Journal of Geographic Information System, 2011, 3, 225-231
doi:10.4236/jgis.2011.33019 Published Online July 2011 (http://www.SciRP.org/journal/jgis)

GIS-Based Spatial Mapping of Flash Flood Hazard in Makkah City, Saudi Arabia

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Received March 29, 2011; *revised May* 12, 2011; *accepted May* 20, 2011

Abstract

Flash floods occur periodically in Makkah city, Saudi Arabia, 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 datasets in a GIS environment that utilizes the Curve Number (CN) method of flood modelling for ungauged arid catchments. Additionally, the computations of flood quantities, such as depth and volume of runoff, are performed in the attribute tables of GIS layers, in order to assemble all results in the same environment. The accomplished results show that the runoff depth in Makkah, using a 50-years return period, range from 128.1 mm to 193.9 mm while the peak discharge vary from 1063 m^3/s to 4489 m^3/s. The total flood volume is expected to reach 172.97 million m^3 over Makkah metropolitan area. The advantages of the developed methodology include precision, cost-effective, digital outputs, and its ability to be re-run in other conditions.

Keywords: Flood Assessment, Rainfall-Runoff Model, NRCS, GIS, Saudi Arabia

1. Introduction

Hazards of flash floods are vital in terms of human lives loss and economical damages. 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 two-week period in the winter, which is the main rainfall season in Saudi Arabia. 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 [1], Egypt [2,3], Nigeria [4], South Korea [5], China [6], and Saudi Arabia [7,8]. This paper aims to develop a GIS approach for assessing the flash flood hazards for Makkah metropolitan area, utilizing the most up-to-date and precise available data sets.

2. Flood Estimation

Flood estimation methods aim to model the rainfall-runoff relationships, and can be categorized into three groups according to their complexity. Simple approaches, such as the rational method and empirical formulas, estimate the peak discharge quickly and with little number of inputs. The Curve Number (CN) is an example of moderate flood estimation methods. Detailed, or complex, models are able to identify the causes of problems rather than producing a simple description of overall conditions [9]. The CN method is quite used in engineering design and flood management projects, particularly in the USA [10-13].

Geographic Information Systems (GIS) and Remote Sensing (RS) techniques have been utilized as efficient tools in flood risk assessment [14,15]. For example, Change *et al.* [16] applied GIS to study the time-based relationship between flood hazards and land use changes. Also, Jasrotia and Singh [17] uutilized the CN method to study the runoff and soil erosion within a GIS environment. Moreover, Chen *et al.* [18] tested a GIS model, which consists of a storm-runoff model and an inundation model, to model flood hazards. In addition, Dongquan *et al.* [19] developed a GIS batch process to delineate catchments and compute their geomorphologic parameters. Furthermore, Guptaa, and Panigrahya [20] has 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.* [21] utilized GIS to develop inundation maps foe extreme flood events. Moreover, Karmakar *et al.* [22] 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.

3. Flash Floods in Makkah City

Makkah city is located in the south-west part of KSA, about 80 Km east of the Red Sea (**Figure 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 1593 square kilometres. The topography of Makkah is complex in nature, and several mountainous areas exist inside its metropolitan area. 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 2009, varies from 3.8 mm to 318.5 mm, with an average of rainfall equals 101.2 mm (**Figure 2**). Due to the complexity of Makkah's topography, flash floods occur periodically with significant variations in magnitude. Mirza and Ahmed [23] 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 (**Figure 3**) showed that the rain intensity reaches 107.5 mm/hour during the first 10 minutes of that storm. Based on records of a single rainfall station, this extreme storm resulted in a runoff volume of more than 41 million cubic meters in the central area of Makkah city, with results of severe damages and human loses [23].

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 Welbull method, among several other formulas, computes the return period T as [24]:

$$T = (n+1)/m \tag{1}$$

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.

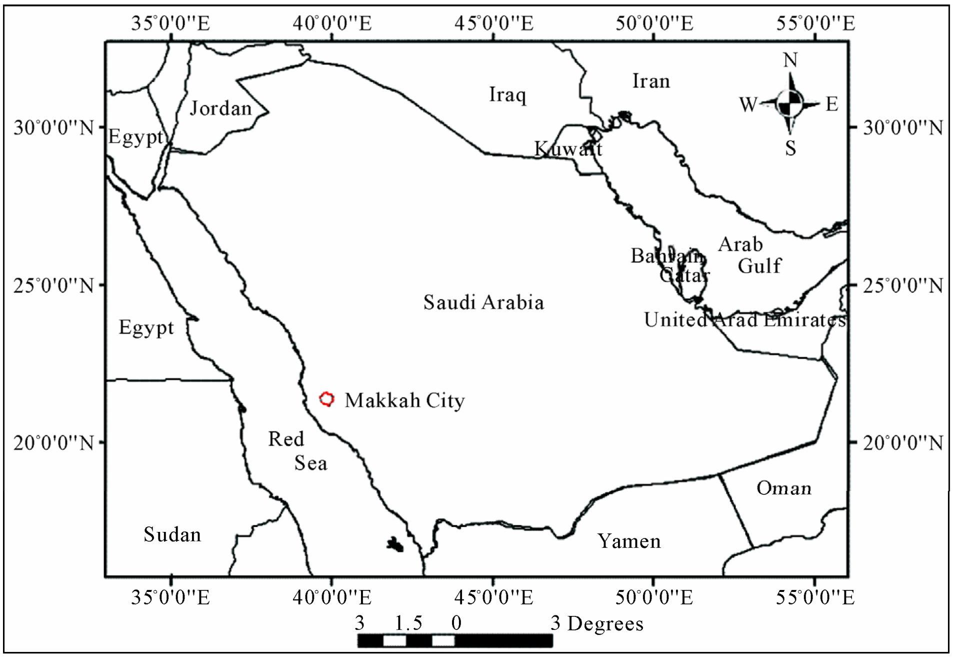

Figure 1. Study area.

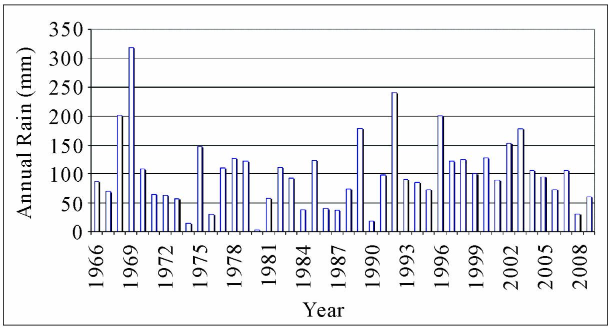

Figure 2. Annual rains in Makkah city from 1966 to 2009.

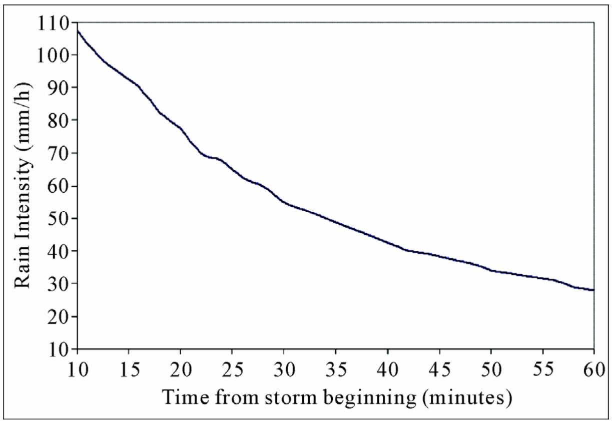

Figure 3. Rain intensity of the 1969 storm in Makkah city.

The computed return period of the 1969's flood has been estimated to 44 years. That piece of information is quite helpful in flood assessment studies, as it means that: 1) that flood magnitude is expected to occur by about 2013; and 2) selected return period value for flood management projects should be equal or greater than 44 years. The rainfall intensity for a 50-years return period has been estimated as 200 mm/h [25] and is used in the current research study.

4. Data and Methodology

Several datasets have been collected for flood assessment in Makkah city. The main data set is a Digital Elevation Model (DEM) over the study area. This DEM was produced by the by King Abdulaziz City of Sciences and Technology (KACST) with a spatial resolution equals to 5 meters. A window covering Makkah metropolitan area (**Figure 4**) has been provided through the Center of Excellence in Hajj and Omrah, Umm Al-Qura university. Mirza *et al.* [26] confirm that this national DEM is 3 times more accurate than previously published global DEMs (e.g. ASTER and SRTM) over Makkah area. From **Figure 4**, it can be noticed that the heights of Makkah metropolitan area range from 80 to 982 meters. The other datasets include digital geological, soil, and

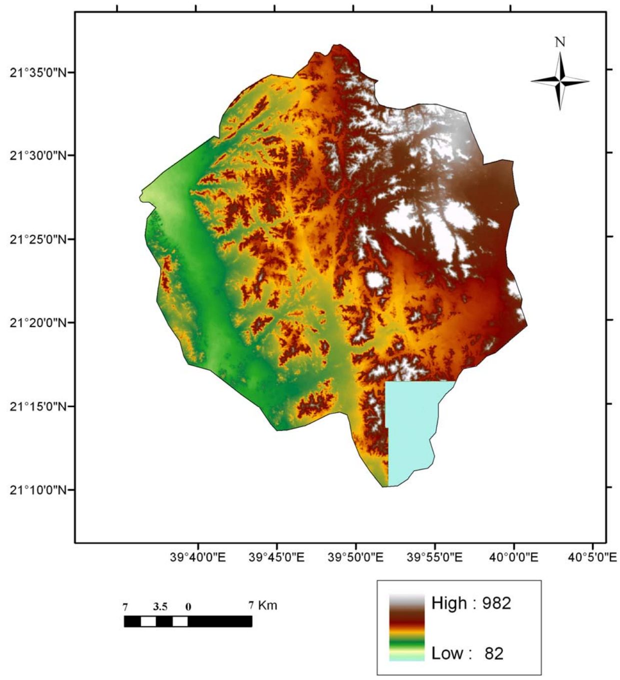

Figure 4. The national 5-m DEM for Makkah city.

land use maps of the study area.

The developed GIS-based flood assessment methodology consists of several stages. **Figure 5** depicts an overview flow chart of that scheme. In the first stage, the Arc GIS software along with the Arc Hydro extension are 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 developed 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. VBA is used to compute the required flood defining parameters that consists of [27]:

$$Q = (P - 0.2S)2/(P + 0.8S) \quad (2)$$

$$S = 25.4((1000/CN) - 10) \quad (3)$$

$$QT = QA \quad (4)$$

$$qp = quAQ \quad (5)$$

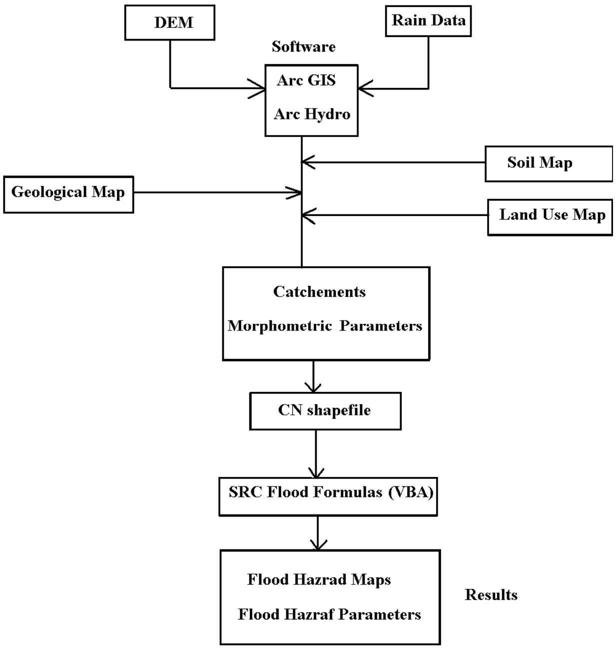

Figure 5. The developed GIS-based flood assessment methodology.

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 (m^3), A is the Area of basin (Km^2), Q is the depth of direct runoff (m), qp is the peak discharge (m^3/s), and qu is the unit peak discharge (m^3/s/km^2/mm) that can be interpolated from a specific charts [28] or computed from corresponding tables [13].

It worth mentioning that P was computed through statistical analysis of rainfall records (e.g. by Log Pearson III method) to determine the expected rainfall depth for a specific storm to be occurred again with the same magnitude.

Other hydrological parameters include:

$$v = 0.2279L/tc \quad (6)$$

$$tc = 1.67\left[L^{0.8}\left(S+1\right)^{0.7}\right] \Big/ \left[1900 * SL^{0.5}\right] \quad (7)$$

$$Sd = 0.133Tc \quad (8)$$

where v is the flow velocity (m/s), L is the basin length (expressed in units of meters), tc is the concentration time (minutes) that can be estimated using several formulas, one of them (NRCS method) is given in Equation (7), SL is the average watershed land slope in percentage, and Sd is the storm duration (hours).

5. Results

The developed GIS-based methodology has been carried out using the available datasets of Makkah metropolitan area. Results of the first stage include several maps and the estimation of many morphometric parameters. It has been found that there are 6 main catchments in Makkah, whose areas range from 74.3 to 360.6 square kilometres, and lengths of their main streams vary from 16.50 to 48.55 kilometres (**Figure 6**). **Table 1** presents statistics of some morphometric parameters of the six catchments.

The second stage of the developed 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 datasets of Makkah city. Additionally, the unit peak discharge (qu in Equation (4)) has been computed through the equation and tables provided in [13]. **Table 2** and **Figure 7** present the flood estimated parameters.

Moreover, the peak discharge values found to vary from 1063 m^3/s (for catchment C2) to 4489 m^3/s (for catchment C5). Additionally, the runoff depths of the six basins vary from 151.7 mm 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.

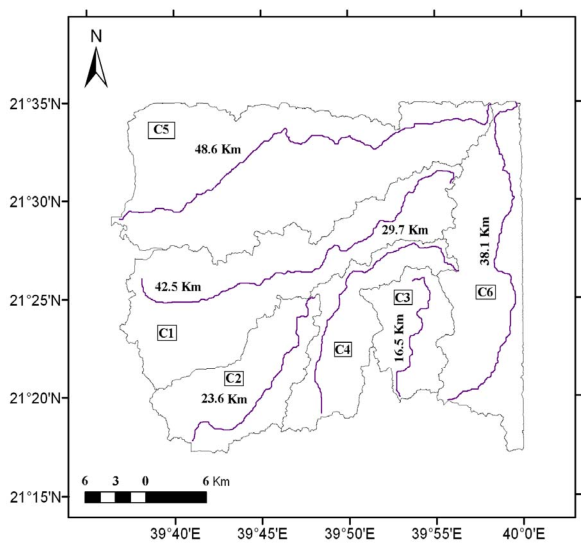

Figure 6. Catchments and their main streams.

Table 1. 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

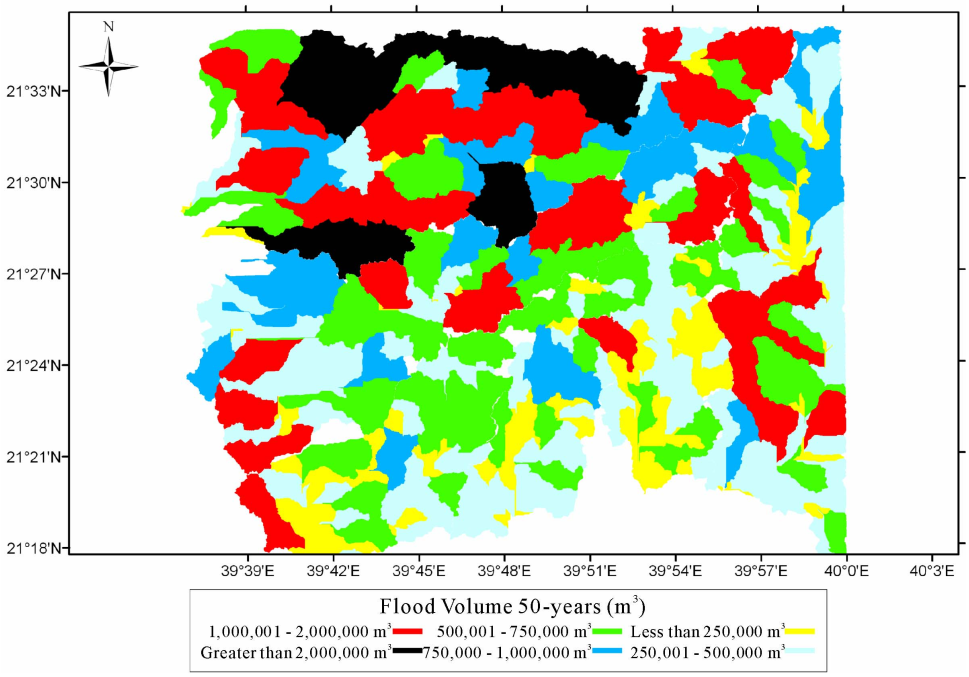

Figure 7. Flood spatial variations in Makkah.

Table 2. Flood characteristics in Makkah city (for a 50-years return period).

Item	C1	C2	C3	C4	C5	C6
Time of concentration (hours)	5.69	3.76	1.73	2.63	6.72	4.17
CN	84	84	93	89	84	83
Runoff depth (mm)	151.7	151.7	178.8	166.7	151.7	148.8
Peak discharge (m^3/s)	1554	1063	1307	1234	4489	1514
Storm duration (hour)	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					

6. Discussion

First, it can be noticed that catchment C3 has the lowest concentration time (1.98 hours), which is the time for runoff to travel from the most distant point to the outlet point. The lower time of concentration, the more hazardous is the runoff. Additionally, catchment C3 is expected to have minimum storm duration (0.26 hours) while catchment C1 has the maximum value (0.80 hours). 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).

Keeping in mind that the lower concentration time, the more hazardous is the runoff, it has been found that catchment C3 has the lower concentration time That is an excepted result, since catchment C3 has the highest relief ratio (40.43 m/km) even though it does not have the highest flow velocity. Additionally, catchment C3 is expected to have minimum storm duration (0.26 hours) while catchment C1 has the maximum value (0.80 hours). It is worth mentioning that the storm duration is a function of the concentration time as seen in Equation (8).

A coloration analysis was performed between the main flood factors. The correlation matrix is presented in **Table 3**. Concerning the flow velocity of the six basins, it has been found that the minimum velocity belongs to catchment C2 while the maximum velocity is for catchment C5. Equation (5) shows that the flow velocity is directly proportional to the catchment stream length, and is inversely proportional to the concentration time. The same conclusion is drawn from **Table 3** where the peak discharge, total flood volume, basin area, and basin stream length have positive strong correlations with the flow velocity (0.97, 0.76, 0.74, and 0.61 respectively), while the concentration time has a negative moderate correlation (–0.48).

Second, catchment C3 also has the highest CN value of 93. The higher CN values, in the study area, is attributed to two factors: 1) the residential area of Makkah city, paved streets, was assigned CN of 98 that reflects the low permeability of rains; 2) a great portion of Makkah's geology consists of Pre-Cambrian igneous and metamorphic rocks, that get relatively high CN according to

Table 3. Correlation between main flood characteristics.

	CN	*tc*	*A*	*L*	*Q*	*QT*	*v*
CN	1						
tc	–0.65	1					
A	–0.66	0.21	1				
L	–0.72	0.39	0.94	1			
Q	–0.30	–0.33	0.85	0.70	1		
QT	–0.62	0.18	0.9987	0.94	0.87	1	
v	–0.14	–0.48	0.74	0.61	0.97	0.76	1

where: *CN* is the curve number, *tc* is the time of concentration, *A* is the basin area, *L* is the basin stream length, *Q* is runoff depth, *QT* is the runoff volume, and v is the runoff velocity.

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. **Table 3** concludes the same result since the basin area and basin stream length has strong correlations (0.85 and 0.70) with the peak discharge.

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 km^2). The correlation between flood volume and basin area is strong (0.9987) as seen in **Table 3**.

The GIS-based CN flood estimation methodology has several advantages. First, it incorporates many input datasets including metrological, geological, soil, land use, and DEM. Other approaches (e.g. the rational method) employ less input items, while some national regression models used in Saudi Arabia depend only on the basin area to estimate expected flood. Dawod *et al.* [29] concluded that the CN method is more precise than some other flood estimation methods over Makkah region. Moreover, this paper presents a GIS-based implementation of the CN methodology where computations have been performed in the attribute tables within the GIS environment (using VBA). So, the flood estimation process is efficient, faster, and can be easily performed for several scenarios and even for several regions in Saudi Arabia once the required input layers are available.

7. Conclusions

Makkah metropolitan area, south west 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) that greatly raises awareness of flood hazards impacts. This research develops a GIS-based approach for mapping and quantifying flood assessment measures. The developed methodology is based on integrating several datasets in a GIS environment utilizing the SRC CN flood modelling method. Results show that the main factors affect the total flood volumes, in Makkah metropolitan area, are the catchment area, the basin stream length, and the peak discharge. Additionally, it has been concluded that the higher CN value (for low permeability soil, geological, and land use features), the higher runoff and flood hazards. Merits of that 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.

8. Acknowledgements

The authors would like to acknowledge the financial support offered by the Center of Research Excellence in Hajj and Omrah (Hajjcore), Umm Al-Qura university, Saudi Arabia.

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