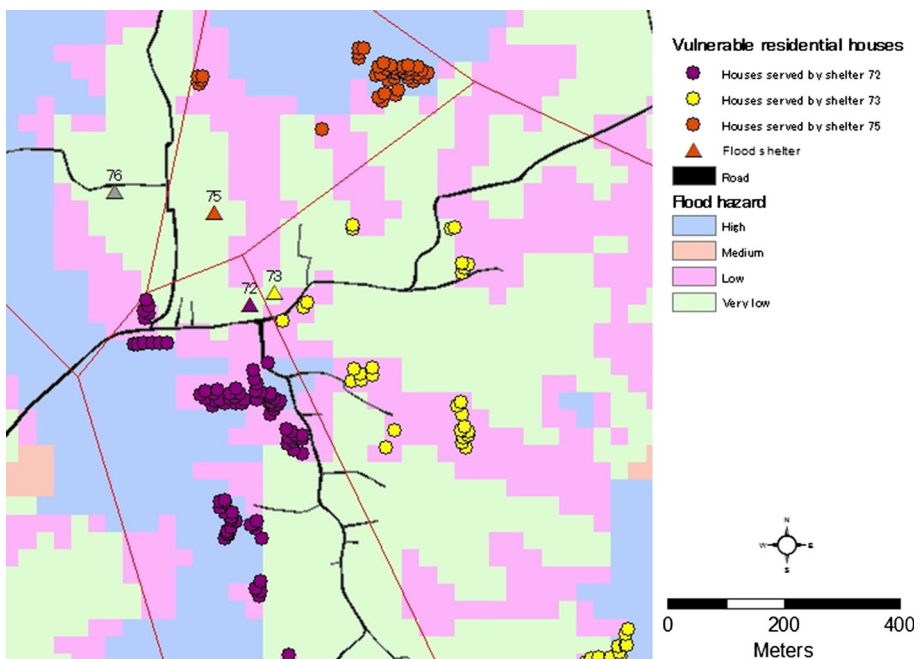


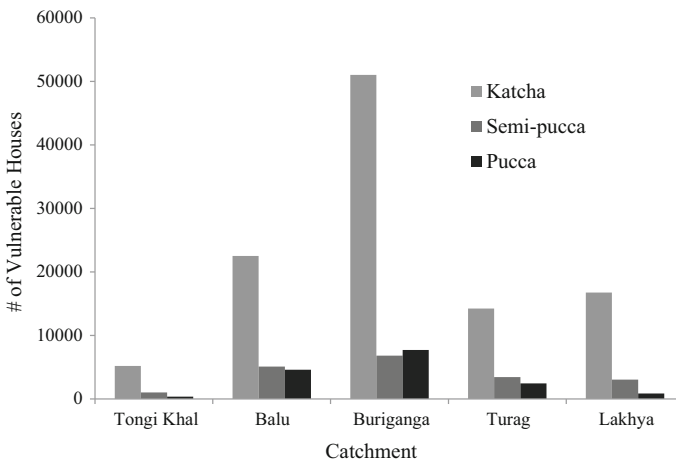
Fig. 7 Location of the flood shelters and vulnerable residential buildings served by the three nearby shelters

Table 5 Identified numbers of flood shelters, numbers of the shelters may not serve to the residents and the numbers of the shelters that would exceed their capacity, according to catchment

Catchment name	# of shelters	# of shelters may not serve to the evacuees	# of shelters may exceed their capacity
Tongi	211	73	68
Balu	1979	1339	176
Buriganga	2147	1456	417
Turag	1055	585	127
Lakhya	145	46	66

Table 6 Numbers of identified vulnerable houses, numbers of vulnerable residents and the numbers of residents living without flood shelters in each watershed

Catchment name	# of vulnerable houses	# of vulnerable residents	# of vulnerable residents w/o shelter
Tongi	6529	82,264	14,227
Balu	32,201	508,166	121,493
Buriganga	65,554	956,487	204,488
Turag	20,082	230,935	138,743
Lakhya	20,628	101,641	16,984

**Fig. 8** Number of vulnerable residential units, according to catchment

residents, 14,227 are at very high risk as they do not have readily accessible flood shelters. In this catchment, around 5172 *katcha* buildings were constructed with fragile materials (estimated as being highly vulnerable to flood). Among the other housing types, 355 *pucca* houses did not satisfy the criteria to be considered safe (Fig. 8).

The Balu river catchment, which is elongated from the north-east through the central to the south-east part of the study area, has the second highest number of flood shelters. This is not surprising given that both population and economic activity are highly clustered in

this catchment. Since the ground elevation is relatively high and some portion is protected with embankment, dykes and flood walls, flood hazard in this area is relatively low except for some low-lying floodplain areas. A total of 1979 potential shelters were identified in this catchment but many of them (1339) were not located within the one-kilometre search radius of vulnerable populations. This could lead to evacuation difficulties during flooding. In addition, out of 640 shelters which are within range of vulnerable residents, 266 may exceed their capacity. A total of 32,201 housing units of various types with 508,166 residents were found to be vulnerable to flood. Out of these residents, nearly 24 % would be in danger due to not being close enough to flood shelter. Among the vulnerable houses, 22,517 were *katcha* type, 5083 were *semi-pucca* and 4601 were constructed with concrete materials. Since the majority of economic activity is concentrated in this catchment, financial loss from future floods is expected to be high.

The Buriganga catchment, located in the Buriganga–Dhaleshwari system, has the highest number of potential shelters (2147), but the overall flood vulnerability of the catchment is high due to the presence of large number of *katcha* dwellings (Fig. 8) that house low-income people. Due to changes in the hydrological regime in the area (Dewan and Yamaguchi 2008), an additional 7715 *pucca* and 6809 *semi-pucca* houses are estimated to be vulnerable to flood. Because this catchment is experiencing rapid urban development in response to massive recent infrastructural investment, the loss incurred by any future flood could be severe. Of the identified potential shelters, 691 shelters would be adequate in terms of their location whilst 495 may not have sufficient capacity. A total of 65,554 residential housing units and 956,487 residents were found to be vulnerable to flood. Among these residents, 204,488 may face evacuation difficulties due to the distance to potential shelters. In addition, the historical urban core, in which economic activities are concentrated, is located in this catchment. This means that large-magnitude floods could cause considerable property damage.

The situation is slightly better in the Turag catchment. However, this catchment still has a large number of people without easy access to flood shelters. Table 5 shows that in this catchment, 1055 structures satisfied the criteria to act as shelters, but 166 may not have adequate capacity during an emergency. In addition, 585 suitable structures are too far away from vulnerable populations to act effectively as flood shelters. Table 6 further shows that around 230,935 people reside in 20,082 vulnerable dwelling units and of those, 138,743 residents do not have ready access to flood shelters. Figure 8 shows that out of the 20,082 vulnerable housing units, 14,228 are of *katcha* type and therefore highly prone to water-related hazards.

The last catchment that of the Lakhya River in the southeast and southwest parts of the study area has the best opportunities for population evacuation since overall population in the catchment is low. A total of 145 buildings have been identified as flood shelters, of which 79 may have inadequate capacity to accommodate the nearest flood victims whilst 46 would not be of direct use as flood shelters due to their distance from vulnerable people (Table 5). Nearly 101,641 people were found to be vulnerable to flood in this catchment, of whom 16,984 do not have suitable nearby shelters. The presence of a large number of *katcha* houses further aggravates this situation (Fig. 8).

5 Conclusions

Using the flood extent and floodwater depth parameters, population census and buildings data, this study examined the spatial distribution of potential shelters in relation to flood hazards in a subset area of the DMDP zone and DM. Taking four major flood events that

occurred in 1988, 1998, 2004 and 2007, a flood hazard map was constructed using a ranking technique. Two hydrological parameters, flood-affected frequency and floodwater depth, were used to assess overall flood hazard. The results revealed that 60 % of the study area is potentially affected by floods (low to high hazard zones).

Using a building feature dataset from 2005, potential flood shelters and vulnerable housing units were identified based on categorical selection criteria and their location in relation to the flood hazard distribution. The spatial distribution of potential flood shelters and the location of vulnerable settlements were then individually intersected with the flood hazard map. Using spatial modelling tools available in ArcGIS, accessibility to shelters was estimated. The analysis showed that around 19.3 % of the dwelling units, containing 24.8 % of the population in the study area, were vulnerable to flood. When the spatial distribution of potential shelters was examined for each of the five catchments, it was found that a number of potential flood shelters in the study area were neither optimally located nor uniformly distributed to serve maximum number of vulnerable housing units. For example, a total of 3499 out of 5537 potential shelters were located more than one kilometre away from the nearest vulnerable housing units. Additionally, 1098 potential shelters would not have sufficient capacity to serve the local population during an emergency. Among five catchments in the study area, the Buriganga was found to have the worst situation as 68 % of the identified shelters were not optimally located. This information would be valuable for emergency managers to minimise loss of life and property from future floods.

A number of improvements to this study are possible. The building feature polygons used for this work were from a survey of 2005. Considering the rapid growth of Dhaka, there may be more flood-resistant high-rise residential houses at the time of this analysis. Further, this study heavily relied on a previous work (e.g. Sanyal and Lu 2009) to compute accessibility to flood shelters, but it is equally important to note that spatial models related to population evacuation also depends on the geographic area being analysed and the availability of relevant spatial data. The work could therefore be improved if better data were available. For instance, a high-resolution road network database would enable identification of time needed to evacuate each flood hazard zone. Suitability of existing flood shelters could also be analysed by incorporating a high-resolution digital elevation model, the location of critical facilities, and a precise hydrological model, etc. For example, a location-allocation model may be used to find optimal location of flood shelters to minimise the risk from future flood driven by climatic variability.

Despite the limitations listed above, we believe that this study could provide information for urban planners and emergency managers in a situation where unchecked urban growth sees thousands of people settling in dangerous locations. This study may also be used as a baseline to construct adaptation policies for DM as intense rainfall induced by global warming is expected to bring about more frequent floods. Such adaptation strategies would be more cost-effective than further extensive and expansive flood control works.

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