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Developing GIS-Based Unit Hydrographs for Flood Management in Makkah Metropolitan Area, Saudi Arabia

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Abstract

Unit hydrographs (UH) are either determined from gauged data or derived using empirically-based synthetic unit hydrograph procedures. In Saudi Arabia, the discharge records may not be available either for several locations or for long time scales, and therefore synthetic unit hydrographs are crucial in flood and water resources management. Available metrological, geological, and land use datasets have been utilized in order to apply the US National Resources Conservative Services (NRCS) methodology in a Geographic Information Systems (GIS) environment. Furthermore, NRCS unit hydrographs have been developed for six watersheds within Makkah metropolitan area, southwest Saudi Arabia. The accomplished results show that the UH time to peak discharge vary from 1.15 hours to 4.47 hours, and the UH peak discharge quantities range from 10.14 m^3/s to 16.74 m^3/s. It is concluded that the third basin in Makkah city may be considered as the most hazardous catchment. Hence, it is recommended that careful flood protection procedures should be taken in this area within Makkah city.

Keywords: GIS, Unit Hydrograph, NRCS, Flood Management, Saudi Arabia

1. Introduction

Flood modeling usually involves approximate descriptions of the rainfall-runoff transformation processes, based on empirical, or physically-based, or combined descriptions of the physical processes involved. The resulting models are quite useful in practice since they are simple and provide adequate estimates of flood hydrographs. Sherman [1] first proposed the unit hydrograph (UH) concept. The UH of a watershed is defined as the direct runoff hydrograph resulting from a unit volume of excess rainfall of constant intensity and uniformly distributed over the drainage area. The UH approach is applied for several engineering designs and environmental studies [2,3] Detailed descriptions of UH types and formulas can be found in several literatures [4,5]. Moreover, the Geographic Information Systems (GIS) technology has been applied for flood management based on utilizing unit hydrographs [6-8].

2. Objectives

The current research study aims to:

- Utilize the unite hydrograph approach for flood characterizing in Makkah city, Saudi Arabia.
- Compute the requited quantities of unit hydrographs for six hydrological basins within the study area.
- Apply the US National Resources Conservative Service (NRCS) methodology to develop unit hydrographs, for the first time in Saudi Arabia.
- Perform flood assessment computations within a GIS environment as a precise, effective, and fast technological tool.

3. Previous Works

Sets of observations of effective rainfall and direct runoff are required for the derivation of unit hydrographs. When no direct observations are available, or when UH's for other locations on the stream in the same watershed or for nearby watersheds of similar characteristics are required, Synthetic, or conceptual, Unit Hydrograph (SUH) procedures must be used [9]. SUH procedures can be categorized as [10]: 1) those based on models of watershed storage; 2) those relating hydrograph characteristics to watershed characteristics [11]; and 3) those based on a dimensionless unit hydrograph [12,13].

In Kingdom of Saudi Arabia (KSA) the Snyder UH is the most common method in a variety of geomorphologic and flood literatures [14,15]. However, a crucial issue in this model is the existence of two parameters (namely: C_t a coefficient represents variations in watershed slopes and storage characteristics; and C_p a coefficient represents the effects of retention and storage) that need to be determined from actual observations for the specific watershed or can be taken from some other watersheds that have similar topographic and morphometric characteristics. Hence, empirical approach is suggested as an alternative for constructing a dimensionless UH for ungauged basins in southwest region of KSA [16,17]. The Soil Conservative Service (SCS) method is seldom utilized, particularly in few academic studies in KSA [18].

4. Materials and Methods

4.1. NRCS Hydrographs' Method

The National Resources Conservative Service (NRCS), formally SCS, UH approach represents an optimum dimensionless UH method, that are extensively utilized in the last few years in several countries [19-22]. The NRCS dimensionless UH was developed based on an extensive analysis of measured data for a large number of actual watersheds and then made dimensionless by dividing all discharge ordinates by the peak discharge and the time ordinates by the time to peak. The time base of the dimensionless UH was approximately 5 times the time to peak, and approximately 3/8 of the total volume occurred before the time to peak; the inflection point on the recession limb occurs at approximately 1.7 times the time to peak, and the UH has a curvilinear shape [23]. The discharge ratios for selected values of the time ratios are given in **Table 1**.

Table 1. Some ratios for NRCS dimensionless UH.

Time Ratio t/T_p	Discharge Ratio q/q_p	Time Ratio t/T_p	Discharge Ratio q/q_p
0	0.000	0.9	0.990
0.1	0.030	1.0	1.000
0.2	0.100	1.5	0.680
0.3	0.190	2.0	0.280
0.4	0.310	3.0	0.055
0.5	0.470	3.6	0.021
0.6	0.660	4.0	0.011
0.7	0.820	4.5	0.005
0.8	0.930	5.0	0.000

After [23, p. 6-59].

The mathematical formulas of the requited parameters, to construct the NRCS UH for watersheds, are:

$$qp = qu\ A\ Q \tag{1}$$

where,

qp = peak discharge (m^3/s)

A = drainage area (km^2)

Q = depth of runoff (mm)

qu = unit peak discharge ($m^3/s/km^2/mm$) that can be interpolated from a specific charts (e.g. NRCS, 1986) or computed from corresponding tables [23, pp. 5-28].

The time of concentration, tc, is the time needed for a drop of water to move from the most distant point in the watershed to the design point downstream (taken as the basin outlet in the current study). There are numerous empirical equations to calculate tc, such as: Jaton formula [24], kirpich formula [25], and kirpich/Ramser formula [8]. However, the NRCS formula for time of concentration [18] is given by [26, pp. 3-9]:

$$tc = 1.67\left[L^{0.8}\left(S+1\right)^{0.7}\right] \Big/ \left[1900 * SL^{0.5}\right] \tag{2}$$

where,

tc = concentration time (minutes),

L = length of basin main stream (feet)

SL = average watershed land slope in percentage.

$$Q = \left(P - 0.2S\right)^2 \Big/ \left(P + 0.8S\right) \tag{3}$$

where,

Q = depth of direct runoff (mm)

P = depth of precipitation for a specific return period (mm)

S = maximum potential retention (mm):

$$S = 25.4\left(\left(1000/\mathrm{CN}\right) - 10\right) \tag{4}$$

where CN is the curve number, a coefficient determined based on geological, soil, and land use properties for each basin.

4.2. Materials

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 kilometers approximately. 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

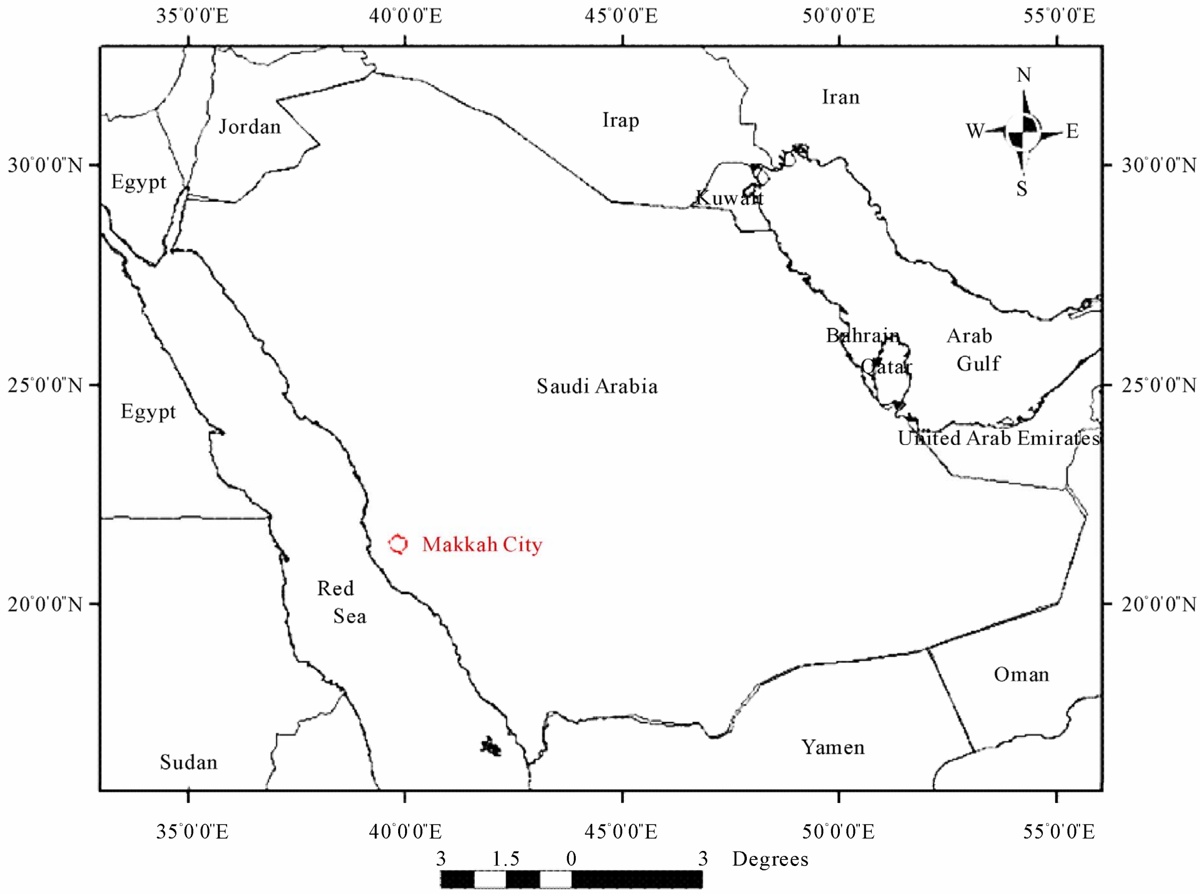

Figure 1. Study area.

extends from 1966 to 2009, varies from 3.8 mm to 318.5 mm, with an average of rainfall equals 101.2 mm. Due to the complexity of Makkah's topography, flash floods occurs periodically with significant variations in magnitude [27]. The rain intensity in a single extreme storm may exceed the annual rain average in that year.

Several datasets have been collected for the cause of flood assessment. The main data set, of the current study, is a Digital Elevation Model (DEM) for the study area. The acquired DEM produced by the by King Abdulaziz City of Sciences and Technology (KACST) with a spatial resolution equals 5 meters. A window covers Makkah metropolitan area has been provided through the Center of Excellence in Hajj and Omrah, Umm Al-Qura university. Mirza *et al.* [28] confirm that that national DEM is 3 times more accurate than published global DEMs (ASTER and SRTM 3). The other collected datasets include digital geological, soil, and land uses maps of the study area. The Arc GIS v.10 software has been utilized, in the current study, to delineates the main catchments in Makkah based on the available DEM. Six main basins are identified those area ranged from 74.3 to 360.6 square kilometers, and lengths of their main streams vary from 16.50 to 48.55 kilometers (**Figure 2**). **Table 2** presents statistics of some accomplished hydrological parameters of these catchments.

5. Results

Dawod *et al.* [29] computed CN, runoff depth, peak discharge, and time of concentration for the six basins in Makkah metropolitan area. In that study, a GIS-based methodology has been developed for quantifying and spatially mapping the flood characteristics. The core of that approach is integrating several topographic, metrological, geological, and land use datasets in a GIS environment that utilizes the NRCS method of flood modelling for ungauged arid catchments. The computations have performed using the depth of precipitation (P) equals 200 mm for a return period of 50 years. Additionally, the calculations of flood quantities, such as depth and volume of runoff (Equations 3 and 4), were performed in the attribute tables of GIS layers, in order to assemble all results in the same environment. **Table 3** presents these quantities.

The NRCS UH methodology, as described above, has

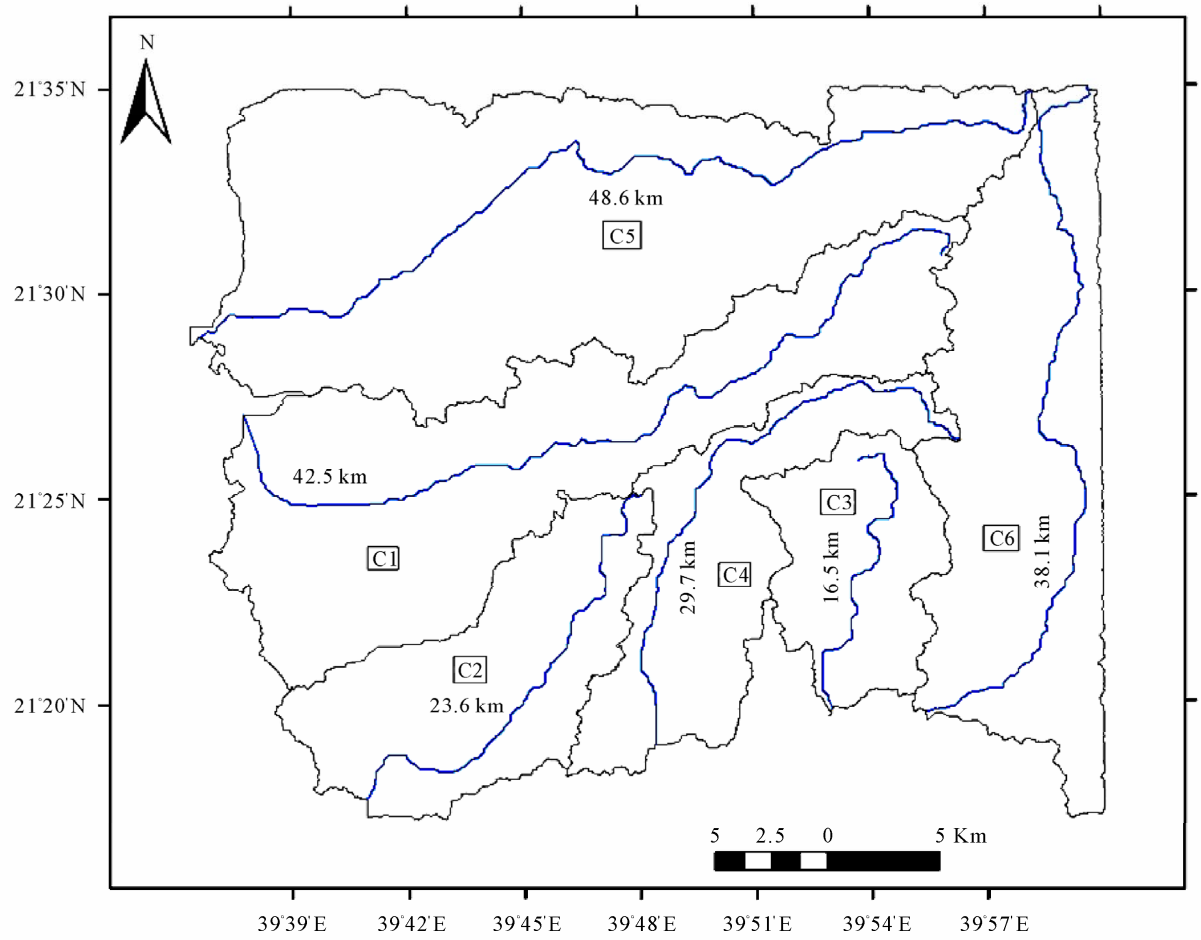

Figure 2. Catchments and their main streams in Makkah.

Table 2. 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
Length of Main Stream (km)	42.48	23.64	16.50	29.70	48.55	38.13

Table 3. NRCS-based hydrological results in the study area.

Item	C1	C2	C3	C4	C5	C6
CN	84	84	93	89	84	83
Time of concentration (hours)	5.69	3.76	1.73	2.63	6.72	4.17
Runoff depth (mm)	152	152	179	167	152	149
Peak discharge (m3/s)	1554	1063	1307	1234	4489	1514

been applied, for the first time in Saudi Arabia, for the six watersheds of Makkah metropolitan area. The accomplished results are presented in **Table 4** and depicted in **Figure 3**. It can be seen that the elapsed time from rainfall start to peak discharge vary from 1.15 hours (in catchment C3) to 4.47 hours (for catchment 6). Secondly, it has been found that the UH peak discharge quantities range from 10.14 m^3/s (for catchment 2) to 16.74 m^3/s

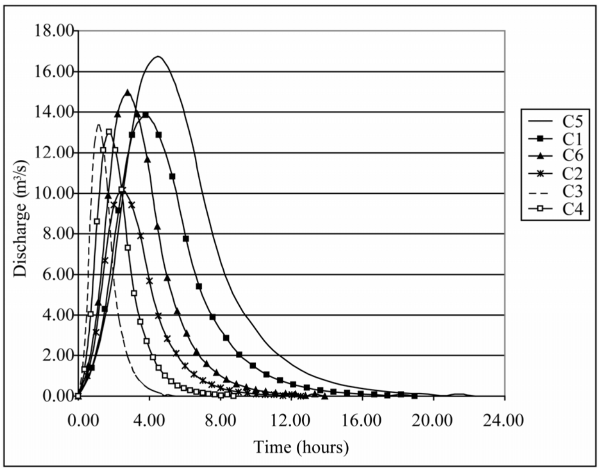

Figure 3. NRCS Unit Hydrographs of Makkah' Catchments.

(for catchment 5). Furthermore, the total runoff time varies from 5.75 hours (for catchment 3) to 22.34 hours (for catchment 5). The same results can be visualized graphically from **Figure 3**.

Moreover, a correlation analysis has been performed between the main morphometric and NRCS UH parameters of the six basins. The results (**Table 5**) showed that the basin area, with a positive correlation equaling to 0.74, is the most effective element that influences the UH peak discharges. In addition, the time of concentration also resulted in moderate positive correlation values, 0.55.

6. Discussion

Results in **Table 4** indicate that the smallest elapsed time is 1.15 hours (in catchment C3). Recall from **Table 3**,

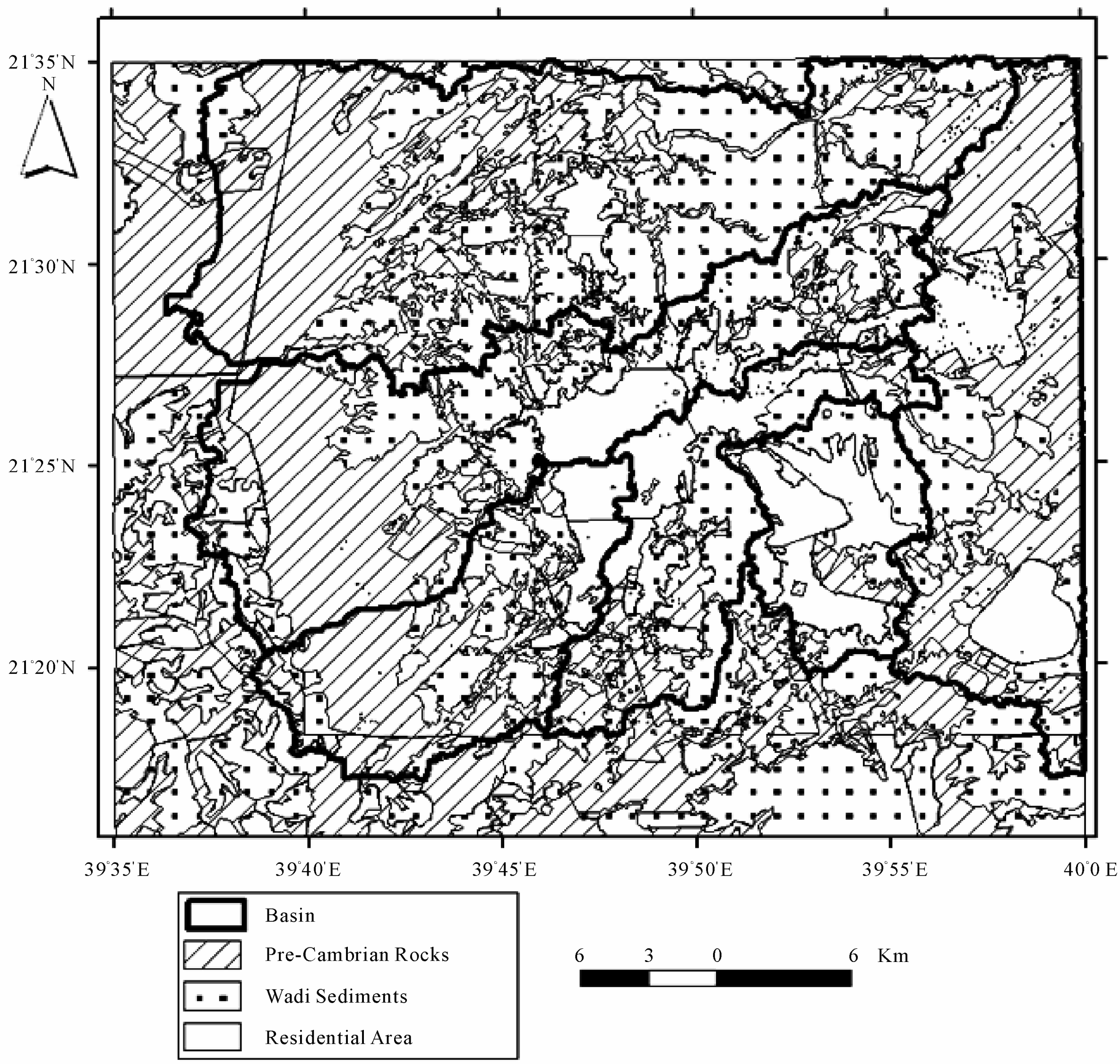

Figure 4. Geology and land use of Makkah' catchments.

Table 4. NRCS UH quantities for Makkah' catchments.

Item	C1	C2	C3	C4	C5	C6
Time to Peak (hours)	3.78	2.50	1.15	1.75	4.47	2.78
UH Peak discharge (m^3/s)	13.86	10.14	13.40	13.04	16.74	14.96
Total Time (hours)	18.92	12.51	5.75	8.74	22.34	13.88

Table 5. Correlation between main morphometric and UH parameters.

Item	UH Peak Discharge	Basin area	Time of concentration
UH Peak Discharge	1		
Basin area	0.74	1	
Time of concentration	0.55	0.97	1

this catchment has the higher CN value, since it mainly constitutes of residential areas (**Figure 4**) which have the least permeability property. Hence, it can be concluded that the third basin in Makkah city may be considered as the most hazardous catchment. Also, the total runoff time for this basin reaches 5.75 hours, which is another evident that the third basin in Makkah city may be considered as the most hazardous catchment. The same conclusions can be drawn from the inspection of **Figure 3**, where the UH of this particular basin has the least time-to-peak and total runoff time. That leads to the fact that there is no enough time, in case of floods, for both the residents and the governmental authorities to evacuate people or apply precaution procedures. Hence, careful flood protection policies should be taken in this area within Makkah city. Moreover, it has been found that the maximum UH peak discharge equals 16.74 m^3/s (for catchment 5). Although this catchment produces the highest peak discharge, its time to peak is relatively large (4.47 hours), which might gives suitable enough time for residents to get ready and receive some governmental assistance.

7. Conclusions

Unit hydrographs graphically represent the direct runoff resulted from a unit volume of excess rainfall of constant intensity and uniformly distributed over the drainage area. Out of several methods of unit hydrographs developments, the NRCS represent an optimum approach for ungauged watersheds, since it incorporates several data types of the area of interest. The current research study has utilized a high-resolution DEM in order to apply the NRCS approach for flood assessment. NRCS- based unit hydrographs have been developed for basins within Makkah metropolitan area, southwest of Saudi Arabia. The attained results show that the time to peak discharge vary from 1.15 hours to 4.47 hours, and the UH peak discharge quantities range from 10.14 m^3/s to 16.74 m^3/s. It is concluded that the third basin in Makkah city may be considered as the most hazardous catchment, since it has the least UH time-to-peak and total runoff time. Hence, it is recommended that careful flood protection procedures should be taken in this area within Makkah city.

8. Acknowledgements

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