Flood Hazards Analysis of Jeddah City, Western Saudi Arabia

Ali M. Subyani

Hydrogeology Department, Faculty of Earth Sciences, King Abdulaziz University
P.O.Box 80206, Jeddah 21589, Saudi Arabia
asubyani@hotmail.com

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Abstract. Flash floods are among the most catastrophic natural extreme events that present a potential threat to both lives and property. They occur immediately after heavy and short rainstorm duration. Jeddah City, located in the middle part of the Red Sea coastal plain of Western Saudi Arabia, has received an unexpected amount of rainstorm in 25th November, 2009 and 29th Jan 2011 that has never happened in the last 5 decades. Flooding events in this city, in fact, often result form the integration of several factors, including rainfall intensity, surface runoff, infiltration, topography and landuse. These factors contribute an important role in flood generation. This study represents an integrated approach of remote sensing, Geographic Information System (GIS) and hydrological models, which will be utilized to identify, asses, and categorize the vulnerable areas in Jeddah City. Nevertheless, this study will help the decision makers for any future planning and for the better management of sustainable development of Jeddah environment.

Keywords: Flood hazards; GIS; Vulnerable areas; Jeddah; Saudi Arabia.

Introduction

In arid and semi arid regions, flash floods occasionally cause heavy destruction to engineering structures, human lives and properties. Unfortunately, residents in the floodplain and inundation areas are not
sufficiently aware of flash floods consequences due to long time aridity prevalence. Thus, land with high risk of flooding is carelessly developed for settlement and infrastructure purposes. However, flash floods are formed rapidly and they flow down over extremely dry or nearly dry watercourses (Farquarson et al., 1992; Flerchinger Cooly, 2000; Subyani, 2010). Flash flood occurrences are rather complex, since they depend on various interactions of many geological, morphological and hydrological characteristics of the basins such as rock types, elevation, slope, sediment transport, flood plain area, and also on hydrological phenomena such as rainfall, runoff, evaporation, and surface and groundwater storages. In addition, land use, human impacts and interactions are also very important factors that affect the flash flood behavior especially in cities.

In Saudi Arabia, rainfall can be described as being little and unpredictable as well as irregular, but very extensive during local storms. The western region of Saudi Arabia receives a moderate amount of rainfall compared with the other regions, because of its geographic nature and location within the subtropical zone. In general, rainfall in this area occurs in winter and spring seasons of the year. Winter and spring rainfalls are due to the African-Mediterranean interaction (Şen, 1983; Alyamani and Şen, 1992; Subyani, 2004; Almazroui, 2011).

Jeddah City, located in Western Saudi Arabia, is bounded by Lat. 21° 15’ and 21° 55’N and Long. 39° 00’ and 39° 30’E. (Fig. 1). In terms of geological features, the study area is characterized by flat coastal plain in the west and underline by Precambrian rocks of the Arabian Shield and flat Harrats in the east. The main channel and tributaries of Jeddah Wadis were filled with Quaternary sediments that derived from host rocks, and provide for groundwater storage (Brown et al., 1989, Qari, 2009). In addition, the study area is characterized by high land value, rapid population growth, and fast expansion of urban areas.

Although the area is considered arid with low rainfall, and it often occurs as thunderstorms of very high intensity during local storm followed by dry periods. Because of high rainfall in short time, heavy flash floods tend to strike cities, towns, farms and utility services causing severe damages (Subyani et al., 2009). In Jeddah area, after the severe floods that struck the area in 2005, 2006, 2008, 2009 and 2011, bridges and roads were destroyed, and flash floods swept through illegal random housing built areas. Many of these built areas were constructed randomly
on dry wadi beds during a long time of aridity. The catastrophic phenomena that occurred in unpredictable space and time series, as unusual flood event, have become more and more serious, resulting in high damage consequences to the population and infrastructures (Şen, 2008).

Several methods were applied for the assessment of hazard areas all around the world, which include geomorphological, meteorological, hydrological, and socio-economical influences. However, GIS techniques appear to be promising, as it is capable of integrating the other techniques of flood risk assessment.

The main objectives of this study are to establish a spatial database for physiographic, and hydrologic features of the study area, and to analyze and produce rainfall-frequency curve for different return periods. The Final results are hazard zonation maps for Jeddah City.

Fig. 1. Location map of Jeddah City and its Land use.
Methodology

Risk is an integral part of life, and its uncertainty always involved some balance between profit and loss. Since risk cannot be completely eliminated, the only option is to manage it. Risk assessment is the first step in risk management and according to Kates and Kasperson (1983) comprises three distinct steps:

a) Identification of hazards likely to result in disasters.
b) Estimation of the risks of such events.
c) Evaluation of the social consequences of the derived risk.

Risk assessment is used synonymously with risk valuation (Kienholz et al. 2004) and risk evaluation (Mock and Lawson, 2001). The task of risk assessment is to judge whether risks, as results of the risk analysis, are acceptable from an individual or a societal viewpoint. Risk assessment is based on the perception and awareness of risks. Ologunorisa and Abawua (2005) described this task as “Risk assessment is inherently subjective and represents a blending of science and judgment with important psychological, social, cultural, and political factors”.

Wei et al., (2003) presents a conceptualization of flood hazards, in which they presume that for a flood disaster to occur, three constituents must be present: 1) Hazard formative factors 2) Hazard formative environment 3) Hazard affected bodies.

Hazard-formative factors are those factors that induce floods such as heavy rainfall. A hazard formative environment is an environment predisposed or well conditioned to flooding due to geographic or topographic characteristics. Finally, hazard affected bodies include people, property, and agricultural product in the affected area. Without these three factors, the flood event would merely be a natural flood and not a flood disaster.

In this research, runoff and flood measurements and records are not available. Hence, the method of flood hazards study by Wei et al., (2003) and Ologunorisa and Abawua (2005) was adopted in this paper. The geomorphology and the hydrology with land use and land cover were investigated, with the remote sensing and GIS techniques to identify areas that are at risk flooding, resulting in the formation of help of flash flood zonation maps (hazard maps).
**Geomorphological Hazard**

Slope factor is one of the major geomorphological parameter needed for flood hazards assessment. However, the aspect of the slope, is the direction that runoff would take under the influence of gravity, which resembles the angle of maximum slope. Using Digital Elevation Models (DEMs) of different grid resolutions (30m-90m) may produce different classes of hazards due to flattening of slope. Re-sampling a DEM to a larger resolution (e.g. > 100 m) will decrease the slope derived from it (Lyon, 2003). In this study, slope hazards are derived using 90m resolution DEMs. Watershed Modeling System (WMS) Software was used to create interpolated slope layer in GIS for all basins in the study area. The degrees of hazard are depending on the slope in percentage as shown in Table 1. Flatter slopes with less than 10% are considered in this study as very slight slope, whereas slopes from 10-20% and 20-30% are considered as slight to moderate hazardous, respectively. Accordingly, steeper slopes (30-40%) are severe and dangerous slopes and very severe slopes are those of more than 40%.

<table>
<thead>
<tr>
<th>Slope %</th>
<th>Definition</th>
<th>Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10</td>
<td>Very Slight</td>
<td>Coastal and Harrats</td>
</tr>
<tr>
<td>10-20</td>
<td>Slight</td>
<td>Harrats and flood plains</td>
</tr>
<tr>
<td>20-30</td>
<td>Moderate</td>
<td>Hills and Wadis</td>
</tr>
<tr>
<td>30-40</td>
<td>Severe</td>
<td>Deep wadis (Canyons)</td>
</tr>
<tr>
<td>&gt;40</td>
<td>Very Severe</td>
<td>High Mountains</td>
</tr>
</tbody>
</table>

**Hydrological Hazard**

The hydrological hazard maps are essentially based on the characteristics of the floodplain. Unfortunately, in the arid environment, main channels and streams are dry all time through the year in mostly all the basins. Hence, analysis of satellite images and field surveys are used along with GIS to draw the flood hazard maps and the inundation areas as well.

Buffering zone is one of the most popular and durable tools in GIS. In fact, as a decision making tool, buffering is widely used by local government agencies, usually to restrict certain land uses along water courses to protect infrastructure and human life. The researchers look at the issue of buffering in terms of design between a fixed-width buffer (FWB) and a variable-width buffer (VWB). Fischer and Fischenich, 2000; Wenger and Fowler, 2000; Lee et al., 2003 suggested that the only
advantage of using minimum fixed-width buffer over variable-width buffer, is that it is easier to implement and administrate. In addition, they described several models for determining buffer width, based on slope, stream width, vegetation density, wetlands and land use.

In the present study, FWB and VWB buffering techniques were adopted. FWB along small and feeder streams were suggested as 50m for high hazard, 100m for medium hazard and 150m for low hazard, on both sides of the stream. For the main channels, the buffer zones are suggested as 100m for high hazard, 200m for medium hazard and 300m for low hazard, on both sides of the channel. VWB is used for cities, villages and agriculture depending on their locations in the floodplain and on streams or channels (Fischer and Fischenich, 2000).

**Land Use\Land Cover Hazard**

Land use and land cover are dynamic entity which varies both spatially and temporally, especially in agricultural area where the crop rotation patterns, crop type, and total acreages planted in crops vary from year to year. Hazard of land use is classified into two main categories, high risk and medium risk. The high risk includes valuable infrastructure which can be the subject of floods. Medium hazard is designated for areas with low population and seasonal agriculture lands, but they located in flood zones. There is no low risk according to human values in any spot.

**Results and Discussion**

In the present study, Figs. 2 and 3 show the DEM and drainage network of Jeddah Wadis, respectively. The city is divided into 4 major basins names: (1) South basin includes Wadi Ghulail, Wadi Mathwab, Wadi Ushair and Wadi Qus, (2) Bani Malik basin, which includes Wadi Al-Asla and Wadi Murayyk, (3) Burayman basin including Wadi Hutail, Wadi Buraiman and Wadi Umm Hablain, and (4) Al-Kura' basin with Wadi Ghurrayah and Wadi Al-Kura' as shown in Fig.3. Table 2 summarizes the different morphological parameters of these main basins. It shows that most of the basins are elongated, with low relief, and moderate drainage density. It also indicates that the basins are of low stream flow discharge due to surface roughness and very low rainfall
intensity in the city basins. Most of drainage patterns have dendritic shape.

Fig. 2. Digital Elevation Model of Jeddah City.

Fig. 3. Drainage network and sub-basins of Jeddah City.
For south wadis (Table 2), drainage density is about 1.85 km\(^{-1}\) which indicates a highly permeable landscape with small potential for runoff. Relief ratio was found to be 0.003 and the low value indicates that the host rocks are more resistant to physical geological processes. Elongation of the south wadis was estimated as 0.48 this value indicate a fairly elongated basin. Circularity was estimated as 4.3 which confirms the elongation of the shape of the wadis.

For Wadi Bani Malik (Table 2), drainage density is about 1.64 km\(^{-1}\) which indicates a highly permeable landscape with small potential for runoff. Relief ratio was found to be 0.005 and the low value indicates that the host rocks are more resistant to physical geological processes. Elongation of the south wadis was estimated as 0.54 this value indicate a fairly elongated basin. Circularity was estimated as 3.4 which confirm the elongation of the shape of the wadis.

For Wadi Buraiman (Table 2), drainage density is about 1.85 km\(^{-1}\) which indicates a highly permeable landscape with small potential for runoff. Relief ratio was found to be 0.01 and the low value indicates that the host rocks are more resistant to physical geological processes. Elongation of the south wadis was estimated as 0.77, this value indicates a fairly elongated basin. Circularity was estimated as 1.7 which confirms the circular shape of the wadis.

For Wadi Al Kura (Table 2), drainage density is about 1.92 km\(^{-1}\) which indicate a highly permeable landscape with small potential for runoff. Relief ratio was found to be 0.01 and the low value indicates that the host rocks are more resistant to physical geological processes. Elongation of the south wadis was estimated as 0.76 this value indicate a fairly elongated basin. Circularity was estimated as 1.73 which confirms the elongation of the shape of the wadis.

Jeddah Wadis, Fig. 4 shows the mean slope produced from DEMs using GIS software. It shows that eastern parts of the city are categorized by a moderate slope hazard due to the available mountains in the east, while the rest of the city has slight to very slight slopes towards the Red Sea. However, the flatted area of Jeddah city, can be affected from local heavy storm events and can be subjected to flooding hazards, especially with lack of complete and effective storm-water drainage network. During winter season (October and November), Jeddah is subjected to flash floods from local heavy storms, and water ponds appear in scattered locations due to low infiltration, as well as, due to very shallow water.
Flood Hazards Analysis of Jeddah City, Western Saudi Arabia

Table 2. Morphometric Parameters of Jeddah Wadis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Abbr.</th>
<th>South Wadis</th>
<th>Wadi Bani Malik</th>
<th>Wadi Buraiman</th>
<th>Wadi Al-Kura'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basin Area</td>
<td>Km$^2$</td>
<td>A</td>
<td>223</td>
<td>412</td>
<td>410</td>
<td>315</td>
</tr>
<tr>
<td>Total Stream Length</td>
<td>m</td>
<td>C_t</td>
<td>413.05</td>
<td>678285</td>
<td>761802</td>
<td>607628</td>
</tr>
<tr>
<td>Basin Slope</td>
<td>m/m</td>
<td>BS</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>Max. Flow Distance</td>
<td>m</td>
<td>MFD</td>
<td>4432</td>
<td>58132</td>
<td>57457</td>
<td>36824</td>
</tr>
<tr>
<td>Dist. to Stream</td>
<td>m</td>
<td>CTO</td>
<td>958</td>
<td>515</td>
<td>1334</td>
<td>555</td>
</tr>
<tr>
<td>Centr. Stream Dist.</td>
<td>m</td>
<td>CSD</td>
<td>23456</td>
<td>28129</td>
<td>23831</td>
<td>17170</td>
</tr>
<tr>
<td>Max. Stream Length</td>
<td>m</td>
<td>C_m</td>
<td>41934</td>
<td>55531</td>
<td>55867</td>
<td>84490</td>
</tr>
<tr>
<td>Max. Stream Slope</td>
<td>m/m</td>
<td>MSS</td>
<td>0.005</td>
<td>0.005</td>
<td>0.003</td>
<td>0.007</td>
</tr>
<tr>
<td>Basin Length</td>
<td>m</td>
<td>L_b</td>
<td>30834</td>
<td>37452</td>
<td>26208</td>
<td>23367</td>
</tr>
<tr>
<td>Circularity</td>
<td>m$^2$/mi$^2$</td>
<td>E_c</td>
<td>4.26</td>
<td>3.4</td>
<td>1.67</td>
<td>1.7</td>
</tr>
<tr>
<td>Sinuosity Factor</td>
<td>msl/l</td>
<td>Sin</td>
<td>1.36</td>
<td>1.48</td>
<td>2.13</td>
<td>1.52</td>
</tr>
<tr>
<td>Basin Perimeter</td>
<td>m</td>
<td>P_b</td>
<td>125702</td>
<td>187175</td>
<td>139919</td>
<td>129255</td>
</tr>
<tr>
<td>Mean Basin Elev.</td>
<td>m</td>
<td>Avel</td>
<td>106</td>
<td>123</td>
<td>74</td>
<td>88</td>
</tr>
<tr>
<td>Ave. Stream Slopes</td>
<td>m/m</td>
<td>ASS</td>
<td>0.006</td>
<td>0.004</td>
<td>0.006</td>
<td>0.007</td>
</tr>
<tr>
<td>Drainage Density</td>
<td>Km$^{-1}$</td>
<td>D_d</td>
<td>1.85</td>
<td>1.6</td>
<td>1.85</td>
<td>1.92</td>
</tr>
<tr>
<td>Relief</td>
<td>m</td>
<td>H_b</td>
<td>80</td>
<td>200</td>
<td>260</td>
<td>240</td>
</tr>
<tr>
<td>Relief ratio</td>
<td></td>
<td>R</td>
<td>0.0026</td>
<td>0.005</td>
<td>0.016</td>
<td>0.01</td>
</tr>
<tr>
<td>Elongation</td>
<td></td>
<td>E</td>
<td>0.484</td>
<td>0.54</td>
<td>0.77</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Fig. 4. Slope classes of Jeddah city.
The study area is classified into three hazard categories according to the hydrologic situation (high, medium and low hazard). These categories are dependant on buffer zones of hazard assessment for cities, roads and villages that are situated mostly in the downstream areas of the basins. Figure 5, within Jeddah city, especially west of Jeddah-Madinah expressway, is subject to high flooding risk, especially during the local heavy storms (which occurred usually in October and November). Flat areas in the city are subject to the accumulation and formation of water ponds and lakes, which will increase of environmental and health hazard (Dengue Fever). In the mountains area (east of Jeddah), the slope factor has more advantage for driving storm water into streams and channels, but it is considered as of medium flood hazard to available human structures and activities.

Also, the land use hazard was produce for Jeddah city, hazard of land use is classified into two main categories, high hazard and medium risk. The high hazard includes valuable infrastructure which can be the subject of floods. Medium hazard is designated for areas with low population and seasonal agriculture lands, but they located in flood zones. There is no low hazard according to human values in any spot. Figure 5 shows the productive and important areas that are prone to flooding with the proposed classification degree of hazards.
Conclusion

Floods are in fact complex phenomena. They are result from superposition of many components including the nature, period and rainfall intensity, morphological setting, hydrogeological properties and land use and land cover. The study area of Jeddah city is considered as arid area. In rain storms, heavy flash floods tend to strike the city and causing severe damages. Physiographically, the study area can be divided into two major units, namely: The Red Sea coastal plain (Tihamah) and the hills. Land use maps were produced for important and strategic areas in Jeddah city. Hazard analysis used slope, land use and land cover, and flood buffer zones through which flood risk zones were determined. The results can be used for future water projects and flood hazards management. More daily rainfall stations network should be established in addition to flood warning systems at the outlet of all wadis due to flash flood hazard potential. In addition, the construction activities along the main wadis channels must be prevented.

Acknowledgements

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**References**


تحليل مخاطر الفيضانات في مدينة جدة، غرب المملكة العربية السعودية

علي محمد الصبياني
قسم جيولوجيا المياه، كلية علوم الأرض، جامعة الملك عبدالعزيز، جدة - المملكة العربية السعودية

المستخلص. تعتبر الفيضانات الوressive من بين أكثر الكوارث الطبيعية التي تشكل تهديداً لكل من الأرواح والممتلكات، وهي تحدث فوراً بعد العواصف المطرية الغزيرة كمية وقصيرة مدة. تعرضت مدينة جدة والتي تقع في الجزء الغربي من المملكة العربية السعودية لهطول كمية عالية جداً من الأمطار في 25 نوفمبر 2009، و29 يناير 2011 والتي لم تحدث منذ عدة عقود. إن حدوث الفيضانات في مدينة مثل مدينة جدة، في الواقع، غالباً ما ينجم عن تداخل عدة عوامل، تشمل شدة هطول الأمطار، والحريان السطحي، والتشييد والطبوغرافيا واستخدام الأرضي... إلخ. كل هذه العوامل تلعب دوراً هاماً في تشكيل الفيضانات. هذه الدراسة هي نهج متكامل بما في ذلك الاستشعار عن بعد، نظم المعلومات الجغرافية والنمذجة الهيدرولوجية، والتي تستعمل في تحديد وتقييم وتصنيف المناطق المعرضة لمخاطر الفيضانات في مدينة جدة. ومع ذلك هذه الدراسة سوف تساعده في عملية صنع القرار في التخطيط المستقبلي وتحسين إدارة التنمية المستدامة للبيئة.

الكلمات الدالة: مخاطر الفيضانات، نظم المعلومات الجغرافية، مناطق المخاطر، جدة، المملكة العربية السعودية.