Chapter 14

Assessment of Exposure to Flash Flooding in an Arid Environment: A Case Study of the Jeddah City Neighborhood Abruq Ar Rughamah, Saudi Arabia

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Abstract In arid areas, flash floods represent one of the most severe hazards for people and infrastructure alike. The associated risks are compounded by increasing exposure and vulnerability through rapid and unregulated urbanization, poor infrastructure, and sociocultural factors, among other elements. This research explores the flash flooding risk in the Saudi Arabian city of Jeddah with a particular focus on the Abruq Ar Rughamah neighborhood, which experienced a destructive flood in November 2009 that resulted in 116 deaths and 1,200 families becoming homeless. The neighborhood is an interesting case study as it has two distinctive urban layouts representing planned and irregular settlement types. In this paper, the focus is placed on exposure to flash flood hazards using a geographic information system to study urban layouts, building types, and resident populations in conjunction with data from satellites, flood mapping studies, and topographic data. The results show that most of the study area is located along a natural flood path. The regions that were affected by the 2009 disaster received no comprehensive site rehabilitation. This paper concludes that it is important to develop a risk management strategy that includes limiting urban expansion in flood-prone areas and redesigning neighborhoods to increase flood resilience.

Keywords Urbanization · Flood hazard · Urban planning · Unplanned area

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383

14.1 Introduction

Urbanization has two distinct but related meanings. The first is the demographic shift in the global population from rural to urban living. Since the mid-twentieth century, the global urban population has expanded rapidly; in 1900, just 15% of the world's population of 1.6 billion lived in cities (Spence et al. 2009), and now, more than half of the 7 billion on the planet live in cities. Moreover, it is projected that the quantity of individuals living in cities will increase to over six billion by 2045 due to both migration and natural population increases (World Bank 2018). The second is the transformation of the landscape as the natural land surface cover is replaced by closely spaced buildings and impermeable surfaces. Much of this urbanization is concentrated in areas that are exposed to natural hazards such as flooding, extreme weather, and geological events (e.g., Small and Naumann 2001), placing a larger number of people at risk. Some of these risks are accentuated by environmental changes at global, regional, and urban levels, many of which are linked to human activities. For example, most cities are located on coastlines near sea level and are projected to experience the effects of sea-level rise due to global warming (Neumann et al. 2015). In addition, impermeable urban surface cover is linked to rising air temperatures (the urban heat island effect) and increased flooding, as storage has decreased while runoff has surged. The types of hazards to which cities are exposed vary with climate and topography; thus, each city may require a unique solution to reduce its risk. However, the great majority of current global urbanization is taking place in economically developing regions (Henderson et al. 2017) where growth is often unplanned and unmanaged (Ali et al. 2015) and the capacity to respond to hazard events is limited.

Saudi Arabia is in an arid and semiarid climatic region. The weather is unpredictable, and the geomorphology is specific, so the region is prone to occasional floods. Settlements, agriculture, roads, and infrastructure together increase the potential for flood hazards because they cause floodwater to be unable to leak into the subsoil, which in turn increases the volumes and speeds of water flows. The expanding population puts pressure on these regions as per capita water use increases, resulting in limited water resources (Wheater 2002; Nemec and Rodier 1979).

Floods are one of the major effects of indiscriminate urbanization, and Jeddah is exposed to different levels of flooding. On November 25, 2009, flash floods occurred in Jeddah during one of the most exceedingly terrible and damaging flood events throughout the entire existence of the city. The official death toll totaled 116 people (Alsaggaf 2012). In addition to claiming lives, the floods also wrecked more than 4,000 cars and caused more than 1,200 families to become homeless; the resulting damage ran into the millions (Alsaggaf 2012). The depths of this flood were 1.34 m in the main channel of the valley and approximately 2 m on the streets, confirming that it was not only natural causes that led to this disaster but also the profound effect of urbanization (El-Hames and Al-Wagdany 2012). The impact of the floods was most severe in the Abruq Ar Rughamah neighborhood.

While there was little research on the topic prior to the disaster (Ameur 2016), following the Jeddah catastrophe, a number of studies focused on the extent of flood damage and explained the outcome in terms of physical processes, such as the intensity of rainfall and the local topography. In the research following the flood event, detailed mapping was performed to assess and analyze flood risk using satellite images and digital elevation models (DEMs). Al Saud (2010, 2015) used high-resolution images before and after the event to identify the affected areas. The study used data derived from climatic records from ground-based stations, remotely sensed data, and additional information such as geological and topographic maps, DEMs at 2 and 30 m accuracies, satellite images, and software (ENVI-4.3, ERDAS9.3, Arc-GIS 9.3). Moreover, the author examined physical and anthropogenic factors such as drainage systems, rainfall distribution, geomorphologic and geological characteristics, and urban expansion. An overview of the flooding experienced in 2009 and 2011 in Jeddah was also included; the study covered the conveyance of floods and torrents and various aspects such as transported water and sediment, injected flows, impact flows, restricted rainwater, and water bodies and flows in urban areas. Al-Saud also used a hydrological analysis of DEMs that included the slopes of basins in the study area, cross sections, channel slopes, and depressions, as well as a geometric analysis of the drainage systems (length/width ratios, shape factors, widths/outlets, and width ratios). The study also presented analyses of drainage systems (morphometric analysis), stream order, and, finally, the meandering ratio. Furthermore, it included an assessment and examination of the localities damaged by the floods in both 2009 and 2011 in terms of the levels of risk. The study also included an overview of the existing flood control measures in the study area in terms of small-scale flood control measures, such as pipes for water tunneling, and large-scale flood control measures, including dams and old water channels. Additionally, erroneous flood control was also noted, including depression dumping, the closure of valley passageways, soil obstacles, and narrow tunnels. Proposed projects and programs were discussed that included some objectives to reduce the impacts of flooding in at-risk areas: setting up infrastructures in urban areas to drain water, stabilizing flood plains, constructing retaining walls, creating channels, constructing dams, cleaning channels, constructing tunnels adjacent to roads, and controlling encroachment on the passageways of valleys.

Moreover, Subyani (2012) used a DEM to identify geomorphological hazards in the study area by determining the slope and considered the level of risk to be connected to the slope percentage. In terms of hydrology, he used buffering tools in a GIS environment to identify vulnerable areas and linked land use with the overall risk of flooding; all low-lying urban areas of the city are considered to be at high risk of flooding. Furthermore, he assessed flood vulnerability in arid areas to aid decision-makers and contributed to flooding protection plans by predicting a yearly maximum 24-h precipitation value alongside 25-, 50-, 100-, and 200-year forecasts using Gumbel's extreme value distribution (EV1) and log-Pearson type III model at 18 rainfall stations around select valleys in western Saudi Arabia.

Additionally, the study by Elfeki et al. (2011) used simulation models to estimate the flood hydrograph of the 2009 storm to determine the impact of floods on

urban areas in Jeddah. Two hydrologic models were used to estimate the floods caused by the 2009 storm: the HEC-HMS 3.3 hydrological modeling system and the WMS 7.1 watershed modeling system were consulted, and a diffusive wave model was developed. In addition, both models and satellite images integrated with GIS were examined to capture the water depths and inundation zone. In their study, Hadadin et al. (2013) applied the synthetic unit hydrograph hypothesis to determine the peak release of the stream during the Jeddah flood; this value is necessary in the establishment of the flood hydrography to evaluate water resources and design different hydraulic structures. Two prediction models were used in the study, the Snyder approach and a routing unit hydrograph, to analyze 12 streams east of Jeddah. The study concluded that there is a strong relationship between the density of drainage systems and the ability of water to infiltrate. Furthermore, El-Hames and Al-Wagdany (2012) also worked on rebuilding the characteristics and hydrograph of the 2009 flood by using HEC-RAS software as well as a dimensionless hydrograph, the Soil Conservation Service (SCS) curve number, GIS, and a DEM. The study found that in the case of the natural conditions of the 2009 flood, the height of the water reached 1.34 m in the main channel and two meters in the neighborhood due to its narrow streets; the floodwater was discovered to have risen to 2.1 m at street entrances. The study contradicted assumptions that the disaster was due to natural causes. The urbanization of hot arid environments with a BWh climate types in the Köppen classification has generally received little attention, although these regions also experience rapid urban growth. These areas are characterized by high temperatures and infrequent rainfall events that result in sparse vegetative cover. The hydrological systems of these regions often consist of wide and shallow channels that are usually dry (wadis) but respond to rapid and intense rainfall events that generate flash floods. These events are difficult to prepare for because they are rare, difficult to predict and provide little lead times for warnings and evacuations (Lin 1999). Moreover, urbanization in areas prone to flash flooding exacerbates flood hazards by obstructing and redirecting flows and enhances risk by increasing exposure.

This paper offers an assessment of the exposure and vulnerability to flash flood hazards in Jeddah city, Saudi Arabia, an area that has experienced many flooding events over the last two decades. The focus is on the role of physical planning (including building construction and urban layout) in managing risk. To illustrate these factors, the November 2009 flood event is selected and the Abruq Ar-Rughamah neighborhood is chosen as the case study; this neighborhood has two distinctive urban forms representing formal (planned) and informal (irregular) settlement types.

14.2 Jeddah Case Study

The city of Jeddah covers an area of 748 km² along a thin and gently inclining coastal plain between the Red Sea line and the Al-Hejaz slope (Fig. 14.1). Its climate is hot and dry; during the summer months, temperatures can exceed 40 °C, while the relative humidity (RH) can approach saturation (Subyani 2009). Rainfall, when it occurs, takes place mostly during the winter period and is associated with convective activity triggered by the passage of low-pressure systems moving in from the west (Haggag and El-Badry 2013). Although Jeddah receives just over 50 mm of rainfall annually, much of it arrives as intense rainfall events of limited spatial extent; at Jeddah Airport, the mean annual rainfall is 63 mm, but the mean daily maximum is almost 36 mm. Uplift over the Al-Hejaz escarpment results in much higher rainfall amounts over these uplifted regions, in excess of 220 mm/year (Haggag and El-Badry 2013). The generated precipitation travels through nearly 80 drainage systems that convey runoff from the escarpments in the east through Jeddah into the Red Sea in the west (Qari 2008). Since 2005, Jeddah has experienced several flood events (Tekeli 2017); one of the most devastating events took place from 24 to November 26, 2009 and severely impacted the Abruq Ar-Rughamah neighborhood in the southern part of the city.

Fig. 14.1 Location of Jeddah’s urban area between the Red Sea coast to the west and the Hejaz escarpment to the east. The red boundary indicates the Abruq Ar Rughamah neighborhood

The population of Jeddah is increasing rapidly; its population has doubled since 1990 and now stands at over 4.1 million. In 2010, Jeddah had a population of 3.5 million, approximately half of whom were non-Saudis and 40% were female. This population occupied 702,527 dwellings (that is, almost five persons per dwelling). Not surprisingly, population growth has resulted in considerable pressure to build houses. At the edges of the city, urban growth occurs in both planned developments and informal settlements. The former are subject to official planning and building permits, while the latter have no legal status and the land on which they are built is cheaper. The two types of urban growth are also distinguished by building construction types and layout. In general, formal settlements are laid out on grids with wide roads and buildings constructed from modern materials. Many newer buildings are multistory apartments that have steel/concrete supports. By comparison, informal settlements are laid out in a haphazard fashion; the buildings are typically one story, enclosed by walls, and are built using bricks/adobe and wooden supports. The streets in these settlements are short and narrow (Fig. 14.2a). Informal settlements are the preferred destination for low-income residents, as the rents are lower in the informal settlements than in the planned developments. Approximately

Fig. 14.2 **a** Traditional buildings and the shape of the streets in the informal settlement area. **b** A villa, one of the common types of residential buildings in Jeddah. **c** A scene depicting a formal settlement, showing the building types and the shape of the streets. **d** Basic structure of modern buildings constructed using concrete columns

one-third of the population lives in approximately 70 of these types of informal settlements (Aleqtisadia 2018).

The Abruq Ar Rughamah neighborhood is located in eastern Jeddah and is built on the basin of the Qus wadi (Fig. 14.1). On November 25, 2009, the flash floods that occurred in Jeddah were most severe in this neighborhood; 116 people lost their lives, 1,200 families were made homeless, and property was damaged and destroyed (Alsaggaf 2012). This neighborhood makes an ideal case study because it is composed of informal and formal settlement types, both of which were severely affected by the flood event. Figure 14.3 shows a satellite image (SPOT-70 0.6M) of the study area from 2016; superimposed on this image are the river channels within the Qus wadi and the area that was severely affected due to the flash flood in 2009 (Al Saud 2015).

Fig. 14.3 Abruq Ar Rughamah neighborhood. The red boundary shows the informal settlement type area, and the dark blue boundary shows the formal settlement type area. The red shading shows the area affected by the 2009 flood, and the light blue lines depict the stream system

14.3 Data and Methods

The main source of data for this study is the 2010 Saudi census (Saudi Arabia General Authority of Statistics) and the associated geographic files. The census is collected from households but is typically available only at the level of the governorate (of which there are 118), the region (13), and the state. Jeddah is a governorate within the Makkah region. For enumeration purposes, each governorate is divided into neighborhoods, sectors, and blocks based on the road network. A block describes a building or a number of contiguous buildings that are not separated by streets and can form irregularly shaped polygons. For this study, the census data for the Abruq Ar Rughamah neighborhood were collated at the block scale. These data are unique, as they were manually entered from the original census returns specifically for this project. Given the time taken to generate these data, relevant variables were created from the full census form. The variables included information on geography, types of houses, nature of occupancies, communication systems, and population that could be used to assess the levels of risk. The geographic location can be used to evaluate exposure to flood risk, while housing type is a measure of each dwelling's strength and its ability to withstand the effects of a flash flood. The census distinguishes between five types of dwellings: traditional, villa, apartment, tent, and shanty; the first three types are present in this neighborhood (see Fig. 14.2). Both the villa and apartment types are classed as modern buildings, owing to the construction techniques and materials used. The age profile, and in particular the male to female ratio, is a measure of the daytime residential population, while communication infrastructure can be used to evaluate the potential for a warning system. The block information is linked to a digital map so that these data can be analyzed geographically. The layout of the blocks and the road network can also be examined using a geographic information system (GIS). The road design plays an important role in blocking and redirecting floodwaters. Moreover, the road width can play a role in accentuating hazards by narrowing channels and raising water levels. During the 2009 event, it was estimated that the depth of the floodwaters was 1.34 m in the main channel of the Qus wadi but approximately 2 m in the streets within the informal settlement area (El-Hames and Al-Wagdany 2012). Finally, the presence of cars along roads will contribute further to hazards by restricting flows along streets and providing debris that can damage walls and dwellings. In the following section, descriptions of these attributes are given in relation to the formal and informal areas of the Abruq Ar Rughamah neighborhood.

14.4 Results

Figure 14.4 and Table 14.1 show the attributes of the neighborhood, depicting the physical forms (building type and road density) and population exposure in the formal and informal areas. There is little difference between the two areas in terms of population exposure: both are densely occupied (>12,000 persons per sq. km), the majority of the occupants are male, and approximately 20% are either elderly (>60 years) or young (<6 years). Most of in the formal settlement live in rented accommodations, whereas approximately half of the occupants living in the informal settlement own their dwellings. Figure 14.4 shows that the population densities and the distributions of old and young individuals are evenly dispersed within each settlement.

In terms of comparative physical geographies, the formal and informal settlements differ significantly. The planned settlement area has long roads, wide streets, and few traditional buildings. Although the built fraction of the landscape in the informal settlement area is nearly the same as that in the formal settlement area, the street lengths in the informal settlement area are, on average, one-quarter of the length of those in the formal settlement area, and the streets are much narrower in the former area than in the latter. Figure 14.2 confirms these basic features. The

Fig. 14.4 Physical and human geographical aspects of the Abruq Ar Rughamah neighborhood: **a** population distribution; **b** dependent population (those under 6 and over 60 years of age); **c** distribution of modern and traditional buildings, and **d** road density

Table 14.1 Properties of the Abruq Ar Rughamah neighborhood

Attribute	Formal	Informal
<i>Physical geography</i>		
Area	0.80 km ²	1.31 km ²
Built fraction	0.62	0.68
Traditional housing unit	116	22,80
Modern housing unit	2,444	976
Average street width	17 m	5.7 m
Average street length	106 m	25 m
<i>Population geography</i>		
Population	10,375	16,169
Population density	13,036 cap. km ⁻²	12,360 cap. km ⁻²
Male	5,583 (54%)	9,423 (58%)
Female	4,792 (46%)	6,746 (42%)
Under 6 years old	1,907 (18%)	2,370 (15%)
Over 60 years old	413 (4%)	589 (4%)
Tenants	1,845	1,572
Owners	624	1,511

planned development area consists of buildings that form rectangular blocks arranged as a grid; the wide roads are aligned with the natural slope so that flood water can move through the settlement with few impediments. The buildings in this region are strong and have multiple floors, enabling evacuation to higher floors. The unplanned development area has many roads (see Fig. 14.2a and c) that are short and narrow with no dominant directions; thus, floodwaters that enter the settlement area are obstructed, and the water level rises. Moreover, the buildings and walls in this settlement area are weaker and more prone to damage than those in the planned development area.

An additional factor that contributes to flood risk in the neighborhood is parked cars. As a result of the availability of cheap fuel and cars in Saudi Arabia, the majority of residents depend on cars for travel; in 2014, there were 336 vehicles per 1,000 persons. It is important to consider that since 2018, Saudi Arabia has begun to allow women to drive, suggesting that the number of cars owned by each family may increase. Therefore, while cars could be used as a means of evacuation if there were sufficient warnings, cars are easily movable and often become debris when floods occur. During the 2009 flood disaster, many roads became impassable due to blockages created by cars; this was especially true in areas with narrow streets (Fig. 14.5). A simple geographic analysis of car locations based on a 2016 satellite image showed that there were approximately 4,500 cars in the informal settlement area, corresponding to a density of over 5,000 vehicles per km² if the built area is excluded. A typical car is nearly 2 m wide or one-third of the average street width in

the informal settlement; in other words, the same density of cars occupies less road space in the formal settlement area than in the informal settlement area.

14.5 Discussion

The Abruq Ar Rughamah neighborhood represents a good case study of urbanization and exposure to flash flood hazards. The neighborhood has experienced two recent flash flood events (in 2009 and 2011) due to its location in the Qus Valley basin; however, Fig. 14.6 shows that urbanization continues as before. The expansion of Jeddah into flood risk zones suggests that the likelihood of flood recurrence is not properly accounted for in land management planning. There is a critical need for a flash flood hazard map that outlines the likely return period for flood events of varying magnitudes. These maps should be central to all urban plans and should be made available to the local population to increase residents' awareness of flood risks and encourage their participation in flood risk management. If further urbanization takes place in at-risk zones, the nature of the flood hazard should be explicitly addressed in urban planning and design. Measures could include upstream dam construction and/or drainage channels to control the path of floodwater and divert it from settled areas. It is also possible to create retention reservoirs to collect some of the flood water temporarily or permanently so that it can be used later, reducing the volume of floodwater and the speed of runoff. Ideally, these systems would be part of land-use plans and urban design prior to urbanization.

Fig. 14.5 A photograph of the 2009 flood disaster in the study area showing the impact of cars forming debris that leads to the obstruction of the entry of rescue teams (Alriyadh Newspaper 2018)

Fig. 14.6 Footprint of urbanization in 2005 and 2016

In addition to design changes, there is also a need for an early warning system that is linked to actions at the neighborhood and household levels. The absence of such a system in the 2009 flash flood event has been noted (Momani and Fadil 2010). Such a system would include meteorological and hydrological observations and modeling coupled with an effective communication system. Smartphone technology, which is widely available in Saudi Arabia, provides an opportunity for direct communication with affected households (Alkhunaizan and Love 2013). The final component of the system requires actions on behalf of household members in response to threats. It is clear from the above analysis that the flood risk differs greatly depending on the physical characteristics of a settlement; thus, the required actions will also differ.

Abruq Ar Rughamah was selected for this study because it is composed of both formal and informal settlements. Although the entire neighborhood is exposed to flood hazards, informal settlements, which mostly feature traditional houses, are more vulnerable to floods for a number of reasons. First, the physical geography of informal settlements enhances the flood hazard by impeding water flow, and the weaker construction materials used to build informal settlements point to a greater likelihood of structural damage. Second, the opportunities to evacuate are reduced in informal settlement areas; for example, the haphazard building layouts increase the presence of flood water in the streets, which transports debris (including cars). Modifying existing neighborhoods to cope with floods is difficult and would result in changes to buildings and their layouts for the following reasons.

- Official building permits are based on the Saudi Code of Building (sbc.gov.sa 2018), which stipulates the quality of construction materials to be used. This

code has not been applied to ‘traditional’ houses that use low-cost materials and do not have legal status. Strengthening buildings in these settlements should be a priority and may comprise the removal/rebuilding of dangerous structures that pose risks.

- Redesigning the layout would have to include creating new streets that are wide and aligned with the natural slope to provide a path through the built-up area. Protective barriers along these streets could limit damage to other parts of the settlement area. Such a dramatic redesign would also entail the removal of some buildings.

Other factors that increase the risk in informal settlement areas are cars parked on narrow roads. These factors impede the movement of emergency vehicles, act as waterborne debris during floods (damaging walls and buildings), and hamper clean-up efforts. Rules about parking that greatly reduce the street space occupied by vehicles are a priority; this may mean setting aside parking areas on the downstream side of the settlement area.

Flood risk assessments must account for community responses (Cutter 1996; Messner and Meyer 2005), but the census data used here offered limited insights into this component of flood risk. Although these data showed that the populations of the informal and formal settlements differed little in terms of demography, further work is needed to examine flood awareness and coping strategies.

14.6 Conclusions

Given the roles played by physical and human factors in this study, both of which led to increased vulnerability and exposure in the study area, this study recommends the redesign of unplanned parts of the city to improve the adaptability of these areas to flood risks. This would include opening drainage channels, especially in the irregular part of the neighborhood, and widening some narrow roads. This study also stresses the importance of finding urgent solutions for traditional buildings, as these buildings increase hazards both in flood scenarios and other natural disasters, such as earthquakes, due to their structural weaknesses.

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