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ASSESSING FLOOD VULNERABILITY OF WADI HANIFA BASIN AND SURROUNDING AREA, CENTRAL SAUDI ARABIA

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Climatic change has been recently raised as a global environmental issue. This change can result in large variations in meteorological conditions. Disastrous events can be exacerbated in time and space, and many have become priority issues in environmental discussions. In this respect, Saudi Arabia, as an arid region, has recently witnessed a number of climatic extremes, with a special emphasis on dust storms and flash floods. Rarely a year goes by without a catastrophic event. Even though the region is characterized by low rainfall, extreme rainfall peaks have become a common event, and they almost always result in damaging floods. This study focuses on assessing the flood vulnerability of Wadi Hanifa and the neighboring basins to the capital, Riyadh. The study area is located in central Saudi Arabia where dense urban settlements exist. The study aims to identify the major components controlling the flood process, through the analysis of related hydrological and morphometric characteristics of the drainage systems and the orientation of the basin. In order to reach this objective a miscellany of data and tools were used, namely thematic maps and a geographic information system (GIS). Results show that the region has a moderate vulnerability to flooding, with some numerical values suggesting high vulnerability, notably in the northeast part of Riyadh city. This is first-hand information for decision makers to act and implement a number of mitigation measures to prevent, or at least reduce the impact of floods.

INTRODUCTION

As a worldwide phenomenon, the change in climatic conditions is usually accompanied with variations in the hydrologic regime on terrain surface and water runoff. However, aspects and rates of variation are different by region. For this reason, several explanations and scenarios have been made using different approaches of analysis to evaluate future climatic trends and their impact on human beings.

Many consequences result from the change in the climatic regime, and they are usually viewed from two principal meteorological parameters, the rainfall rate and temperature. Nevertheless, these parameters influence, in a broad sense, the climatic behavior and in many instances, result in climatic extremes, such as flash floods, hail and dust storms, torrents, avalanches, etc. Torrential rain can be the most dangerous since it results in flooding and often ends up being a natural disaster that affects human beings and nature as well. The social and economic costs of natural disasters are rising. There has been a five-fold increase in economic cost over the last 30 years. On average, over 110,000 persons lose their lives each year on account of natural disasters (UN, 1998). Some severe floods can cause several million of dollars of damage. The great 1998 flood in the Nenjian River, China, cost around $35 billion (Zhou et al., 2000).

The irregularity of rainfall frequently leads to torrential downpours giving rise to catastrophic floods. An increasing frequency of flooding disasters is being witnessed in the last few decades in the Middle East region at different scales and magnitudes due to the diversity in the climate patterns that dominate the region.

Saudi Arabia is a typical example where rainfall can be described as being little and unpredictable as well as irregular, but very intense during local storms (Subyani et al., 2009). Rainfall normally occurs in winter and spring seasons of the year. Winter and spring rainfalls are due to the African-Mediterranean interaction (Alyamani and Sen, 1992).

Recently, in Saudi Arabia, a country representing mainly the terrain body of the Arabian Peninsula, flash floods have been increasingly common. A typical example is the flood that took place in Jeddah city and its surroundings in November 2009. The existing valleys in this region transported rainwater with huge amounts of sediments towards the city, and resulted in severe impacts in the urbanized areas. This motivated considering these geo-environmental issues and threats in similar regions of Saudi Arabia.

The impact of the floods in the region resulted in severe damage that can be attributed to the following reasons:

1. The region is situated in an arid zone and, therefore, measures to prevent and reduce flood disasters are few and sometimes are completely lacking,

2. Unavailability of sequential and uniform rainfall data and a weaknesses in the monitoring approaches and early warning systems,

3. The high temperature rate creates fragmented rocks as well as the unconsolidated sediments that are formed due to aeolian erosion. These rock and sediments aggregates are easily moved by rain water and increase the degree of impact,

This study focuses on the capital Riyadh and the neighboring regions where dense urbanized suburbs are located, composing the largest human settlement in the country. It is situated within a number of valleys (wadis), and the Wadi Hanifa Basin (WHB) is the largest. The other major wadis are Wadi Al-Haniyah and Wadi Nessah.

The study area includes the three wadi basins, and has an area of approximately 14681 km^2. It is located within the following geographic coordinates (Figure 1):

- Latitudes: 23° 55' 56" and 25° 13' 24" N.
- Longitudes: 45° 23'15" and 47° 27' 23" E.

The aim of this study is to analyze the major components that govern flood occurrence. These include characterization of the drainage system and the morphometric behavior of the tributaries and their relation to each other, as well as to diagnose the basin characteristics including mainly shape dimensions. Thus, the resulting analysis will clarify the vulnerability of WHB and its surrounding wadis to flooding. For this purpose, thematic maps were used including mainly the topographic and geologic maps with appropriate scales. In addition, the available rainfall records were utilized to determine rainfall peaks and their behavior. Consequently, the obtained maps were digitally produced and manipulated in the GIS system.

MATERIALS AND METHODS

Factors influencing flood occurrence

Other than anthropogenic involvement, there are a number of physical factors influencing the occurrence of floods. They are found to be different from region to region depending mainly on the physical setting of these regions. However, human interference, and mainly urban expansion, has an essential role in increasing or reducing the flood impact. In general, physical factors are

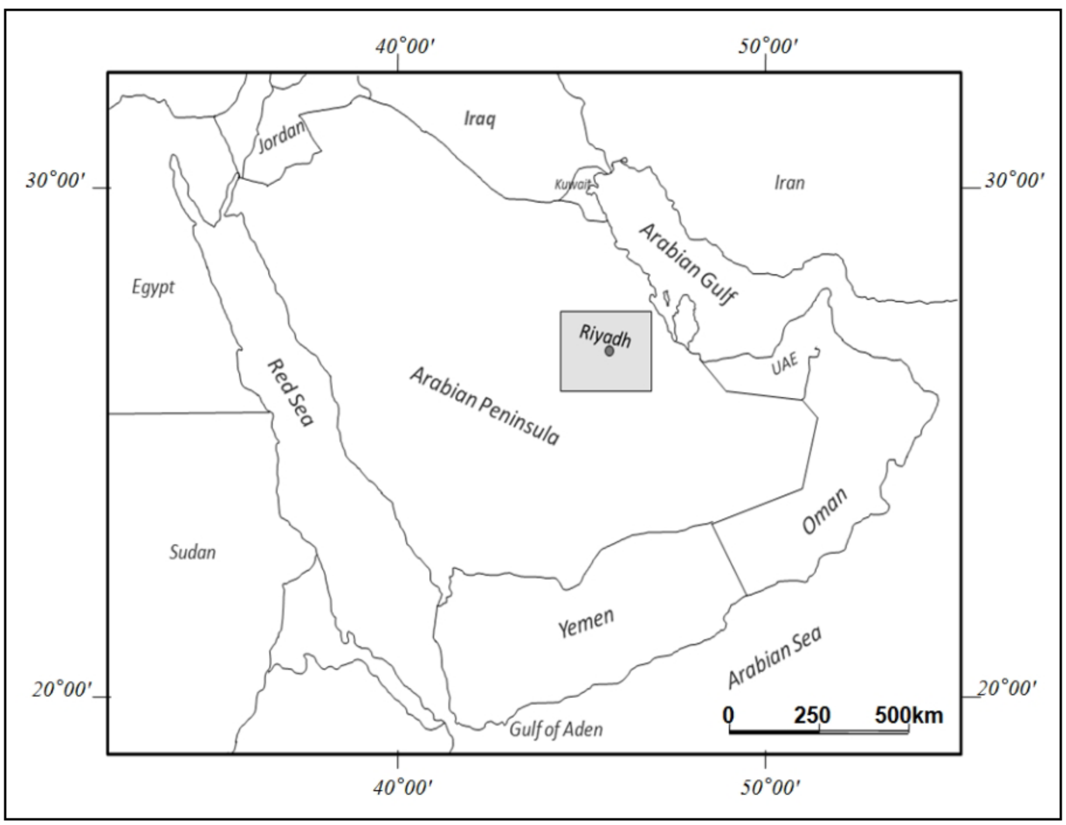

Figure 1. Location map of the study area.

represented mainly, in addition to rainfall intensity, by the characteristics of the water catchment area (watershed or basin) and the morphometry of the drainage system within the watershed. Amongst these factors, rainfall intensity is the most effective since it represents the generating agent. Without rainfall, flooding does not occur.

For this reason, geo-spatial data and climatic records are essential tools to predict flood occurrence. Meanwhile, new advanced techniques (e.g. GIS) can help by analyzing geo-spatial data and producing flood-vulnerability maps.

Rainfall

It is essential to involve rainfall amounts and its behavior in the assessment of floods. A low rainfall rate and lack of torrents will not produce any flooding event. In this regard, the WHB is considered as a low-rate rainfall basin, since the annual average rainfall does not exceed 100 mm and usually ranges between 30 to 60 mm/yr, and is averaging 45 mm (Al-Saif, 2009). The rainy period almost extends over four months (between December and March).

Considering the areal extent of the basin, which is 14681 km^2; however, the total volume of rainfall water on the basin will be:

$45/1000 \times 14681 \times 10^6 = 661$ million m^2/yr

Therefore, each 1 km^2 receives about 45000 m^3/yr.

Even though the volume of rainfall is relatively low, yet there is a noticeable recurrence of rainfall peaks in the region (Figure 2). This is a observed in the last few decades, notably in the context of changing conditions of climate. Hence, in the absence of sequential and complete records rainfall peaks in this study were extracted from the space tools and more certainly from the Tropical Rainfall Mapping Mission (TRMM), which is a useful tool for climatic data analysis.

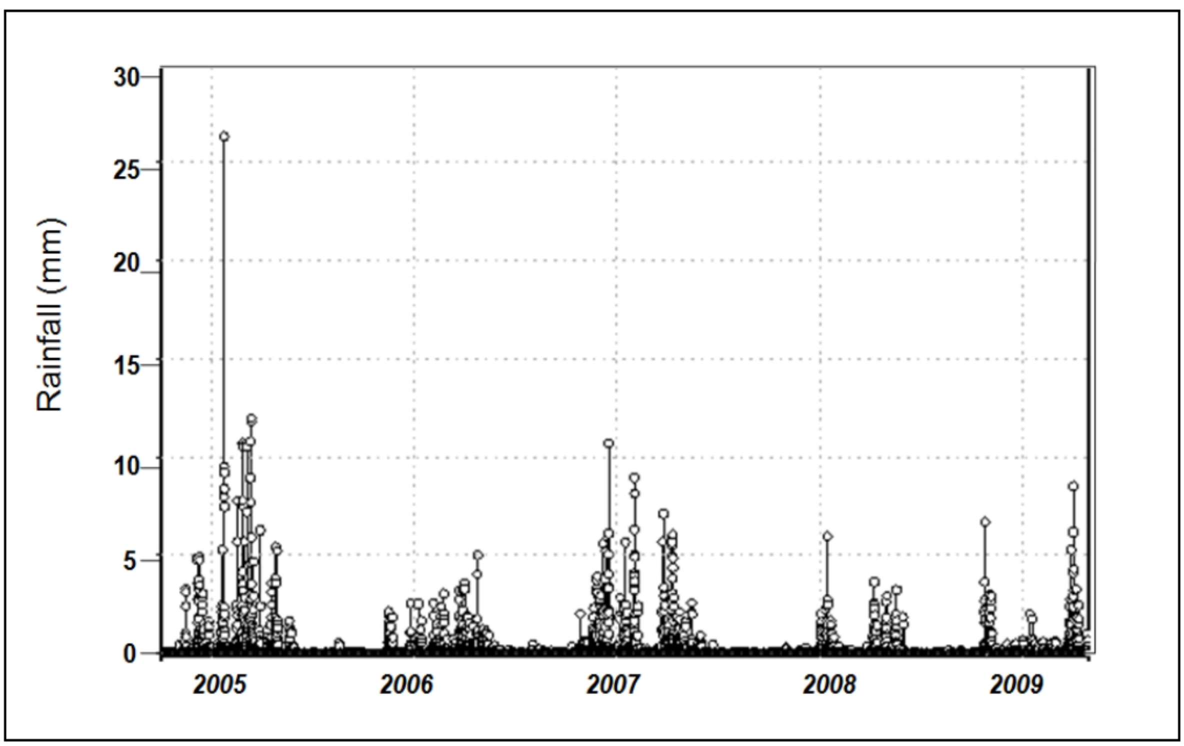

Figure 2. Rainfall peaks over the study area between 2000 and 2009 (NASA, 2010).

Watershed characteristics

Following geomorphologic procedures the catchment area of WHB and the surrounding basins were delineated by direct tracing of the drainage tributaries from topographic maps (scale 1:50000). Drainage system boundaries were identified. This was accompanied with a systematic digitizing of the traced tributaries and basin systems in the Geographic Information System (GIS) by using Arc-GIS 9.3 software. Thus, a drainage system map was produced including the major three catchment areas in the region, including Wadi Hanifa Basin, Wadi Al-Haniyah and Wadi Nessah (Figure 3).

Accordingly, there are a number of hydrological characteristics that can be involved to assess the vulnerability of drainage basin to flooding. However, the most effective characteristics are the mean catchment slope and the shape, with a special emphasis on width/length ratio and elongation ratio.

Mean catchment slope (C_{ms})

This characteristic is a function of the general slope gradient of the entire catchment. It is governed by the geology of the basin, including mainly the lithology and structures. This hydrologic characteristic controls the energy of flow, and thus the degree of erosion. Gordon et al. (1992), described the mean catchment slope (C_{ms}) as:

$$C_{ms} = (\text{Elevation at } 0.85\ L - \text{Elevation at } 0.10\ L) / \text{Elevation at } 0.75\ L$$

where L is the maximum length of the catchment, and thus measurements are taken along this line (0.01 L near the lower part of the catchment, 0.85 L towards the upper end).

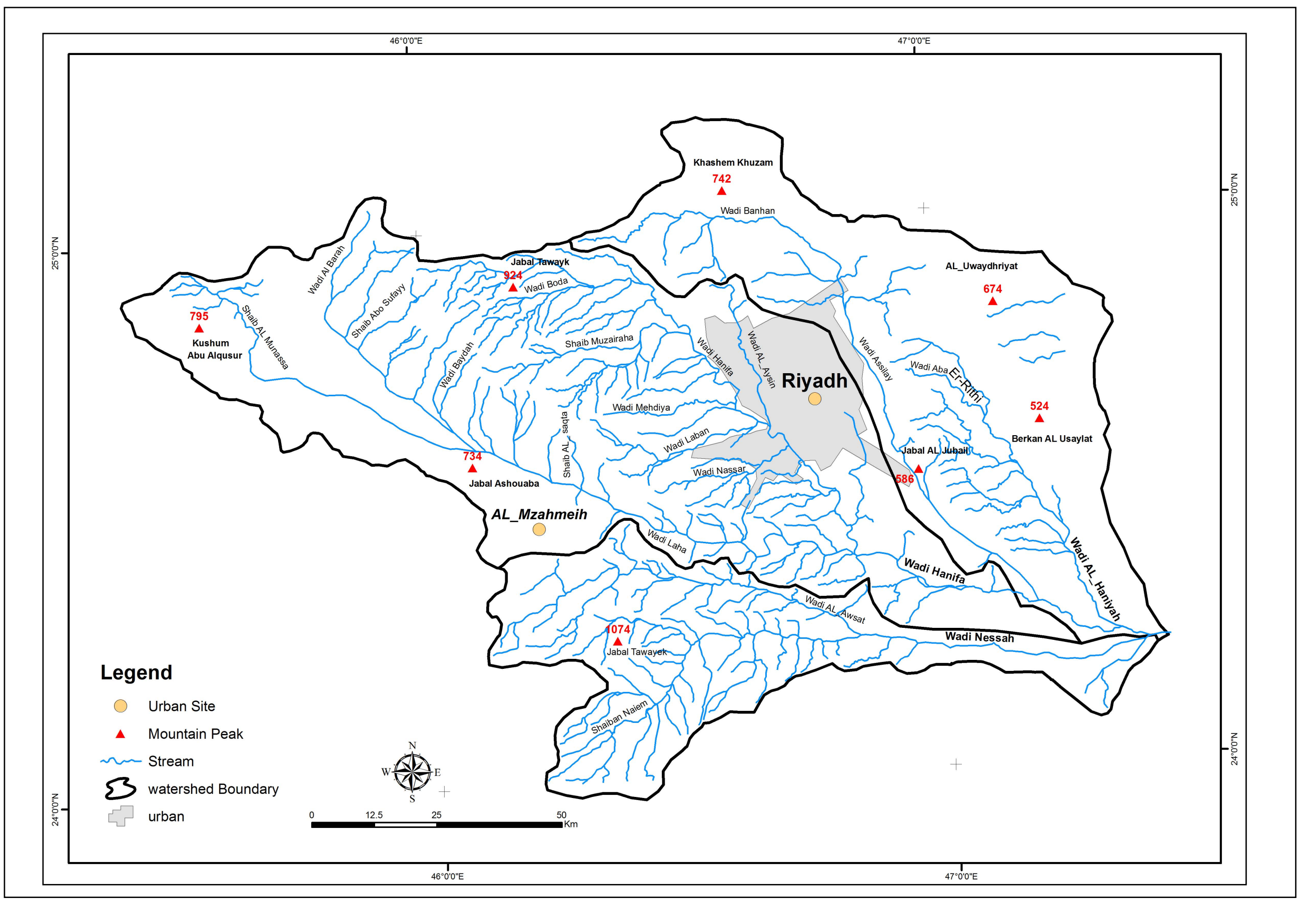

Figure 3. Drainage system map of WHB and the surrounding basins around Riyadh.

Shape

The characteristic of the outer boundary (shape) of the catchment area is a function of the flow regime within the surface hydrologic system. It controls the duration of runoff from the threshold areas to the outlet. Hence, it has an essential role in the flow behavior and velocity, in which the latter may result flash flooding.

The principal shape components that are related to flood occurrence are the width/length ratio and elongation ratio.

Width/length ratio (WL_r)

The ratio between the width to length (WL_r) of a catchment may increase or decrease runoff, and thus governs the connection between different water reaches and the primary watercourses. This relationship can be simply expressed as:

$$WL_r = \frac{W}{L}$$

Therefore, when WL_r increases, the runoff duration will increase and vice versa. Figure 4 shows an example of the width/length ratio, where two catchments have the same width, but with different lengths, hence catchment number 1 has a higher runoff than number 2.

Elongation ratio (E_r)

It is the stretching of the basin through its elongation with respect to the area of the basin. For a perfect circle, it equals one, while it is zero for a straight line. Figure 5 exhibits an example of different elongation ratio where they govern the surface runoff. Hence, the larger the E_r the higher peak flow.

Schumm (1956) described the elongation ratio in the following equation:

$$E_r = 2/L_m\ (A/p)^{0.5}$$

where L_m is the maximum length of the catchment parallel to the principal drainage lines.

Drainage morphometry

The morphometry of a drainage system represents the interrelation between different tributaries (i.e. drainages) and their characteristics. However, in flood assessment, the most important of

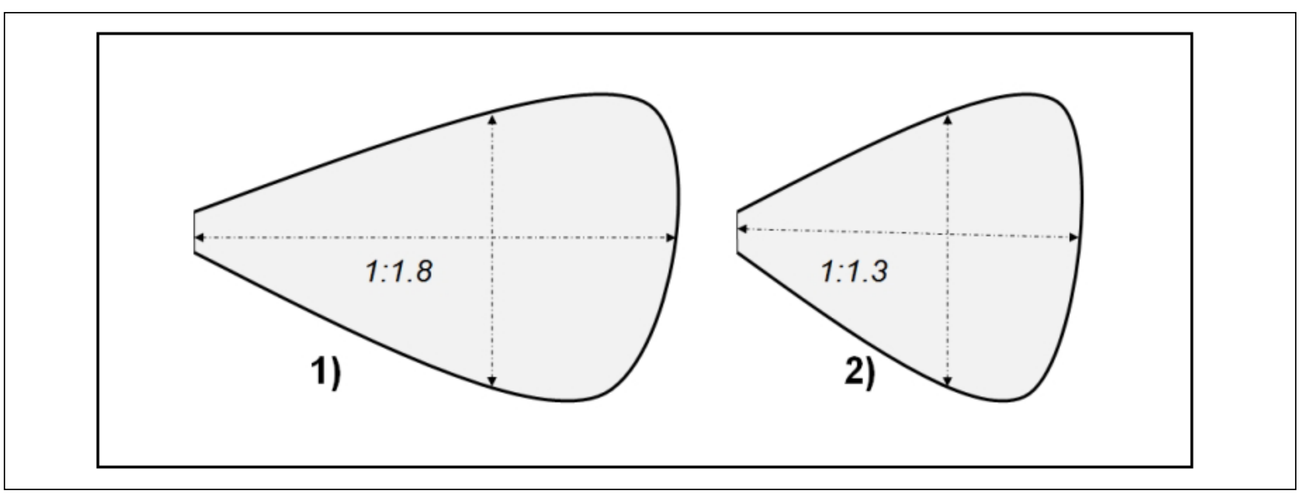

Figure 4. Schematic figures showing two catchments with different WL_r.

these characteristics are the drainage density, drainage frequency, meandering ratio and stream order and bifurcation.

Drainage density (D_d)

Drainage density is a mathematical function used to describe the total lengths of drainages within a specific area. Therefore, the higher the density of drainage, the lower infiltration rate and thus much more probability for flood.

Drainage density is expressed by the formula:

$$D_d = \frac{\Sigma L_l}{A}$$

where ΣL_l is the total length of drainages, and A is the area in km^2.

Drainage frequency (D_f)

Drainage frequency is a mathematical function similar to drainage density, but it encountered the total drainages within a specific area. Therefore, the higher the frequency of drainage, the lower infiltration rate and thus much more probability for flood.

Drainage frequency is expressed as:

$$D_f = \frac{\Sigma N_l}{A}$$

Meandering ratio (M_r)

One of indicators for stream stage maturity is the degree of meanderings, notably in the primary watercourses. Hence, meandering ratio **(**M_r**)** is usually considered. It represents the ratio between straight and curved lengths of the major stream in the basin, where the existing stream length is larger than the straight one. The lower meandering ratio indicating older stream stage and vice versa. This formula is expressed as:

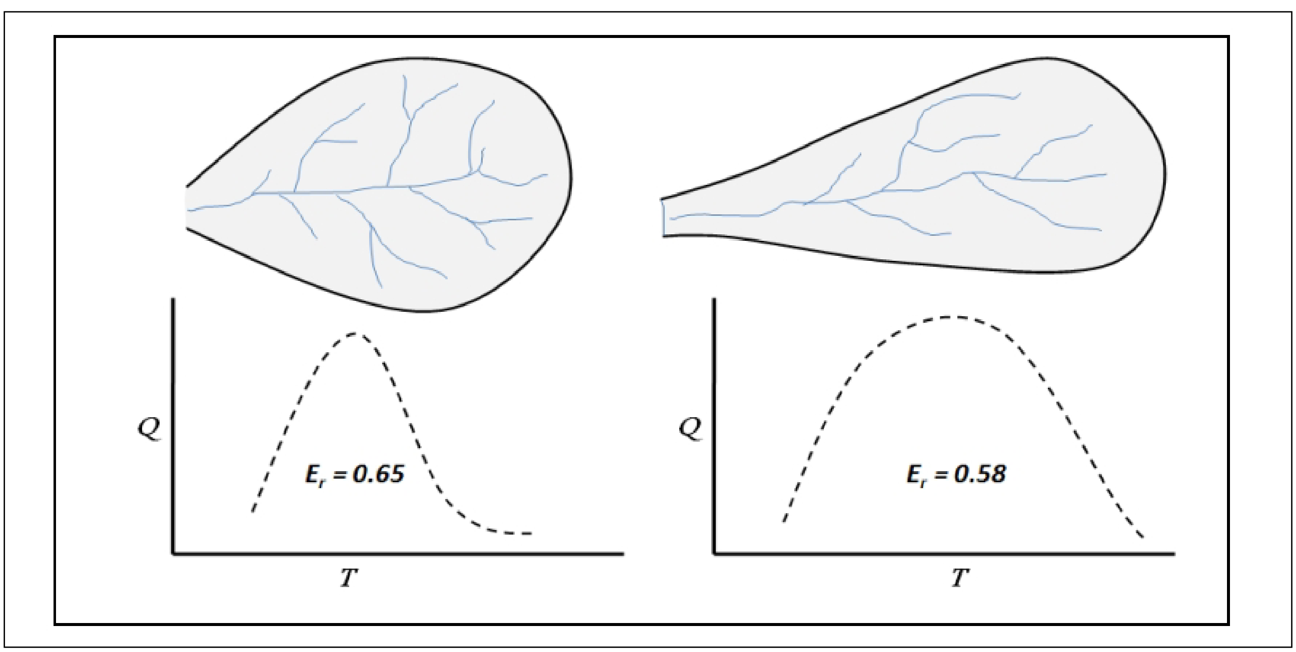

Figure 5. Schematic figures showing two catchments with different E_r.

Mr = *Ls* (straight stream length) / *Lc* (curved stream length)

Stream order and bifurcation ratio (B_r)

The designation by a dimensionless integer series (1, 2, 3, etc) of the relative position of stream segments in the network of a drainage basin is described as stream order. Strahler (1952) adopted this convention. Thus, the starting reach (stream), which is usually connected from the lower side is classified as 1st order 1. When two 1st order streams are connected, the resulting stream will be 2nd order and so on. Figure 6 shows different stream orders in the WHB and the neighboring basins (Wadi Al-Haniyah and Wadi Nessah).

According to Horton's Law (1945), the ratio of the number of streams of any order with respect to the number of streams of the next highest order is called "Bifurcation ratio". It is expressed by the formula:

$$B_r = \frac{N_u}{N_u + 1}$$

where the number of streams of order *u* equal to (N_u), and the number of streams in the next order is N_{u+1}.

RESULTS AND DISCUSSION

Numerical data has been used with the previous formulas to assess the hydrologic and geomorphologic setting of WHB and the surrounding basins around Riyadh city. This determined

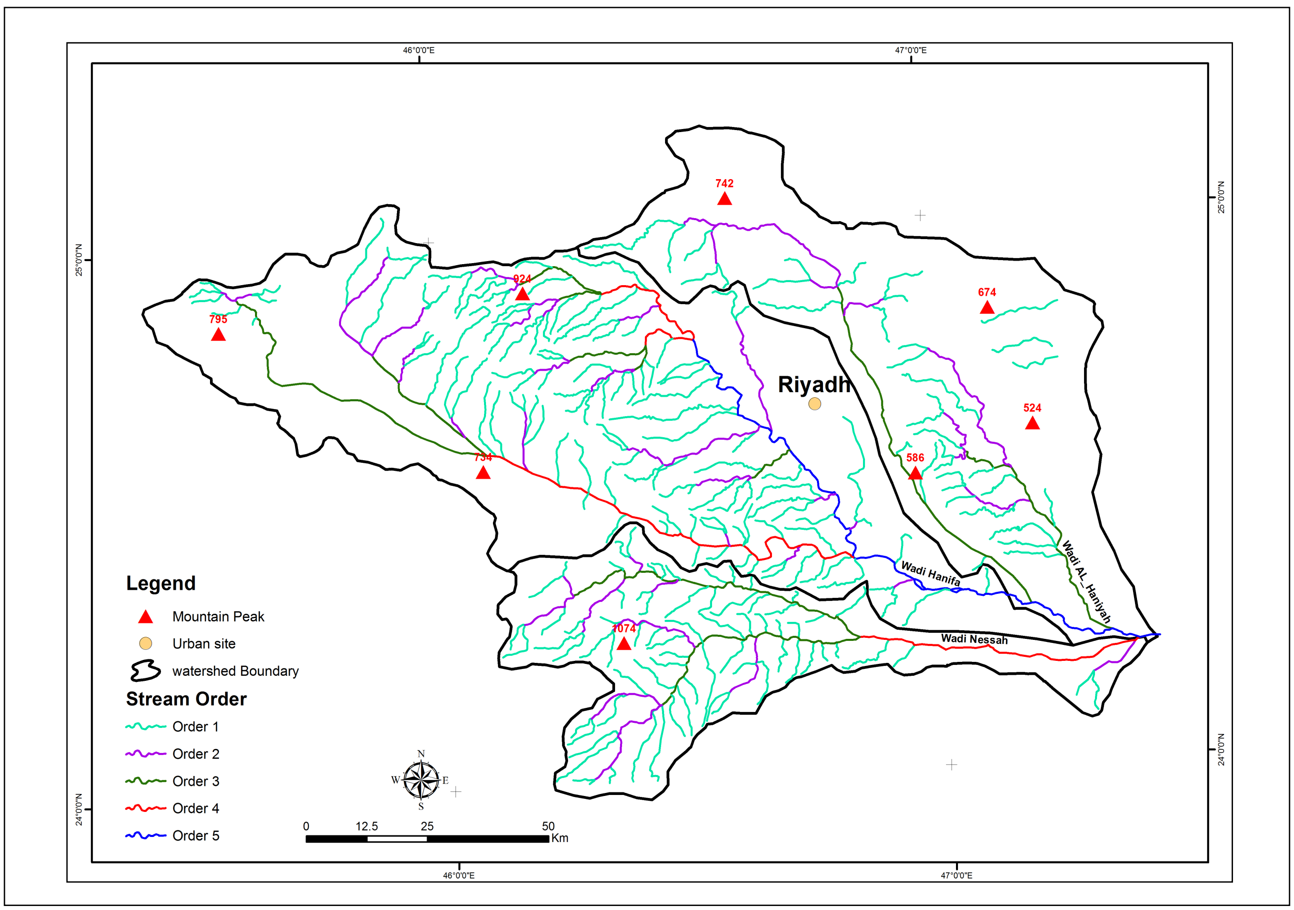

Figure 6. Drainage map showing different stream orders in WHB and the surrounding basins.

through the analysis of topographic maps in the GIS system. Hence, the two principal aspects, watershed and morphometry of the existing basins in the study area, were diagnosed.

Watershed characteristics of WHB and the surrounding basins show the three major variables (Table 1). It is obvious that the mean catchment slope for the three basins is low since they range between 0.32 and 0.70, and they are vulnerable to flood peaks. Width/length ratios are also low, especially in Wadi Nessah (i.e. 0.18). In addition, for the elongation ratio, the three catchments (basins) show availability to peak flow during rainy periods.

The morphometric characteristics of the existing basins in the study area are shown in Table 2. The drainage density and frequency are low, with a special focus on Wadi Al-Haniyeh, which has very low values (i.e. 0.15 and 0.01 for drainage density and frequency respectively). This indicates

Table 1. Watershed characteristics of WHB and the surrounding basins.

Basin	Area *(km^2)*	Mean catchment slope (C_{ms})	Width/length (WL_r)	Elongation ratio (E_r)
Wadi Al-Haniyah	2782	0.32	0.31	0.43
Wadi Hanifa	7353	0.44	0.23	0.49
Wadi Nessah	4546	0.70	0.18	0.58

that they are basins vulnerable to flooding, notably the Wadi Al-Haniyeh basin. The meandering ratios for all basins are relatively moderate.

The stream order and bifurcation ratio were extracted and calculated using *Arc-GIS 9.3* software (Table 3). The resulting data are used for basin assessment following the mathematical illustrations obtained by Al-Shamy (1992). In order to plot these illustrations, the relationship between

Table 2. Morphometric characteristics of WHB and the surrounding basins.

Basin	Total length of streams *(km)*	Drainage density (D_d) *(km/km^2)*	Number of streams *(segment)*	Drainage frequency (D_f) *($segment/km^2$)*	Meandering ratio
Wadi Al-Haniyah	695	0.15	46	0.010	0.87
Wadi Hanifa	1787	0.24	169	0.022	0.71
Wadi Nessah	874	0.31	103	0.037	0.69

bifurcation ratio and drainage density and frequency are required, and more certainly the D_d/B_r and D_f/B_r (Table 4).

The resulting values were put on dedicated illustrations to categorize the basin into A, B or C zones (Figure 7).

Al-Shamy (1992) categorized these zones as:

- Zone A: low flood probability and high recharge property
- Zone B: high flood probability and low recharge property
- Zone C: moderate to high flood probability and moderate recharge property.

Figure 7 shows the distribution of different variables of the three basins within the illustrated figures for basin assessment. Therefore, it is obvious that Wadi Al-Haniyah and Wadi Hanifa are located in zone C, which is characterized by moderate to high flood probability and moderate recharge property, according to Al-Shamy (1992), with much more vulnerability of Wadi Al-

Table 3. Stream orders and bifurcation ratio of WHB and the surrounding basins.

Stream order	Number of streams					Average
Basin	Order 1	Order 2	Order 3	Order 4	Order 5	Bifurcation ratio (B_r)
Wadi Al-Haniyah	35	8	2	0	1	2.09
Bifurcation ratio (B_r)	-	4.37	4.0	0	0	
Wadi Hanifa	124	29	10	3	3	2.85
Bifurcation ratio (B_r)	-	4.2	2.9	3.3	1	
Wadi Nessah	73	13	16	1	-	7.46
Bifurcation ratio (B_r)	-	5.6	0.8	16	-	

Table 4. Drainage density and frequency with respect to bifurcation ratio.

Basin	Drainage density	Drainage frequency	Bifurcation ratio (B_r)	D_d/B_r	D_f/B_r	*Basin assessment*
Wadi Al-Haniyah	0.15	0.010	2.09	C	C	C
Wadi Hanifa	0.24	0.022	2.85	C	C	C
Wadi Nessah	0.31	0.037	7.46	A	A	A

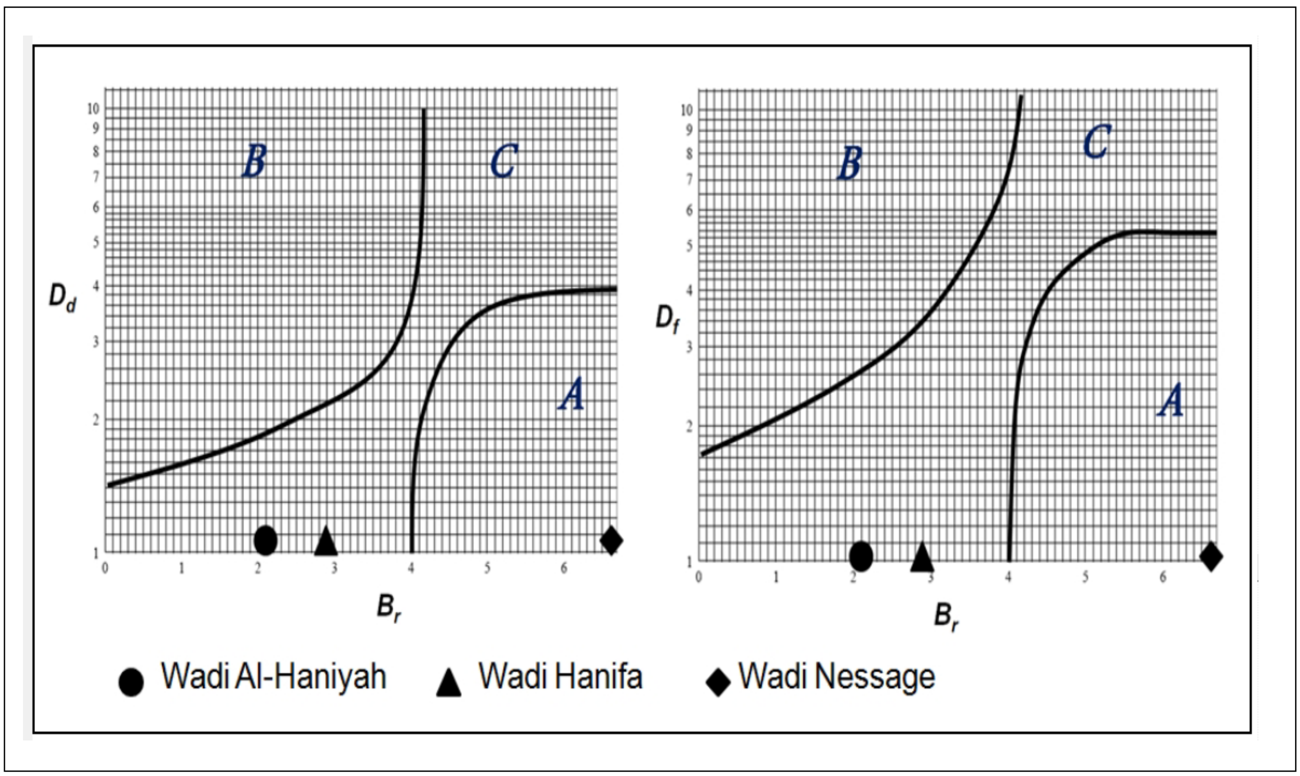

Figure 7. Basin assessment illustrations for floods in WHB and the surrounding basins.

Haniyah than Wadi Hanifa. Wadi Nessah is located in zone A, which encompasses low flood probability and high recharge property.

The low values of drainage density (D_d) and drainage frequency (D_d) are attributed to the small-scale (1:250000) used in the topographic maps.

CONCLUSION

The assessment of any region to flood vulnerability is achieved by analyzing a number of hydrologic and geomorphologic parameters, and this is usually followed a comprehensive environmental management plan. However, there are studies concerned with determining flood-prone areas, which are usually applied on local scale regions where all terrain elements and data are available. Nevertheless, assessment is also applied to evaluate the entire setting of a hydrologic system, and thus assessing its vulnerability to flooding, and this is in turn is considered as an inventory phase to build up a flood-prone areas map.

In Saudi Arabia, concerns with natural hazards are little, and even the studies in this regard are rare, but the increasing development of many catastrophic events in the last decades has raised the ideas of many researchers. Thus new perspectives to establish projects and studies related to environmental risk assessment have come to the fore, notably after the catastrophic flood even that occurred in Jeddah in November 2009. Hence, the status quo indicated the urgent need to involve the environmental security issue in a national program of the country.

In this study, focus was on basins assessment and its vulnerability to flood peaks in WHB and the surrounding basins around Riyadh city, which is a highly populated area. For this purpose, the major three existing basins (watersheds) were diagnosed using a number of systematic approaches for analysis, with a special emphasis on the applicable use of a GIS system.

Even though the three studied basins show a relatively moderate vulnerability for flooding, yet there are a number of indicative elements to be considered as follows:

1. Referring to the watershed and morphometric characteristics, Wadi Al-Haniyah basin is the most vulnerable basin for flooding with respect to the other two ones, especially in terms of low mean catchment slope (C_{ms}), low drainage density (D_d) and frequency (D_f). The lack of the basin with a sufficient channeling system will result in a chaotic surface flow regime, which is rather an overland flow than surface runoff. In addition, this was indicated by in the basin assessment illustrations using bifurcation ratio (B_r).

2. Considering the slope gradient in the region, however, the anticipated chaotic flow will be exacerbated towards the Riyadh city, notably at its northeast part (upstream of Wadi Assilay).

3. In spite of the moderate vulnerability of the entire basin system of Wadi Hanifa to floods, the upper-east part of the basin shows flood ability, since the drainage system is irregular and almost low. This part is geomorphologically linked with Wadi Al-Haniyeh basin, and more certainly between Wadi Al-Aysin and Wadi Assilay.

4. Based on the hydrologic assessment for flood peaks in this region (area between Wadi Al-Aysin and Wadi Assilay), man-made channeling systems are recommended to be constructed to reduce the impact of flooding during rainfall peaks.

5. According to the resulting numerical values, except for the remarkable width/length ratio (WL_r), as well as the basin assessment illustrations, Wadi Nessah basin reveals almost stability for flooding compared to the other two basins.

6. Similar study is recommended with a comprehensive assessment and larger scale in order to evaluate precisely the flood vulnerability in Riyadh city and its suburbs.

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