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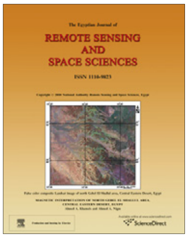

GIS-modelling of the spatial variability of flash flood hazard in Abu Dabbab catchment, Red Sea Region, Egypt

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Abstract In the mountainous area of the Red Sea region in southeastern Egypt, the development of new mining activities or/and domestic infrastructures require reliable and accurate information about natural hazards particularly flash flood. This paper presents the assessment of flash flood hazards in the Abu Dabbab drainage basin. Remotely sensed data were used to delineate the alluvial active channels, which were integrated with morphometric parameters extracted from digital elevation models (DEM) into geographical information systems (GIS) to construct a hydrological model that provides estimates about the amount of surface runoff as well as the magnitude of flash floods. The peak discharge is randomly varied at different cross-sections along the main channel. Under consistent 10 mm rainfall event, the selected cross-section in middle of the main channel is prone to maximum water depth at 80 cm, which decreases to nearly 30 cm at the outlet due to transmission loss. The estimation of spatial variability of flow parameters within the catchment at different confluences of the constituting sub-catchments can be considered and used in planning for engineering foundations and linear infrastructures with the least flash flood hazard. Such information would, indeed, help decision makers and planning to minimize such hazards.

1. Introduction

Flash flooding is one of the main natural disasters in Egypt (De Roo, 1999; Broadman et al., 1994). Previous records of flash floods indicate that they have been devastating, where parts of Upper Egypt, Sinia and Red Sea areas were hit by severe flash floods for example in 1976, 1982, 1996 and recently in January 2010. Often, considerable loss of life and damage to properties and cultivated crops are resulting. However, the hydrological models previously applied in Egypt have been simple, empirical and uncalibrated (El Bastawesy et al., 2009). In many catchments in the mountainous areas such as the Red Sea coastal zone floods associated with soil erosion creates a major problem. The Egyptian Red Sea coastal zone is much targeted for oil industry, mining activities and tourism

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recreation. Although these developments are essential and valuable to the local economy most of these infrastructures are, however, under the threat of natural environmental hazardous particularly flash floods.

Morphometric characteristics of drainage basins provide a means for describing the hydrological behaviour of these basins. Using multivariate statistical analysis help in establishing correlations between the morphometric parameters and the key hydrological variables such as, the catchment area, the time of concentration, the shape of the unit hydrograph, and discharge (Bardossy and Schmidt, 2002). Although these morphometric parameters provide information for hydrological modelling, it, however, must be well defined and able to be derived from the available data using standardized techniques (Willemin, 2000). The most important outputs of these hydrological models are the temporal and spatial distribution of flow discharge patterns (i.e. hydrograph). These hydrographs (particularly peak discharges) are simulated from design storms of long return periods to accordingly locate and design mitigation measures for engineering structures within the catchment.

The perception of considering surface area of catchments as the key morphometric parameter to determine flash flood hazard including hydrographs and peak discharge, has driven most of research toward repeatedly studying the larger catchments in Egypt (e.g. El Fakharany and Dahab, 1997; El Shamy et al., 1988; El Rakaiby, 1989). Consequently, the catchment of Abu Dabab in the Eastern Desert of Egypt, which is of a small area (185 km2), has therefore not been investigated for a detailed flash flood assessment.

The Abu Dabbab region is mostly crystalline basement rocks constituting a part of the Arabo-Nubian Shield. The drainage basin of Wadi Abu Dabbab runs through these rocks to reach the coastal plain in front of Mersa Abu Dabbab, where it transects Tertiary and Quaternary rocks. There is a well defined succession of rock units exposed in the study area together with the hydrogeological characteristics of each unit of Phanerozoic including significant ores (EGSMA, 1983). The implementation of a state-mega project for tantalum and tin production hosted in the basement rocks in the upper reaches of the catchment justifies the feasibility and environmental hazards studies (http://petroleum.gov.eg/en/AchieveProjects.aspx). Such mining activities require the establishment of local community needs including housing, domestic water pipelines, roads and other facilities. Therefore, it is essential for the safety of such planned activities to identify the environmental threats and quantify the surface runoff. Climatic conditions in the area drive the intensity of rainfall and therefore influence the flash flood hazard that requires an efficient tool to identify the existing infrastructures and therefore select the proper site for such activities with the proper mitigation measures (Montz and Gruntfest, 2002).

Geographical Information System (GIS) offers variety of techniques to automatically extract hydrological variables from high-quality digital elevation models (DEMs), such as flow direction and watershed delineation (Jenson and Domingue, 1988; Wilson and Gallant, 2000). Together with remotely-sensed data that able to provide near real-time information about terrain, landscape, local environment, as well as weather conditions (e.g. rainfall). The integration of both techniques could offer a near real-time management for the natural hazards of flash floods (Walsh et al., 1998; NASA, 2004).

Unless there is reliable and accurate data about rainfall, the determination of surface runoff will be problematic. The localized meteorological station always fails to provide an accurate coverage of climatic parameters. Recently remotely-sensed data offered a 3-hourly rainfall data via the Tropical Rainfall Monitoring Mission (TRMM) satellite data archives that provide the rainfall estimates from January 1998 to recent (NASA, 2004). TRMM was used, in this research, to assess the number of rainy days, together with the number and intensities of rainfall events over the catchment area of Abu Dabbab for the last 10 years.

Such comprehensive climatic data could help evaluating the repeatability of rainstorms over the study area. Then, propose a scenario of the runoff pattern following an event of maximum daily precipitation could be developed, which in due course could be used to construct a physical hydrological model that enabled to quantify the peak discharge, determine the water depth and estimate the stream power. This paper aims at determining and quantifying the magnitude of the flash flood hazards on Abu Dabbab area using remotely sensed data and both GIS and hydrological modelling.

2. Study area

Abu Dabbab drainage basin is located in the middle of the western coast of the Egyptian Red Sea (Fig. 1). The basin is located in an intermediate topographic terrain 20 km north of Marsa Alam City. There are few mining activities in the area, however it is under prominent future developments. The drainage basin occupies the area between longitude, 34°30′E to 34°45′E and latitude, 25°10′N to 25°25′N.

3. Climatic conditions

The area of study is a typical arid environment where the summer is hot and the winter displays lower temperatures and the rates of evaporation significantly exceed the rates of precipitation. Climate is the key driving force of the environmental hazard in this area and always triggers various hydrological and geomorphological processes. Rainfall is the main climatic parameter that initiates and controls the occurrence of flash flood events. Not only rainfall but also wind and thermal heat turbulence are major parameters.

Meteorological data including rainfall is normally obtained from weather stations that are installed near the drainage basins. Although these data can provide valuable information on a particular region, it is not truthful to be used for modelling and predicting flash flood events that occur in large or medium sized drainage basins. This creates two significant constrains:

(1) the climatic stations always represent a limited geographic extent for a point where it is installed through their measurements reflect this limited geographic coverage with possible limited radius, and
(2) these stations are basically installed for helping navigation in both sea and aviation and accordingly they are located along the coastal line of the Red Sea region.

Therefore, the obtained climatic data from these stations are not precisely representing the remote mountainous reaches that receive the rainfall responsible for the flash floods.

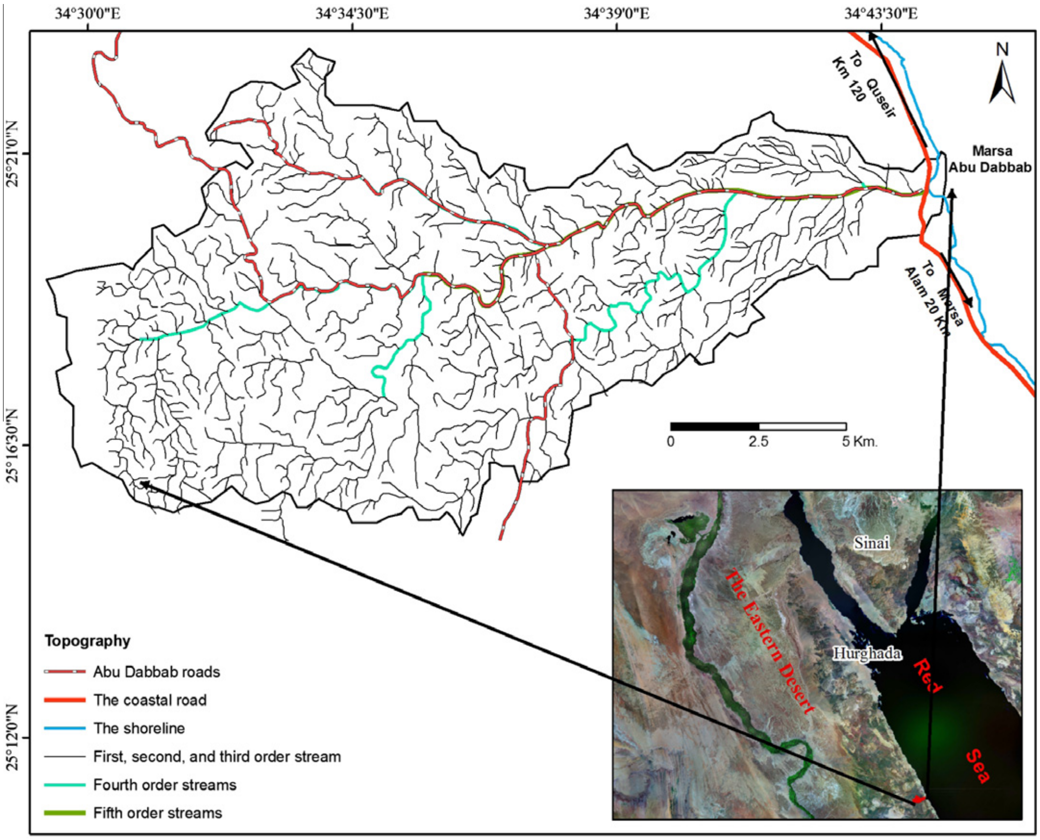

Figure 1 The area of study – Abu Dabbab drainage basin.

There are no climatic stations in Abu Dabbab drainage basins. Climatic data for the Abu Dabbab drainage basin are traditionally acquired from the closest climatic stations that are located far away from the basin at distances of 20 and 150 km (the Marsa Alam Airport and Ras Banas weather stations respectively). Table 1 shows monthly average precipitations for the last three years measured in the Ras Banas station. Unfortunately, this dataset failed to provide detailed records in terms of frequency, magnitude and spatial coverage for significant modelling of the flash flood events in the Abu Dabbab drainage basin. Therefore, this research has searched for another alternative source of accurate and reliable meteorological data. The Terrain Rainfall Monitoring Mission (TRMM) remotely sensed data was used as a near real time source of climatic data for the study area in both spatial (i.e. the whole drainage basin) and temporal coverage (i.e. 3-hourly, daily, monthly and yearly). Fig. 2 shows an example of the 3-hourly cumulative rainfall data between 2006 and 2008 obtained from the TRMM superimposed by the outline boundary of Abu Dabbab drainage basin.

Table 1 Monthly average meteorological data from Ras Banas weather station for the last three years.

	2008				2007				2006			
	Min. temp. (2008)	Max. temp. (2008)	Precipitation (2008)	Wind speed (2008)	Min. temp. (2007)	Max. temp. (2007)	Precipitation (2007)	Wind speed (2007)	Min. temp. (2006)	Max. temp. (2006)	Precipitation (2006)	Wind speed (2006)
January	12	19	0	16	12	20	0	16	13	21	0	14
February	13	21	0	16	12	22	0	12	14	22	0	14
March	11	25	0	15	15	23	0.2	15	16	24	0	14
April	20	27	0	15	19	26	0.8	14	18	27	0.2	12
May	23	29	0	16	23	30	0	13	22	28	0	15
June					25	32	0	15	25	31	0	18
July					26	33	0	11	26	32	0	13
August					26	33	0	13	27	33	0	13
September					26	33	0	13	25	31	0	16
October					23	29	0.1	13	22	28	0	13
November					18	25	0	15	16	24	0.1	17
December					14	22	0	15	13	21	0.3	17

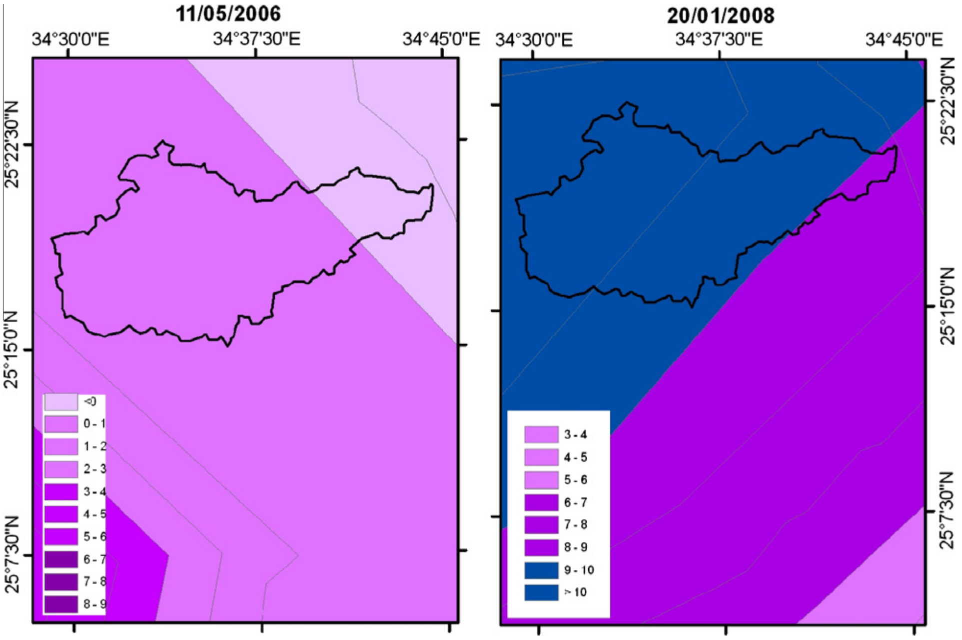

Figure 2 The 3 h accumulated rainfall (mm) in Abu Dabbab region, the catchment is outlined by solid black line. An example of two independent storms (11/5/2006 and 20/1/2008).

4. Materials and methods

The 3-hourly rainfall climatic data, from January 1998 to August 2008, were acquired from the Tropical Rainfall Monitoring Mission (TRMM) satellite. The study area is virtually rainless, with rain occurring on average three–five times a year, however the TRMM estimated the mean annual rainfall at 35.0 mm. It is known in this area that if the rainfall occurs in a considerable intensity (around 8–12 mm) it is capable of producing significant surface runoff.

The systematic approach of the methodology includes:

4.1. Digital elevation model

Digital elevation model (DEM) is the digital representation of the earth surface terrain. It is an essential component in the hydrological models. The DEM is significant to calculate both topographic parameters such as slopes, slope length and shape and aspects as well as hydrologic parameters such as flow direction, flow accumulation, watershed delineation, stream networks, and flow length. Consequently, both flow accumulation and flow length would be used to extract the surface runoff. The DEM of Abu Dabbab drainage basin is generated

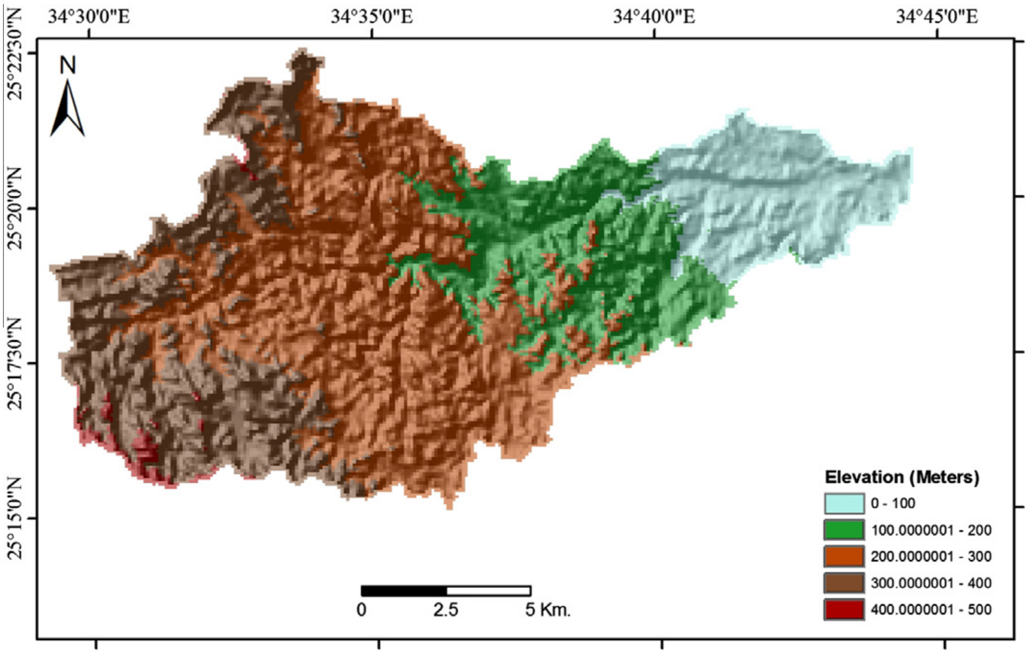

Figure 3 The digital elevation model (DEM) of Abu Dabbab drainage basin.

from the Shuttle Radar Topography Mission (SRTM) data available at the United States Geological Survey website (www.usgs.gov) (Fig. 3).

4.2. The DEM-derived spatially distributed time-area zones (synthetic hydrographs)

Since the basic hydrological data are not available for the catchment; alternative techniques for extracting channel morphological and hydrological properties from the DEM in order to estimate the flow characteristics. However, most open channel methods require that channel cross sections are generalized prior to estimating overland and channeled flow (Hey, 1979), so the SRTM DEM should provide a reasonable approximation for the relatively large channels considered here.

Overland and channel flow velocities were estimated empirically using the Manning Equation:

$$V = R^{2/3} * S^{0.5}/n \tag{1}$$

where V is the cross-sectional average velocity (ms^{-1}); n is the Manning coefficient of roughness; R is the hydraulic radius (m); s is the slope of the water surface, which is assumed to be parallel to the slope of the channel bed. The widths of the channels at selected cross-sections were measured from the active channels mapped on the satellite images. These selected cross-sections were overlaid on the DEM for estimation of the mean depth. Slope was estimated from the DEM using the embedded functions in ARCGIS. Hydraulic radius (which is nearly equal to the depth of flow in shallow braided channel systems in dryland areas (White, 1995) was calculated from the measured cross-section areas and perimeter. Manning's n are usually obtained from the standard table (Hornberger et al., 1985). Herein it was set to 0.02 for channels and 0.06 for hillslopes; these values are typical of reported values from similar catchments in dryland (El Bastawesy, 2006).

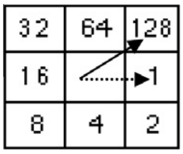

Figure 4 Schematic diagram shows the D-8 algorithm of flow direction.

Then, D-8 algorithm is used to calculate the flow direction within each cell in the catchment area throughout the eight neighbouring cells (i.e. either diagonal – solid arrow, or orthogonal – dotted arrow) (Fig. 2). The grid resolution of the DEM is known, therefore it was possible to calculate the flow length within each cell which is either equal to the grid cell length (L) in case of orthogonal or $L\sqrt{2}$ in case of diagonal (Figs. 4 and 5).

The travel time of flow is function of the flow length and velocity. The "time-of-flow" grid, representing the time required for the runoff generated at each cell to reach the outlet was estimated using the flow length function in ArcInfo package, which uses the following convolution equation (2) (ESRI, 2000).

$$V_{ij} = \sum_{p} cp \times dp \tag{2}$$

where V_{ij} = the output result of the convolution for cell (i, j); c = the unit-distance cost value; p = the minimum-cost path; d = the slope distance between the centres of two adjacent cells along the minimum-cost path.

A "cumulative travel time" grid is produced from the "time-of flow" grid in order to categorise the catchments into different "time-area zones" (in minutes) separated by isochrones. The "time-area zones" map can represent the spatially distributed unit hydrograph without the need for empirical functions for the lumped time of concentration factor, but

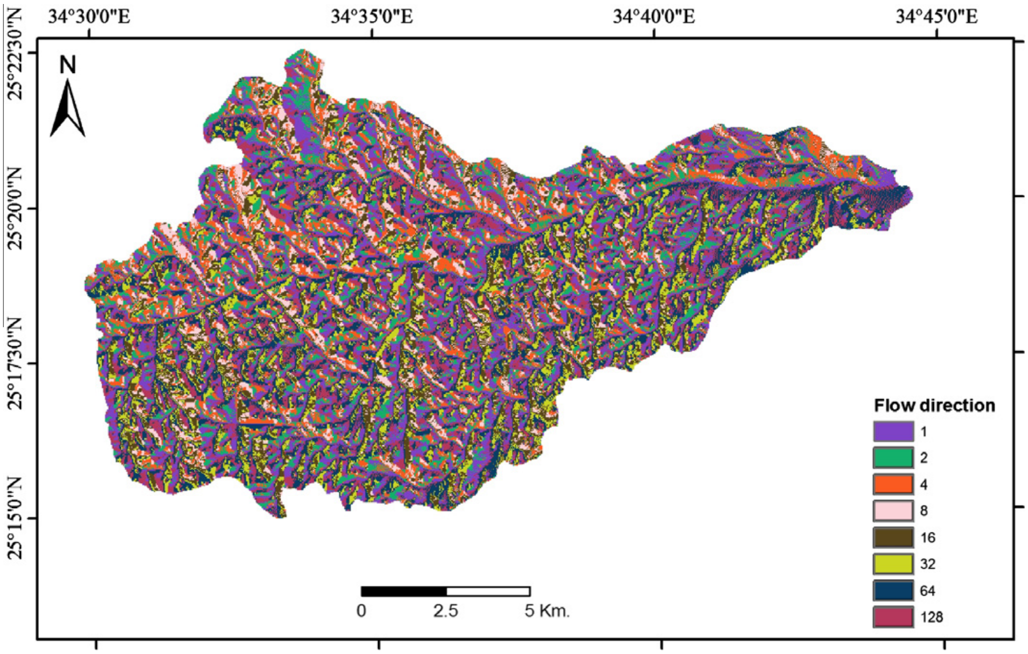

Figure 5 The flow direction of Abu Dabbab drainage basin.

the overland and channel flow is purely translated downstream without any transmission losses.

4.3. Runoff generation and routing

Since it is obvious that any infrastructure lines (such as asphaltic road, pipeline, and power grid) will be only feasible along the main channel of the catchment to reach the mining facility. The developed hydrological model for Abu Dabbab is composed of two main components; (1) the runoff generation and the channel flow routing and (2) the runoff hydrographs including maximum flow depths at certain cross-sections along the main channel (i.e. outlets) in the upper, middle and most lower parts of the main channel. This is to investigate the influence of tributary flow from different sub-catchments, and the changes of geometry along the main channel on the attenuation of peak discharges and the resulting flow depth. Thus, flow discharges will be assessed at different cross sections of the main channel, which receive tributary flows from the neighbouring sub-catchments.

Since the catchment area is composed of massive crystalline rocks, the infiltration into hillslope rock units is assumed to be negligible. The rainfall component of the model is assumed to be at 10 mm/h intensity and has a spatial uniform distribution over the whole catchment and duration of 1 hour. Therefore, the potential runoff volume (Q) generated at each time-area zone will be given by Eq. (3)

$$Q = A * I * 1000 \tag{3}$$

where: Q = runoff volume (m^3); A = area (km^2); I = rainfall intensity (mm).The U-shape model of channel was adapted to measure the channel width at the outlets. After the generation of the runoff hydrographs, the peak discharge rate were divided by the width of these main channels to obtain the maximum flow depth particularly at the 10 mm rainfall storms (Eq. (4))

$$D = Q/C \tag{4}$$

where: D = channel width (m); Q = water discharge ($m^3\,s^{-1}$); C = cross section area (m^2)

4.4. Stream power

A key issue for any infrastructure and engineering constructions is determining the energy of such mass associated with any flash flood event. Stream power is the energy available to transport mass of water and sediment (Worthy, 2005). The mass of water and debris transmitted to the main channel is estimated as stream power using Eq. (5). This water mass and sediment load are supposed to be the threatened power to the existing or the proposed infrastructures

$$\Omega = \gamma * Q * S \tag{5}$$

where: Ω = stream power ($N/s/m^2$); γ = specific weight of water ($N\,m^{-3}$); Q = water discharge ($m^3\,s^{-1}$); S = slope percentage.

5. Results

This model has subjectively subdivided the whole drainage basin into various sub-catchments that are linked together at a number of outlets that are located along the main channel (Fig. 6). The hydrological model has defined three main outlets along the main channel of Abu Dabbab drainage basin. These outlets are designated at "A", "B", and "C". Each outlet receives surface runoff water from a number of sub-catchments (Fig. 6). Accordingly, the whole fluvial system of Abu Dabbab is classified into three major accumulative hydrologic zones. These zones vary in sizes and morphologic characteristics, which in due course vary in the quantity of runoff they deliver and the depth of runoff in the main channel.

The simulated hydrographs for the time area zones for each outlet is presented in Fig. 7. Each time area zone in the figure indicates the total amount of rainfall that is going to be trans-

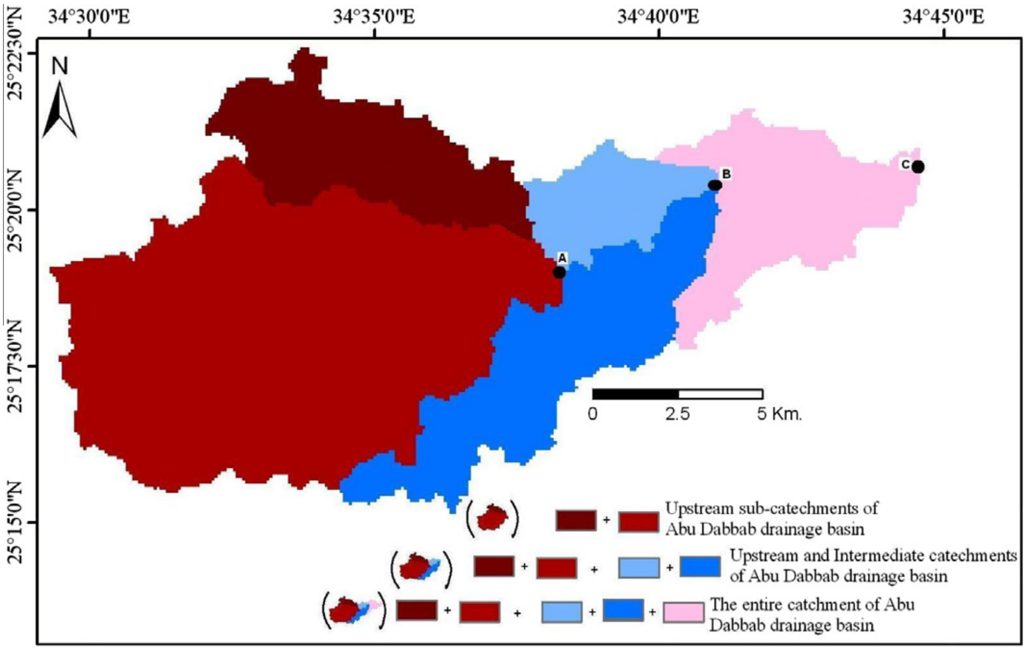

Figure 6 Model-generated sub-catchments of Abu Dabbab drainage basin.

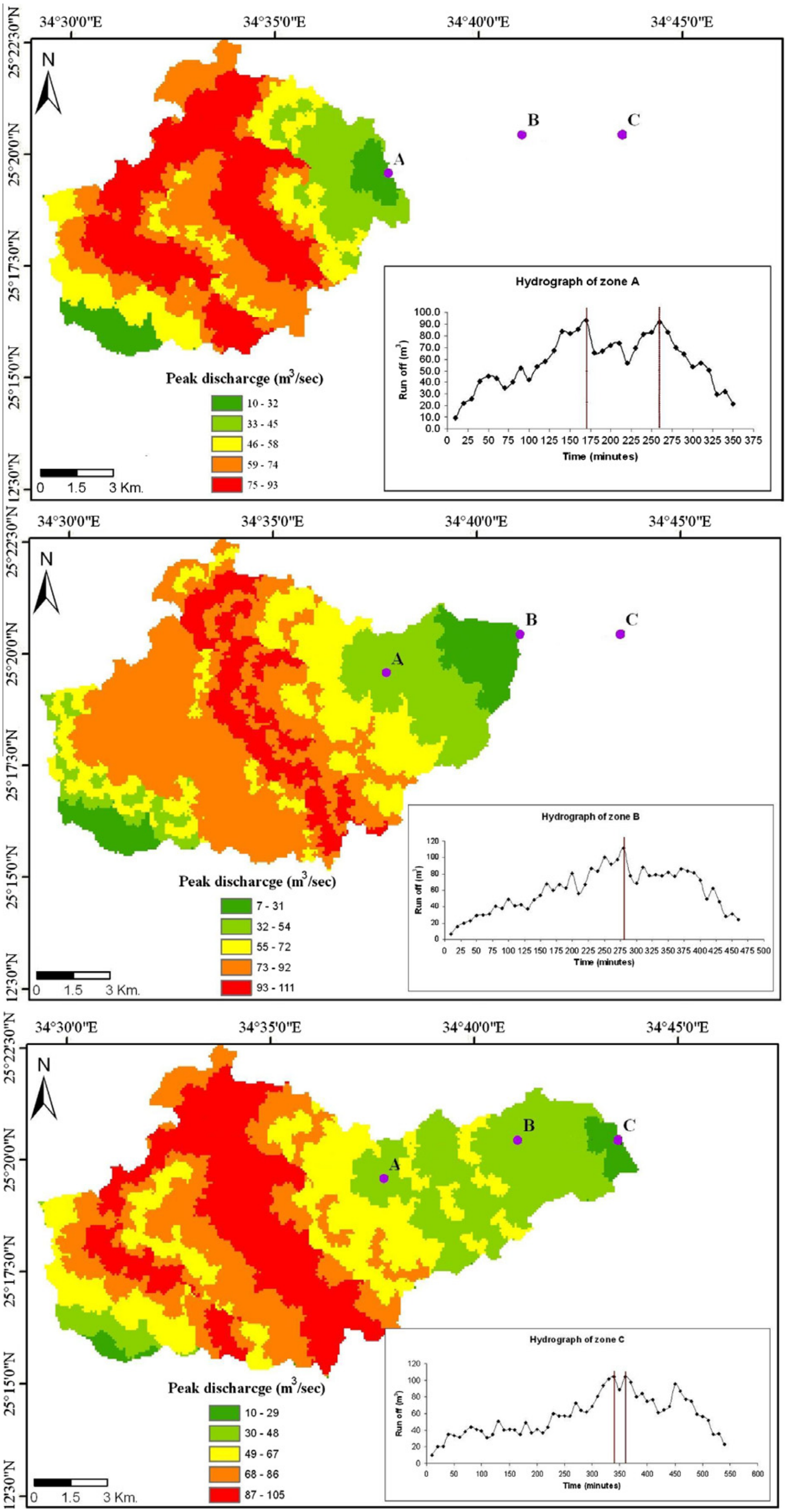

Figure 7 The time area zones and the peak hydrograph at outlets A, B and C.

mitted to the outlet after a particular time interval from the occurrence of the 10 mm effective rain storm. The peak discharges were 93.0, 111.0 and 104.0 $m^3 s^{-1}$ at zone A, B and C, respectively. The maximum water depths were therefore estimated as 30, 79 and 35 cm for the outlets A, B and C, respectively.

The stream power at each outlet is estimated at 506.8, 3327 and 340.0 $N m^{-3} h^{-1}$. Knowing such stream power would help in the engineering design of any construction to be strong enough to cope with the extreme case of such stream power.

6. Discussion and conclusion

The peak discharge of flows developed from rainfall events that uniformly cover the whole catchments is of different attenuation at different cross sections along the main channel. This is related to the changes in channel widths and depths, the variation of tributary flows from sub-catchments areas and the influence of infiltration to flash floods into the alluvium channel beds. It is recommended that the infrastructure networks of this catchment should consider the non regular variations in tributary discharges from the different sub-catchments and its impact on the attenuation of peak discharge in the main channel. The analysis of simulated hydrographs and peak discharges suggest that the middle cross-section (B) is more prone to peak discharges and stream power. Therefore, the hazard potentials are not necessarily increase or decrease in the downstream directions. This mean that the local controls such as cross sections geometry, tributary flow and transmission losses will add much spatial and temporal variability in the flow transmission in different reaches of the channel. Finally, it should be mentioned that these results are obtained given static uniform precipitation over the entire catchment. Therefore, flows are concurrently routed from the different sub-catchments into the main channel. Under local rainfall conditions, the flows will not be augmented in the downstream direction and therefore, the peak discharge is gradually and always diminishing downstream because of transmission loss.

References

Bardossy, A., Schmidt, F., 2002. GIS approach to scale issues of perimeter-based shape indices for drainage basins. Hydrol. Sci. J. 47 (6), 931–942.

Broadman, J., Ligneau, L., De Roo, A.P.J., Vandaele, K., 1994. Flooding of property by runoff from agricultural land in northwestern Europe. Geomorphology 10, 183–196.

De Roo, A.P.J., 1999. Modelling runoff and sediment transport in catchments using GIS. In: Gurnell, A.M., Montgomery, D.R. (Eds.), Advances in Hydrological Process, Hydrological Applications of GIS. John Wiley and Sons, Chichester, England.

EGSMA (Egyptian Geological Survey and Mining Authority), 1983. Geologic Map of the Ras Banas Quadrangle, Scale 1: 100,000.

El Bastawesy, M., 2006. Influence of DEM source and resolution on the hydrographical simulation of Wadi Keed catchment, Southern Sinia, Egypt. Egypt. J. Remote Sensing Space Sci. 9, 68–79.

El Bastawesy, M., White, K., Nasr, A., 2009. Integration of remote sensing and GIS for modelling flash floods in Wadi Hudain catchment, Egypt. Hydrol. Process. 23, 1359–1368.

El Fakharany, M., Dahab, K., 1997. Hydro-geological studies on wadi Al-Qarn basin, Eastern Desert, Egypt. Bull. Faculty Sci., Menoufia Univ. 6, 179–202.

El Rakaiby, M.L., 1989. Drainage basins and flash flood hazard in selected parts of Egypt. Egypt. J. Geol. 33, 307–323.

El Shamy, I.Z., 1988. Quantitative geomorphology and surface runoff control for Wadi Qena, central Eastern Desert, Egypt. In: Proceedings of the 6th Geophysics Society Annual Meeting, pp. 13–26.

ESRI (Environment System Research Institute), 2000. GIS Manual, ESRI Ltd., California, USA, p. 335.

Hey, R.D., 1979. Flow resistance in gravel-bed rivers. J. Hydraul. Div. HY 4 (105), 365–379.

Hornberger, G.M., Beven, K.J., Cosby, B.J., Sappington, D.E., 1985. Shenandoah watershed study: calibration of a topographically based, variable contributing area hydrological model to a small forested catchment. Water Resour. Res. 21, 1841–1850.

Jenson, S.K., Domingue, J.O., 1988. Extracting topographic structure from digital elevation data for geographic information system analysis. Photogramm. Eng. Remote Sens. 54, 1593–1600.

Montz, B.E., Gruntfest, E., 2002. Flash flood mitigation: recommendations for research and applications. Environ. Hazard. 4, 15–22.

NASA (National Aeronautics and Space Administration), 2004. Global Precipitation Mission [Online]. Available at <http://gpm.gsfc.nasa.gov/index.html> (accessed 29.11.2004).

Walsh, S.J., Butler, D.R., Malanson, G.P., 1998. An overview of scale, pattern, process relationships in geomorphology: a remote sensing and GIS perspective. Geomorphology 21, 183–205.

White, K., 1995. Field techniques for estimating downstream changes in discharge of gravel-bedded ephemeral streams: a case study in southern Tunisia. J. Arid Environ. 30, 283–294.

Willemin, J.H., 2000. Hack's law: sinuosity, convexity, elongation. Water Resour. Res. 36, 3365–3374.

Wilson, J.P., Gallant, J.C., 2000. Digital Terrain Analysis: Principals and Applications. In: Wilson, John P., Gallant, John C. (Eds.), John Wiley and Sons, Inc., ISBN 0-471-32188-5.

Worthy, M., 2005. High-resolution total stream power estimates for the Cotter River, Namadgi National Park, Australian Capital Territory, Regolith, In: Roach, I.C. (Ed.), Regolith 2005 – Ten Years of CRC LEME, CRC LEME, pp. 338–343.