

GIS-based estimation of flood hazard impacts on road network in Makkah city, Saudi Arabia

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Abstract Makkah city, Saudi Arabia, is periodically exposed to flash floods that result in major human and economical damages. That is due to several factors including its rugged topography and geological structures. Hence, precise assessment of floods becomes a more vital demand in development planning. A GIS-based methodology has been developed for quantifying and spatially mapping the flood characteristics. The core of this new approach is integrating several topographic, metrological, geological, and land use data sets in a geographic information system (GIS) environment that utilizes the curve number method of flood modelling for ungauged arid catchments. Based on the estimated flood volume of sub-basins, a hazard factor has been developed to quantify the expected hazard level for each road. Applying this proposed approach reveals that 21 % of the road network in Makkah city is subjected to low flood hazards, 29 % is facing medium hazards, and 50 % of roads are exposed to

harsh flood impacts. The developed approach may be considered a digital precise method that can be easily re-run, in other situations or regions, to estimate flood hazards on roads.

Keywords Flood assessment · Rainfall-runoff model · Road network · GIS · Saudi Arabia

Introduction

Hazards of flash floods are vital in terms of human lives loss and economical damages. Roads, in particular, are affected seriously by flash floods. Makkah city, west of Kingdom of Saudi Arabia (KSA), exhibits two unique features that increase the hazardous flood consequences: (1) its topography is very complex; (2) about three million Muslims are gathered annually in Makkah to perform Hajj over a 2-week period in the winter, which is the main rainfall season in Saudi Arabia. The topography of Makkah, which in general can be considered as a plateau rises about 300 m above mean sea level, is not entirely flat. Several mountains, whose elevations reach more than 900 m, exist within the metropolitan extents of the city. Hence, a number of hydrological catchments, with significant natural ground slopes, have been formed inside the city, leading to an increasing probability that rainfall could be converted to dangerous runoff. Surface runoff generally affects the road network in Makkah city in terms of serious traffic problems, road destruction, mudflow, and landslides. Due to the increasing interest in flood impacts over the last couple of decades, extensive flood estimation studies have been carried out in different countries, such as USA (e.g., USGS 2009), Egypt (e.g., Azab 2009; El Bastawesy et al. 2009), Nigeria (e.g., Yahaya et al. 2010), South Korea

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(e.g., Kim et al. 2010), China (e.g., Liang et al. 2010), and Saudi Arabia (e.g., Dawod and Koshak 2011; Al Saud 2010; Fred and Mostafa 2008). Also, geographic information system (GIS) is utilized for road maintenance (e.g., Yunus and Hassan 2010). This paper aims to utilize a GIS approach for assessing the flash flood hazards on road networks within Makkah metropolitan area, utilizing the most up-to-date and precise data sets.

Flood estimation

Flood estimation deals with modelling the rainfall-runoff relationship. This relationship plays a key role in numerous human activities such as flood risk evaluation of floodplains, flood damage evaluation for project planning, design of hydraulic structures for flood control, flood-runoff forecasting for project operations, and water resources planning and maintenance projects. Moreover, flood estimations on small urban drainage basins are required for a number of engineering structures such as dams, levees, culverts, and soil conservation purposes. Defining the rainfall-runoff relationship leads to estimation of several flood properties such as runoff depth, runoff speed, peak discharge, and total flood volume. Evaluating flood characteristics is essential for planners and decision makers. For example, such quantities assist municipalities in preparing urban expansion strategies, and they are critical for civil defence organizations in developing rescue plans.

It is economically costly and physically difficult to gauge all streams in a region, particularly in a large country such as KSA (Sen and Al-Suba'i 2002). For ungauged hydrological catchments, where measured flood discharge data records are missing, the flood estimation becomes more complicated. Countless approaches have been proposed globally trying to estimate flood peak discharge quantities based on topographic and morphometric characteristics of hydrological regions. Such approaches may be categorized into three groups according to their complexity. The first group, or simple approaches, includes the so-called rational method and empirical formulas. Even though those methods estimate the peak discharge quickly and simply with little number of inputs, they did not take into account important parameters particularly the land use and land cover of the catchment area. The curve number (CN) is an example of the second, or moderate, flood estimation methods, where more input factors are needed to estimate the flood characteristics. CN is a rainfall-runoff coefficient that depends on geological, soil, and land use properties of a catchment. The third group consists of detailed or complex models that are able to identify the causes of problems rather than producing a simple description of overall conditions. The soil and water

assessment tool (SWAT) is an example of those process-based complex models (Mihalik 2008). The CN method is quite used in engineering design and flood management projects, particularly in the USA (e.g., IDoT 2009; US ACE 2004; NH DoT 1998; and US DoT 2002).

GIS and remote sensing (RS) techniques have been utilized as efficient tools in flood risk assessment (e.g., Saleh and Al-Hatrushy 2009). Remote sensing images provide a significant source of extensive geospatial data particularly when the ground surveys or recent topographic maps are not available or not updated. For example, road networks can be extracted precisely from a high-resolution RS images. In addition, post-flood RS images can be used to calibrate developed floodplains in a hydrological basin. In addition, soil and geological maps, needed for flood estimation, can be developed based on RS imageries. GIS-based software can delineate hydrological catchments having a digital elevation model (DEM) being available. Global DEMs provide a free-of-charge terrain representation to be used in flood estimation. The Shuttle Radar Topography Mission (SRTM) is one of the most famous global DEMs, which is a joint project between the US National Imagery and Mapping Agency (NIMA) and the National Aeronautics and Space Administration (NASA). Chang et al. (2009) applied GIS to study the time-based relationship between flood hazards and land use changes. Furthermore, Jasrotia and Singh (2006) have utilized the CN method to study the runoff and soil erosion within a GIS environment. Moreover, Chen et al. (2010) tested a GIS model, which consists of a storm-runoff model and an inundation model, to model flood hazards. In addition, Dongquan et al. (2009) developed a GIS batch process to delineate catchments and compute their geomorphologic parameters. Furthermore, Gupta and Panigrahy (2008) have utilized several data sources and two runoff models in a GIS platform to investigate the flood characteristics and variations of large basins in India. Additionally, Gogoase et al. (2011) utilized GIS to develop inundation maps for extreme flood events. Moreover, Karmakar et al. (2010) proposed a methodology for six major damage centers in the Upper Thames River watershed, Canada to assess the flood risks, i.e., flood probability of occurrence, vulnerability to flood, and exposures of land use and soil type to flood.

Regarding flood impacts on roads, some researchers have investigated this aspect in several countries. Blanton and Marcus (2009) have documented the geographic distribution of roads and railroads in the alluvial floodplains of the continental United States and the regional variability of their potential impacts on lateral connectivity and resultant channel and floodplain structure and function. Youssef et al. (2010) have presented the utilization of remote sensing data; SRTM DEM coupled with geological,

geomorphological, and field data in a GIS environment for the estimation of the flash flood risk along the Feiran–Katherine road, southern Sinai, Egypt. In this study, morphometric parameters were computed and classified, such as basin area, circulation ratio, relief, relief ratio, drainage density, drainage frequency, number of orders, total drainage number, total drainage length, and slope. Each morphometric parameter, then, is converted to a flood risk parameter based on a statistical method. Then all parameters were summed and normalized in order to obtain a unique morphometric number for each sub-basin. The basic idea in this research study is that the higher the morphometric number, the higher is the flood hazard rank for a sub-basin and for its existing road. However, those two studies are based on flood hazards estimation thorough analyzing morphometric characteristics of basins in which roads exist. That means that the flash floods, themselves, have not being estimated. In the current paper, GIS has been utilized to quantify some flood characteristics in Makkah city and then estimate dangerous impacts on the road network.

Flash floods in Makkah city

Makkah city is located in the southwest part of KSA, about 80 km east of the Red Sea (Fig. 1). It extends from 39°35'E to 40°02'E, and from 21°09'N to 21°37'N. The area of the metropolitan region (the study area) equals 1,593 km². The topography of Makkah is complex in nature, and several mountainous areas exist inside its metropolitan area. Table 1 presents statistics of the terrain slopes' categories of Makkah city. About 4.6 % of the study area posses highly slopes greater than 20°. Such areas increase the probability of rainfall conversion to immediate runoff.

The winter is considered as the main rainy season in Saudi Arabia. The annual rain over Makkah city, for a period extending from 1966 to 2010, varies from 3.8 to 318.5 mm, with an average of rainfall equals 101.2 mm (Fig. 2). It worth mentioning that this data set has been combined from several metrological stations' records varying in geographical locations (inside and close to Makkah city) and in time span. It is considered the most recent and longest metrological information available for Makkah. Due to the complexity of Makkah's topography, flash floods occur periodically with significant variations in magnitude, and cause serious damages particularly on road network (Fig. 3). Mirza and Ahmed (2001) have reported that the extreme flood type is repeated with a return period of 46 years, while a second-order flood takes place occasionally with a return period of 33 years, and a low-dangerous flood comes about every 13 years. Using the magnitude of the annual rain average (which equals

101.2 mm) as a rain intensity factor might not be optimum in flood estimation process. The rain intensity of a single extreme storm may exceed the annual rainfall average for a year. For example, the 1969 storm records (Fig. 4) showed that the rain intensity reaches 107.5 mm/h during the first 10 min of that storm. Analyzing the flood series frequency, the return period or recurrence interval can be computed. That period defines the average number of years during which a flood of a given magnitude will be equalled or exceeded once. The Weibull method, among several other formulas, computes the return period T as (Raghnath 2006):

$$T = (n + 1)/m \quad (1)$$

where, n is the number of events, or number of records, m is the order or rank of the event (flood item) when flood magnitudes ranked in descending order.

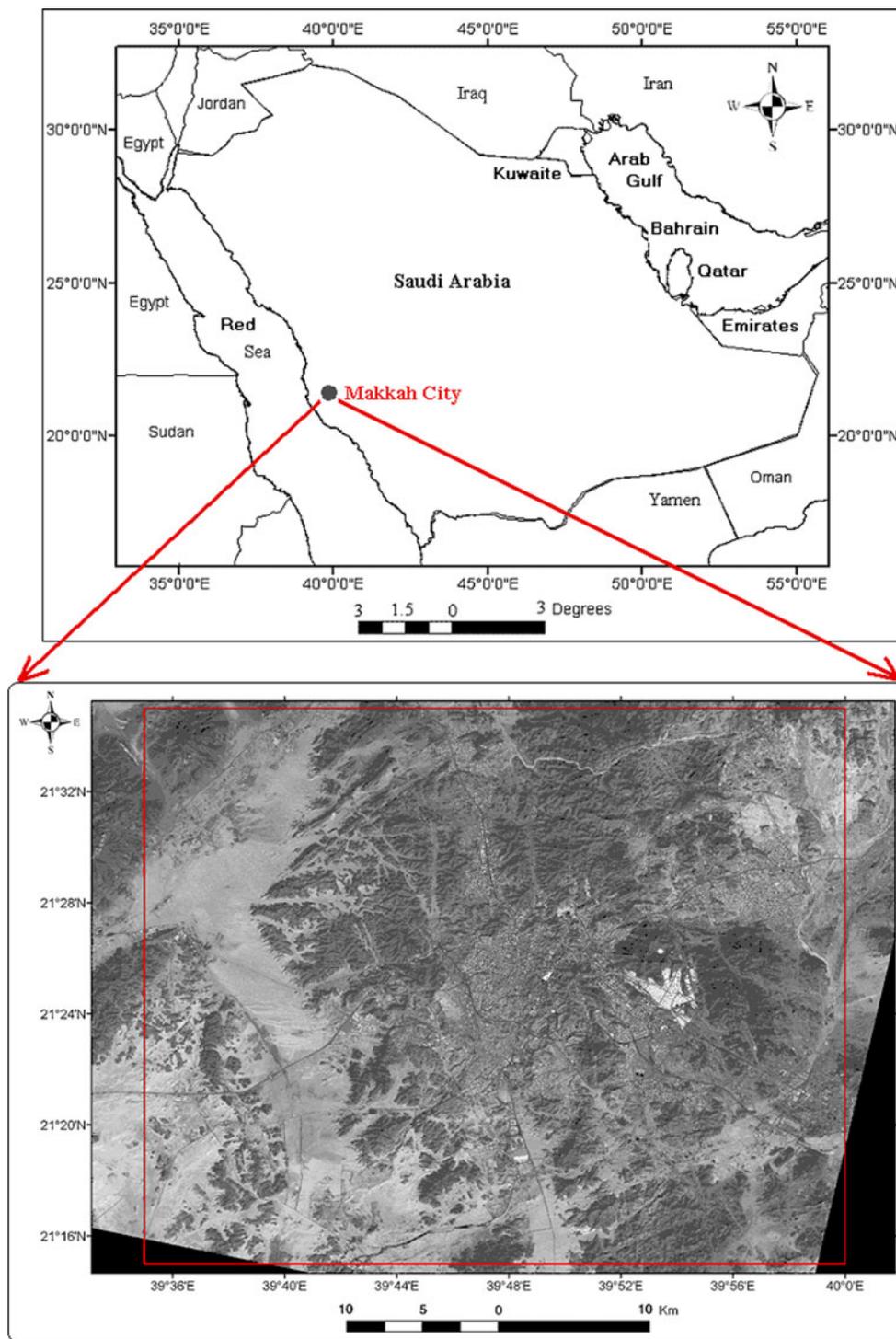
The computed return period of the 1969s flood has been estimated to 45 years. That piece of information is quite helpful in flood assessment studies, as it means that: (a) that flood magnitude is expected to occur by about 2014; and (b) selected return period value for flood management projects should be equal or >44 years. The rainfall intensity for a 50-years return period has been estimated, through the Log Pearson II statistical method, as 200 mm/h.

Additionally, floods are affected by the geology of the area in question, since infiltration rate differs from a geology structure to another. The geology of Makkah metropolitan area consists mainly of three geological structures (Table 2). The Precambrian igneous rocks occupy about 809 km² (with 51 % approximately of the total area). That rock type implicitly implies a low-permeability property that increases the ability of rainfall to be converted into dangerous surface runoff. The deposits, or wadi alluvium, exist mainly along the wadis streams, constitute about 48 %, with an area equals 770 km² approximately. The rest of Makkah area, about 12 km² only, represent the tripartite rocks. Soils of Makkah city are chiefly shallow clay soils over nearly impervious material, i.e., they have high runoff potential and very slow infiltration rates. Thus, these soils belong to group 4 (or the D type) in the curve number's hydrologic soil categories.

Data and methodology

Several data sets have been collected for flood assessment in Makkah city. The main data set is a national DEM produced by the by King Abdulaziz City of Sciences and Technology (KACST) with a spatial resolution equals to 5 m. A window covering Makkah metropolitan area (Fig. 5) has been provided through the Center of

Fig. 1 Study area



Excellence in Hajj and Omrah, Umm Al-Qura University. From Fig. 5, it can be noticed that the heights of Makkah metropolitan area range from 80 to 982 m. The other data sets include digital geological, soil, and land use maps of the study area.

The utilized GIS-based flood assessment methodology consists of several stages. Figure 6 depicts an overview

Table 1 Makkah slopes' categories

Slope (°)	Area (%)
<10	79.7
10–20	15.7
20–30	3.7
>30	0.9

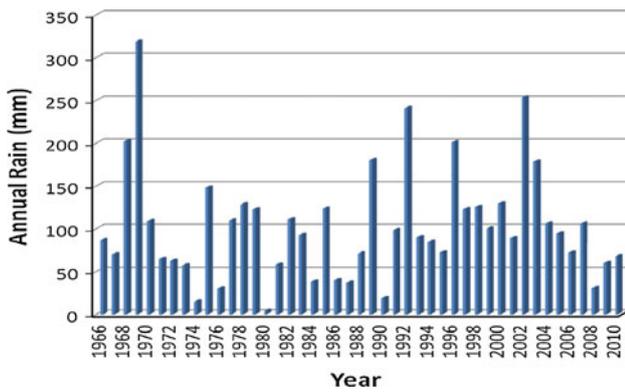


Fig. 2 Annual rains in Makkah city from 1966 to 2010

flow chart of that scheme. In the first stage, the Arc GIS software along with the Arc Hydro extension is used to obtain several shapefiles describing the geomorphology of the study area. These shapefiles include: the main basins and the sub-basins of each main catchment, along with drainage network using Strahler method (a simple widely-

utilized network order method), and the longest stream path in each catchment. The second stage of the utilized methodology is based on the flood assessment method developed by the US Natural Resources Conservation Service (NRCS), formerly known as the Soil Conservation Service (SCS). It worth mentioning that there are several hydrologic methods used for flood estimation, but the SCS method has been applied in the current research study. This method, also known as the curve number (CN), makes use of geological information to assign a unique CN value for each area, which will be further used to estimate the surface runoff depth and the peak discharge magnitude. The visual basic applications (VBA), a programming environment within the Arc GIS software, is used to compute the required flood defining parameters that consist of (Sen 2008):

$$Q = (P - 0.2S)^2 / (P + 0.8S) \tag{2}$$

$$S = 25.4((1,000/CN) - 10) \tag{3}$$

$$QT = QA \tag{4}$$



Fig. 3 Flood hazards on road network in Makkah city in 2010

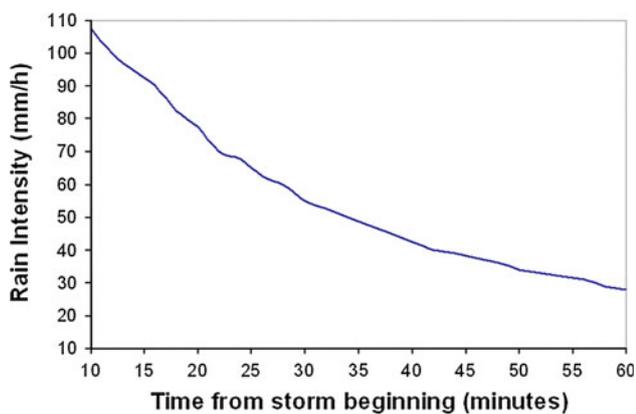


Fig. 4 Rain intensity of the 1969 storm in Makkah city

Table 2 Makkah geological categories

Geological structure	Area (km ²)	Area (%)
Precambrian igneous rocks	809	50.8
Wadi alluvium	770	48.4
Tripartite rocks	12	0.8

$$q_p = q_u A Q \tag{5}$$

$$t_c = 1.67L^{0.8}(S + 1)^{0.7}/1,900 Y^{0.5} \tag{6}$$

$$S_d = 0.133t_c \tag{7}$$

$$v = 0.2278L/t_c \tag{8}$$

where: Q is the depth of direct runoff (mm), P is the depth of precipitation for a specific return period (mm), S is the maximum potential retention (mm), CN is the curve number, QT is the volume of runoff (m³), A is the area of basin

(km²), Q is the depth of direct runoff (m), q_p is the peak discharge (m³/s), q_u is the unit peak discharge (m³/s/km²/mm) that can be interpolated from a specific charts (e.g., US NRCS 1986) or computed from corresponding tables (e.g., US DoT 2002, pp. 5–28), t_c is the time of concentration (min), L is the basin length (km), Y is the slope (m/km %), S_d is the storm duration (h), and v is the flow velocity (m/s).

Computing the morphometric parameters of a catchment provides a useful tool in understanding the basins natural properties and their roles in flood hazards. A number of common parameters are usually utilized in order to describe the morphometric and geomorphologic properties of a watershed. Although details can be found in several literature (e.g., Huggett 2007; Horton 1945), the utilized morphometric parameters of basins are computed by the following formulas.

$$\Delta H = H_{max} - H_{min} \tag{9}$$

$$R_{hp} = \Delta H/P \tag{10}$$

$$R_l = 2[\sqrt{(A/\Pi)}]/L_u \tag{11}$$

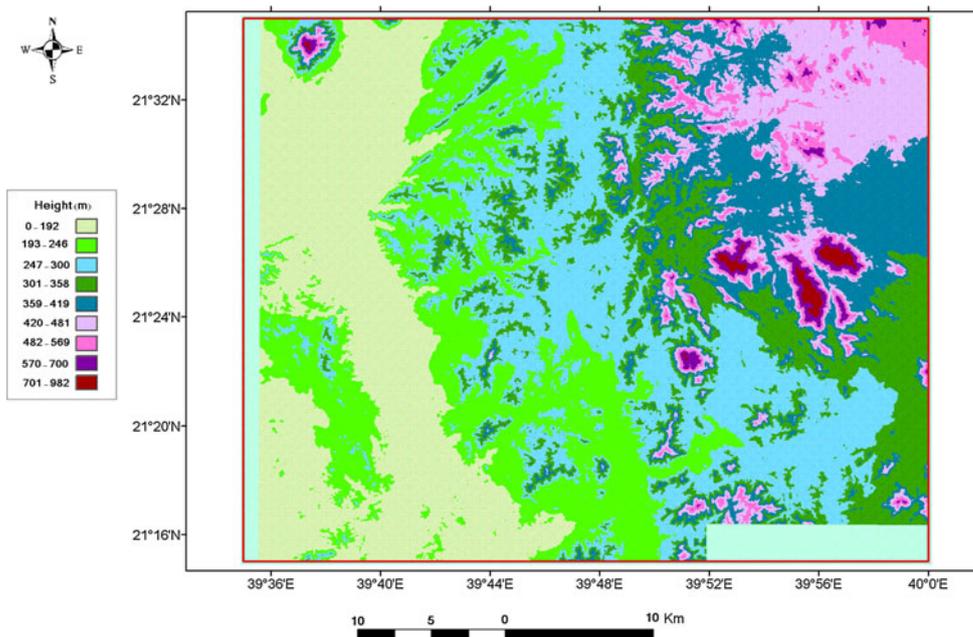
$$R_c = 4\Pi A/P^2 \tag{12}$$

$$D = L_u/A \tag{13}$$

where, ΔH is the basin total relief, H_{max} is the elevation of the highest point in the basin, H_{min} is the elevation of the lowest point in the basin, R_{hp} is the relative relief, P is the perimeter of basin (km), R_l is the elongation ratio, A is the basin's area (km²), L_u is the total stream length of all orders, R_c is the circularity ratio, $\Pi = 22/7$, and D is the drainage density (km/km²).

In the third stage of the proposed GIS approach, an estimation has been developed to quantify flood impacts on

Fig. 5 The National 5-m DEM for Makkah city



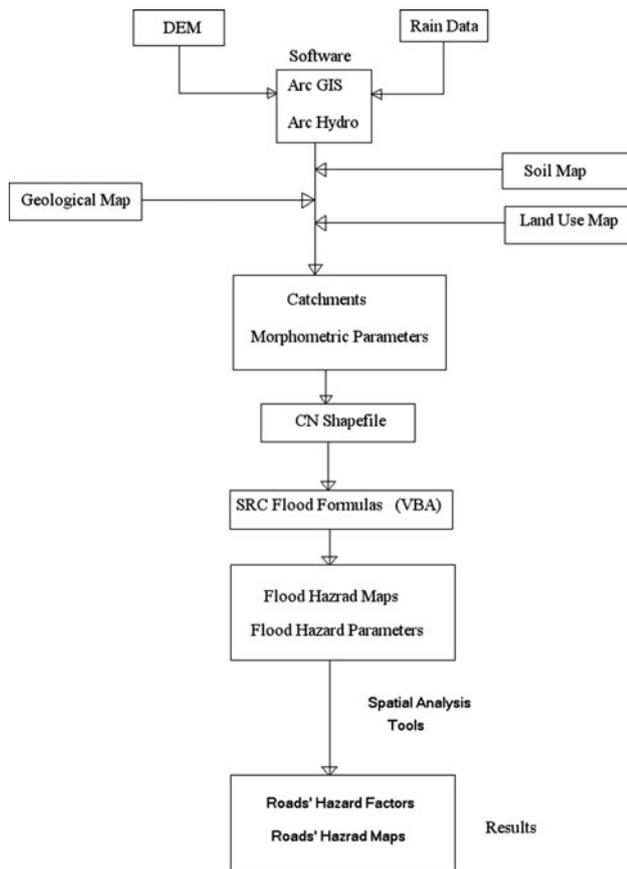


Fig. 6 The developed GIS-based methodology for flood assessment on road network

roads. It is implicitly based on an idea that the large flood volume in a sub-basin, the more hazards on roads within that sub-basin. Since the flood computations have been performed on a sub-basin level, the flood volume of each sub-basin may be considered as the most effectual factor that affects the flood impact. Hence, the spatial analysis tools of the Arc GIS software are utilized to re-classify flood volumes in ten categories, and each category is

assigned a unique number. That number, called the hazard factor, will be assigned to the road exist in a particular sub-basin. By this approach, each road in the transportation network gets a unique hazard factor that represents the flood hazard level.

Results

The utilized GIS-based methodology has been carried out using the available data sets of Makkah metropolitan area. The attained results of the first stage include quantities of several many significant morphometric parameters (Table 3). It has been found that there are six main catchments in Makkah, whose areas range from 74.3 to 360.6 km², and lengths of their main streams vary from 16.50 to 48.55 km (Fig. 7). The total relief varies from 333 to 769 m, while the relief ration, in m/km, range between 12.6 and 40.4. The circularity ratio is the ratio of the basin area to the area of a circle has the same circumference. It is influenced by the length and frequency of streams, geological structures, land use, and the slope of the watershed. Catchment no. 3 has the highest circularity ratio (0.37) and catchment no. 2 has a closer value (0.32). It can be seen from Fig. 7 that these two basins are the closer to a circular shape. On the other hand, the elongation ratio represents how close a basin to a rectangular shape. From Table 3, it can be seen that two basins have rectangular ratio greater than 0.5, while the other four have elongation ratios <0.4. Hence, the six catchments in Makkah metropolitan area are far from a complete rectangular shape (see Fig. 7).

The network properties are considered the major morphometric characteristics of watersheds. Stream order is used to denote the hierarchical relationship between stream segments and allows drainage basins to be classified according to size. Several stream-ordering systems exist, the most commonly used being those devised by Arthur N. Strahler and by Ronald L. Shreve. In Strahler’s ordering

Table 3 Statistics of morphometric quantities

Item	C1	C2	C3	C4	C5	C6
Basin area (km ²)	252.7	122.3	74.3	109.9	360.6	200.2
Basin premier (km)	134.6	69.13	50.23	89.09	134.76	102.03
Basin length (km)	42.48	23.64	16.50	29.70	48.55	38.13
Total relief (m)	546	333	667	769	632	714
Relief ratio (m/km)	12.6	14.1	40.4	25.9	13.0	18.7
Elongation ratio	0.42	0.53	0.59	0.40	0.44	0.42
Circularity ratio	0.18	0.32	0.37	0.17	0.25	0.24
Maximum stream order	6	5	5	5	6	5
Total no. of streams	1,082	523	294	424	1,448	831
Drainage density (km/km ²)	2.67	2.71	2.58	2.56	2.59	2.73

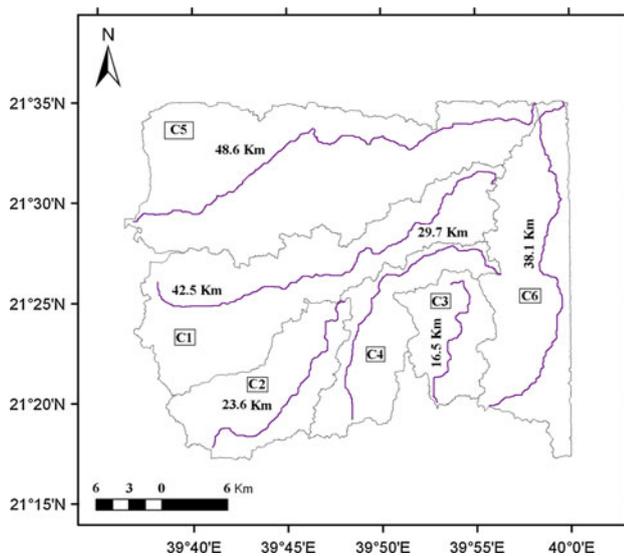


Fig. 7 Catchments and their main streams

system (which is used in the current research), a stream segment with no tributaries that flows from the stream source is denoted as a first-order segment. A second order segment is created by joining two first-order segments, a third-order segment by joining two second order segments, and so on. It has been found that the maximum stream order in the six watersheds, in the study area, equals 5 for the four small sub-basins (No. C2, C3, C4, and C6) and reaches order 6 in the other two sub-basins (C1 and C5), which have the maximum basin areas. The drainage density is a measure of how frequently streams occur on the land surface. It indicates the closeness of spacing between channels and is a measure of the total length of the stream segment of all orders per unit area. It reflects a balance between erosive forces and the resistance of the ground surface, and is therefore related closely to climate, lithology, and vegetation. Drainage densities can range from $<5 \text{ km/km}^2$ when slopes are gentle, rainfall low, and bedrock permeable, to much larger values of more than 500 km/km^2 in upland areas where rocks are impermeable, slopes are steep, and rainfall totals are high (Huggett 2007). The drainage density for Makkah's sub-basin range from

2.56 to 2.73 km/km^2 . So, it can be classified, in general, as a medium drainage density pattern.

The second stage of the applied approach results is the determination of flood characteristics in Makkah city. The computations have performed using the depth of precipitation (P) equals 200 mm for a return period of 50 years. That value is the result of the Log Pearson III statistical analysis for the available rainfall data sets of Makkah city. Additionally, the unit peak discharge (q_u in Eq. 5) has been computed through the equation and tables provided in US DoT (2002) (Equation 5–26, pp. 5–28). Table 4 presents the flood estimated parameters on the catchment's level. First, it can be noticed that the peak discharge values found to vary from $1,063 \text{ m}^3/\text{s}$ (for catchment C2) to $4,489 \text{ m}^3/\text{s}$ (for catchment C5). Additionally, the runoff depths of the six basins vary from 151.7 to 178.8 mm. The flood volume range between 13.28 m^3 (for catchment 3) and 54.69 m^3 (for catchment 3), with a total of 172.97 million m^3 over Makkah metropolitan area. Additionally, catchment C3 is expected to have minimum storm duration (0.26 h) while catchment C1 has the maximum value (0.80 h). Concerning the flow velocity of the six basins, it has been found that the values range from 22.44 m/s (for catchment C2) to 73.37 m/s (for catchment C5).

Furthermore, the utilized approach has been performed at the sub-basin level in order to get more detailed flash flood analysis. Table 5 and Fig. 8 present the accomplished results. It can be seen that the six main catchments contain 350 sub-basins whose area vary between 0.019 and 20.676 km^2 , with an average equals 3.092 km^2 . Additionally, the sub-basin runoff depth varies between 128 and 194 mm with an average equals 157 mm. Also, the runoff volume on the sub-basin level (QT in Eq. 4) range from 2,446 and $3,171,609 \text{ m}^3$ with a mean of $478,925 \text{ m}^3$. Moreover, it can be noticed that the highest runoff depth and runoff volume values exist in sub-basins with high CN values. Such high CN values are attributed to the fact that those sub-basins belong to either a residential land use type or an igneous-rocks geological category. Hence, these maps should be considered in future development planning of that area in Makkah city.

Table 4 Catchments flood characteristics in Makkah city (for a 50-years return period)

Item	C1	C2	C3	C4	C5	C6
Runoff depth (mm)	151.7	151.7	178.8	166.7	151.7	148.8
Peak discharge (m^3/s)	1,554	1,063	1,307	1,234	4,489	1,514
Time of concentration (min)	5.69	3.76	1.73	2.63	6.72	4.17
Storm duration (h)	0.76	0.50	0.23	0.35	0.89	0.56
Flow velocity (m/s)	28.34	23.86	36.19	42.87	27.44	34.68
Volume of runoff (million m^3)	38.34	18.55	13.28	18.32	54.69	29.79
	Total = 172.97 million m^3					

Table 5 Sub-basins flood characteristics in Makkah city (for a 50-year return period)

Item	Minimum	Maximum	Average
No. of all sub-basins		350	
Sub-basin area (km ²)	0.019	20.676	3.092
CN	76	98	86
Runoff depth (mm)	128	194	157
Total volume of runoff (m ³)	2,446	3,171,609	478,925

Regarding the flood impacts on roads, a shapefile has been first constructed containing the road network of Makkah city. It was decided to work with main roads only, whose lengths are >1,000 m, just for simplicity in the current research. So, that road network consists of 511 roads whose lengths range from 1,003 to 20,530 m, with a mean of 2,348 m. The Arc GIS spatial analysis tools have been utilized to: (a) divide the sub-basins’ runoff volumes into ten groups using the natural-break classification method, which identifies break points by picking the class breaks that best group similar total flood volume values, (b) re-classify those flood volume groups to unique label values ranging from 1 to 10, just for simplicity, which will be considered as the hazard factor, (c) convert that shapefile into a raster format; and (d) project that raster onto the road network in order to assign each road with the corresponding unique hazard factor. By this approach, the flood hazard impact on each road is assigned on a scale from 1 to 10 (based on the total flood volume for the corresponding sub-basin), that is a simple scale to be

interpreted. This quantitative classification is presented in Table 6. Next, the flood hazards on roads have been classified into three groups, just for simplicity too, as seen in and Table 7 and Fig. 9. Obviously, a great part of the road network in Makkah city is subjected to high dangerous flood impacts. That category constitutes 260 roads, representing 51 % of the network, with a total length of 528 km.

Discussion

Analyzing the morphometric parameters, it has been found that the catchment C3 has the maximum relief ratio even though it does not have the maximum height difference (total relief). That might be due to the smallest basin area of that catchment (only 74.3 km²). Hence, that catchment can be considered the most topographical-complex basin in the study area, which will result in more steep morphometric characteristics. Also, it has been found that this catchment has the highest circularity ratio even though it is the smallest watershed, which is considered as a hazardous indication since it means that the flash floods could reach great volume over a small area. Furthermore, it can be noticed that catchment C3 has the lowest concentration time (1.98 h), which is the time for runoff to travel from the most distant point to the outlet point. That is an expected result, since this catchment has the highest relief ratio (40.43 m/km) even though it does not have the highest flow velocity. Additionally, this catchment has the minimum storm duration (0.26 h) while catchment C1 has the maximum value (0.80 h). It is worth mentioning that

Fig. 8 Flood spatial variations in Makkah city

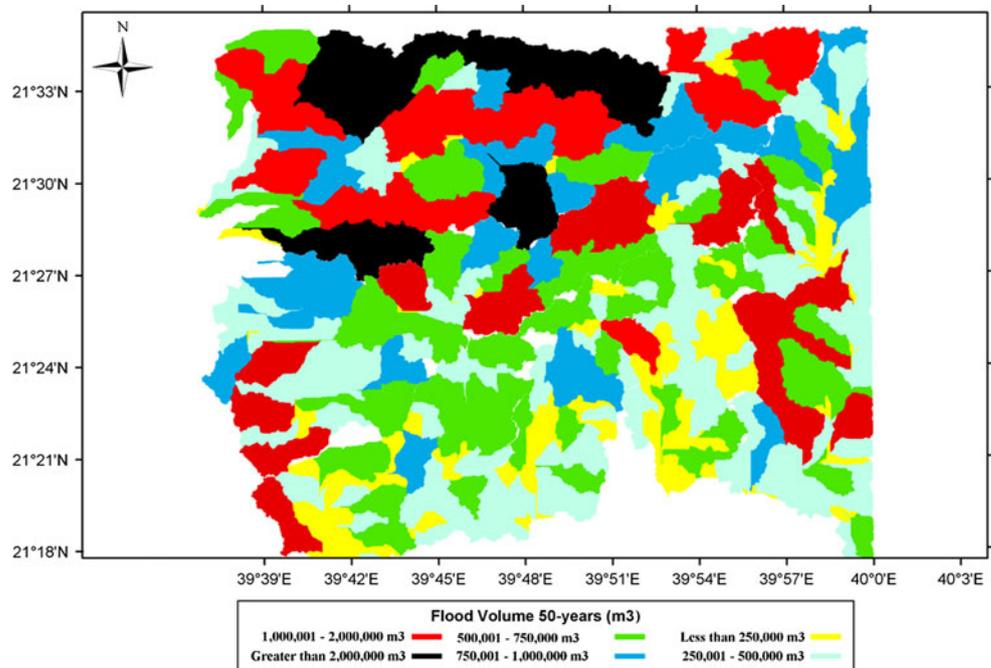
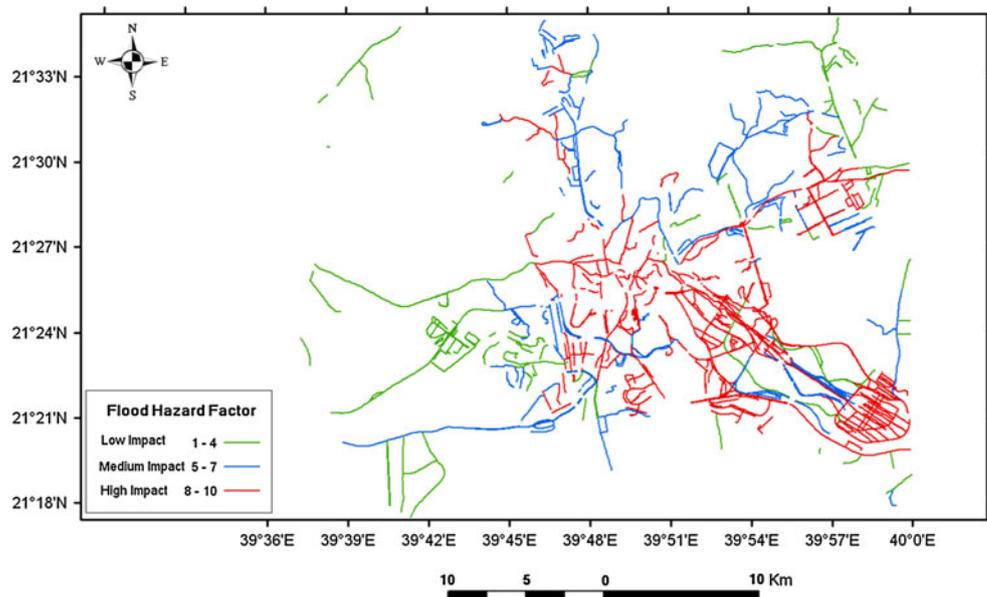


Table 6 Flood hazard estimation on road network in Makkah city

Item	No. of roads	Percentage of roads	Total length of roads (km)
Hazard factor = 1	12	2.3	20.890
Hazard factor = 2	31	6.1	74.974
Hazard factor = 3	42	8.2	80.746
Hazard factor = 4	20	3.9	70.418
Hazard factor = 5	24	4.7	70.591
Hazard factor = 6	44	10.7	115.824
Hazard factor = 7	68	13.3	134.497
Hazard factor = 8	75	14.6	144.588
Hazard factor = 9	89	17.4	205.089
Hazard factor = 10	96	18.8	178.210

Table 7 Categories of flood hazard on road network in Makkah city

Hazard category	Hazard factor	No. of roads	Percentage of roads	Total length of roads (km)
Low	1–4	105	20.5	247.028
Medium	5–7	147	28.7	320.912
High	8–10	260	50.8	527.887

Fig. 9 Flood impacts on road network in Makkah city

the storm duration is a function of the concentration time as seen in Eq. 8.

The higher CN values, in the study area, are attributed to two factors: (a) the residential area of Makkah city, paved streets, was assigned CN of 98 that reflects the low permeability of rains; (b) a great portion of Makkah's geology consists of igneous and metamorphic rocks, which get relatively high CN according to the SRC classification. Moreover, it can be noticed that four catchments (C1, C2, C5, and C6) have similar CN values, but C2 has the least basin area. That leads to this catchment produces the minimum peak discharge. As expected, catchment C5

produces the highest peak discharge because of its big basin area. Additionally, it can be concluded that the highest runoff depth belong to catchment C3, which has the highest CN value. Regarding the flood volume, it can be seen that catchment C5 produces the biggest value due to the fact that it has the biggest area (360.6 km²). The proposed approach of estimating flood impacts on roads is based on the computed flood volumes of sub-basins. So, it might be considered more appropriate than the other approaches that are based only on analysing morphometric characteristics of the basins themselves. That is due to the fact that the runoff volume is the chief factor distinguishes

the expected flood damages on roads. The attained results reveal that almost half of Makkah's road network is subjected to severe flood impacts. Consequently, certain precautions should be taken by the governmental authorities to protect such roads.

Conclusions

Makkah metropolitan area, southwest of Saudi Arabia, is distinguished by two items: a complex topography; and the gathering of about three million Muslims to perform Hajj over a specific short time period annually. This research utilizes a GIS-based approach for mapping and quantifying flood assessment measures particularly on road network. The used methodology is based on integrating several data sets in a GIS environment utilizing the SRC CN flood modelling method. A hazard factor has been developed to quantify the expected flood hazards on roads. Results show that 50.8 % of Makkah's road network, with a total length of 528 km, is subjected to high or serious flood impacts. Properties of this GIS-based methodology include precision, cost-effective, digital outputs, and its ability to be re-run for other scenario (e.g., other design return period). Hence, it is recommended that the attained results be utilized in governmental planning in Makkah city, and that approach should be applied to all other cities in Saudi Arabia.

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