

Flood Risk Modeling for Holy Sites in Makkah

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Abstract

Arafat as part of the Holy Sites in Makkah is a place where around three million pilgrims gather to pray to Allah during the season of Hajj. The Holy Site's environment consists mainly of mountains with steep slopes that can give rise to heavy flooding during the rainy season. In order to support the existing efforts for flood hazard prevention an estimation of the flood to be expected during one rain storm event for one of the major watersheds that is part of the Holy Sites (575 km² in size) has been made. Using a Digital Elevation Model (DEM), a simplified surface water model and field data from similar physical environments, discharge at the outlet of the watershed has been computed. The paper provides illustrations using 2D and 3D visualization tools and points to the needs of further research in this field.

Keywords

Holy Sites, flood risk modeling, GIS, discharge

1 Introduction

The Commission will work out the development plan for Makkah, Madinah and the Holy Sites. It has to report directly to the King, make recommendations and call on local and foreign expertise and the resources of all government facilities and research centers. Its main mission is to draw up comprehensive plans that meet the needs of pilgrims over the next 20 years. The Commission has selected GIS to be the major tool for planning. An enterprise GIS has been established at the Commission in July 2007. The GIS Center of the Commission as the core of this GIS serves customers within and outside the Commission. It initiates projects on his own as well as one of them is described in this paper.

2 Objectives

The objective of this study is to research the likelihood of flooding at the outlet of the Aranah Watershed at bridge of road No. 8 in Arafat over the Wadi Aranah. This likelihood has been determined using hydrological modeling with a GIS.

3 Natural Characteristics of the Aranah Watershed

The Aranah Watershed in which the Holy Sites of Arafat and Muzdalifah are located consists mainly of hilly areas intersected by wadis with flat open land. With exception of the surrounding of the Holy Sites most of the area is undeveloped. Having only a mean annual precipitation of 130 mm only sparse vegetation can survive in this environment. However, as a high percentage of this annual precipitation may be concentrated in a few rainstorm events and given the above mentioned natural conditions flooding is a common phenomena in this region. Such flooding can cause major damage to buildings and infrastructure elements. If Hajj falls in the rainy season flooding can have a big negative impact of the performance of Hajj.

The total area of the Aranah Watershed as shown in the LANDSAT satellite image below (Fig. 1) is 575 km².

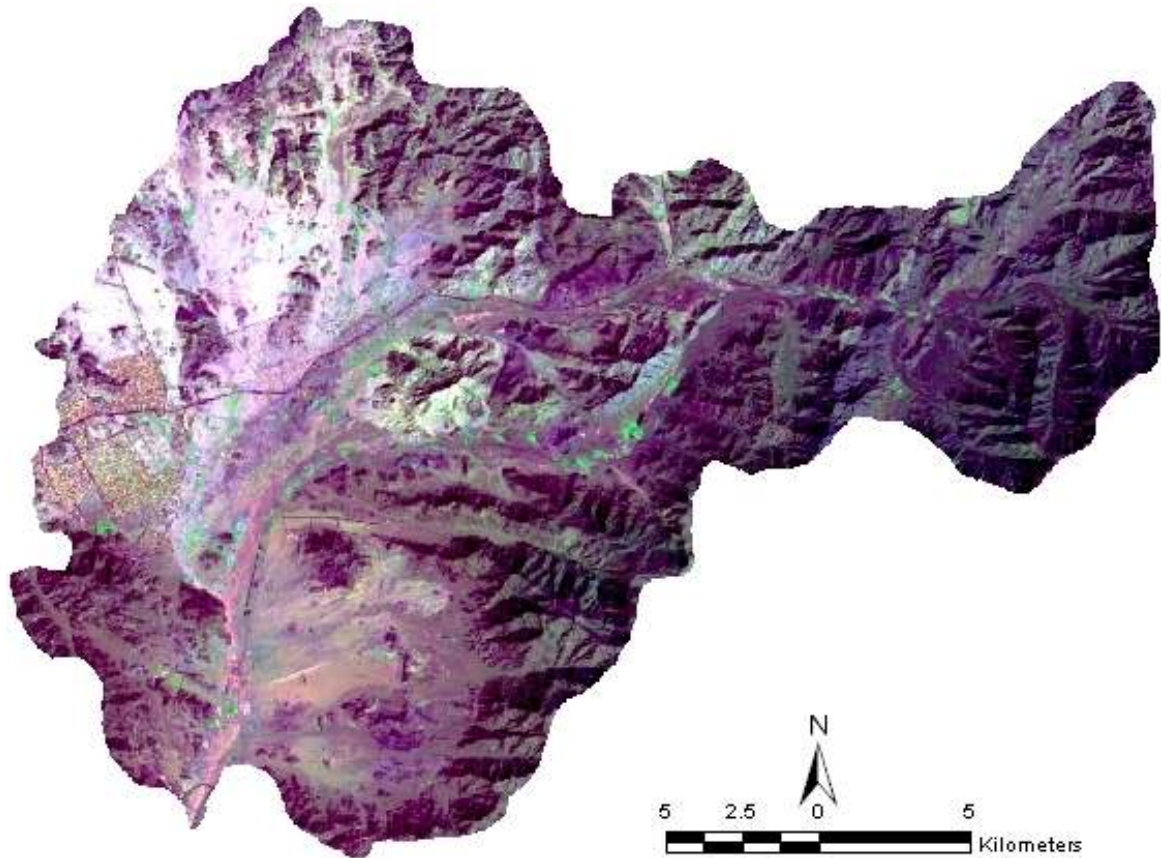


Fig.1: LANDSAT Satellite image of the Aranah Watershed

4 Methodology

4.1 Introduction

A hydrological model is a simplified simulation of the complex hydrological system of a certain watershed. The major problem in modeling the hydrological processes based on their physical governing laws is the variability in space and time of the parameters that control these processes (Porter and McMahon, 1971). In the first generation of hydrological models this has been dealt with by assuming homogeneous properties for the hydrological processes over the whole catchment area or, in the best cases, for subdivisions of the catchment area (Moore et al, 1993).

With the emergence of remote sensing techniques as potential sources of data of the hydrological processes and the improved capabilities of generating and processing Digital Elevation Model (DEM) data, GIS techniques have gained a prominent role in hydrological modeling. Better description of the catchment topography and the distributed properties of the hydrological processes acting on

it can be achieved much easier now.

This role has developed from the traditional use of GIS as an interface to the hydrological models for pre-processing and post processing of data into "rethinking hydrological models in spatial terms so that better GIS-based hydrological models can be created" (Maidment, 1993).

In this paper a simplified GIS-based hydrological model has been used to generate runoff records for the Aranah Watershed, an un-gauged arid catchment in the Makkah region, Kingdom of Saudi Arabia. The model applied for this watershed is composed of two components, the runoff generation component and the channel flow routing component. All processing has been done using different tools of ESRI's ArcGIS.

4.2 Derivates of DEM

A DEM forms the basis for computing topographic derivatives (slope, flow direction, flow accumulation, drainage networks and flow length), which have been employed in the runoff for the study area. The DEM used in this study consist of a 10 m grid for the major part of the watershed and a 130 m grid resampled to the same size as the former for the remaining part where more accurate data were not available (Fig. 2; both data sets courtesy of King Abdulaziz City for Science and Technology).

Stream network delineation is a prerequisite for comparing the output results with the drainage networks of source topographic data. It is important to ensure that the extracted drainage network follows the same flow paths as the source data in order to obtain accurate flow lengths. Flow lengths have been obtained by using the 'FLOWLENGTH' function in ArcGIS, which can be used to simulate convolution processes involved in the channel flow routing procedure. Standard procedures for extracting drainage network have been applied that are described in the following paragraphs in more detail.

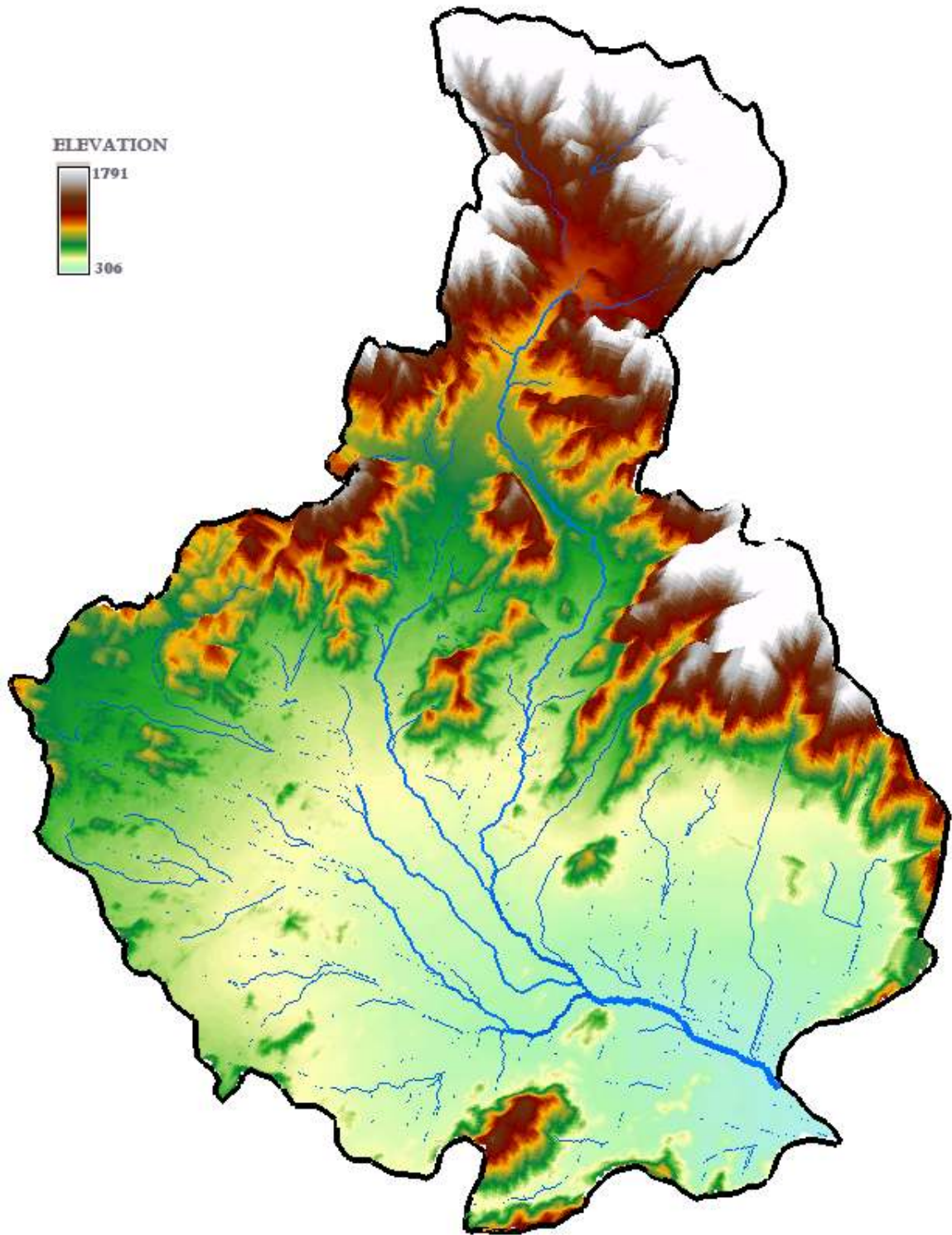


Fig. 2: DEM of the Aranah Watershed with stream network (3D view)

4.2.1 Filling sinks

Filling sinks is the first step in the extraction of drainage networks from a DEM. A sink-less DEM is required in order to maintain a connected network, flowing down slope. The presence of local depressions in any landscape is common, but it is

essential to level these sinks off with the surrounding pixels, to extract continuous drainage lines.

4.2.2 Flow direction

Determining flow direction function is the second step in DEM processing extracting for drainage features. With ArcGIS the overall flow pattern could be differentiated into eight flow directions on a cell-by-cell basis.

4.2.3 Flow accumulation

After flow direction is established, the third step in delineating drainage parameters is the determination of upslope contributing pixels. Flow accumulation is a fundamental

component in any physically based hydrological model, as it shows the spatial pattern and distribution of subcatchment contributing areas. Therefore, at any location of the watershed, the area contributing to a flow into that point can be easily and quickly expressed.

4.2.4 Stream delineation

Stream networks can be developed by assuming a threshold for the flow accumulation, at which a stream segment is initiated. A threshold of 200 was found to be appropriate to portray drainage network of the study area (Fig. 2). That threshold was selected after applying random different thresholds and overlaying the resulting automatic network with the digital drainage data. A threshold value of 200 means that the minimum upslope contributing areas for any drainage segment is more than 0.08 km².

4.2.5 Slope

A slope layer was created from the DEM in order to calculate velocities for overland flow. The Aranah Watershed possesses a very heterogeneous relief with very slight slopes in the Wadis and high slopes in the surrounding hills and mountains. Because some cells in the DEM had a slope of zero percent what would have resulted in an infinite travel time, they could not be incorporated into channel flow velocity calculation directly. Therefore, the value of these cells had to be modified.

4.2.6 Time-of-flow grid

Overland flow velocity (Fig. 3) requires the calculation of both magnitude and direction. Magnitudes were estimated using the Manning equation, where slope was derived from DEM and Manning's n values from standard tables (USDA Forest Service (2008). Hydraulic radii should be equal to the depth of flow. It was assumed to be minimal for overland flow (Hornberger et al., 1998). Since the flow

direction grid represents the direction of flow within each cell in the catchment as either diagonal or orthogonal, and the grid resolution is known, the cell flow length will be equal either to the grid cell length (L) or $L\sqrt{2}$. The flow direction grid has been reclassified to obtain the flow length within each cell. Once both the flow velocities and the flow lengths are known for each cell, the travel time of flow in each cell is obtained by dividing the flow length by the velocity. The time-of-flow grid, representing the time required for the runoff generated at each cell to reach the outlet, was produced using the 'Flowlength' function in ArcGIS. According to this calculation the furthest point in the Aranah Watershed requires 17 hours for its discharge to reach the outlet.

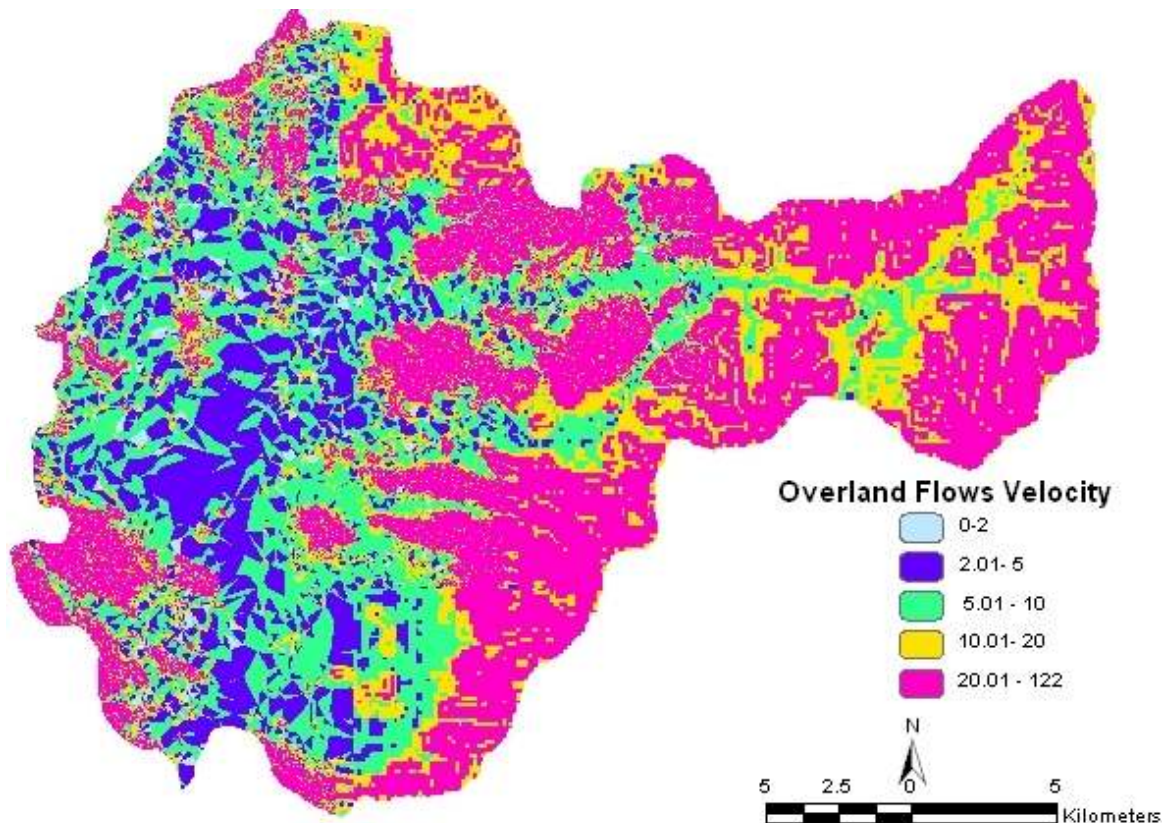


Fig. 3: Overland flow velocity

Rainfall intensities have been well documented for the last 30 years for the gauge station at the Great Mosque in Makkah (KSA Ministry of Public Works and Housing, 2002). As these measurements show (Table 1) that usually heavy storms lasts only about one hour and yield about half of the rainfall in the first 10 minutes the time-of-flow grid has been classified into 17 zones with intervals of 1 hour (Fig 4). The lines bounding these zones or sub-catchment areas are called isochrones of travel time, and each zone will transfer its flow to the outlet with a delay of 1 hour.

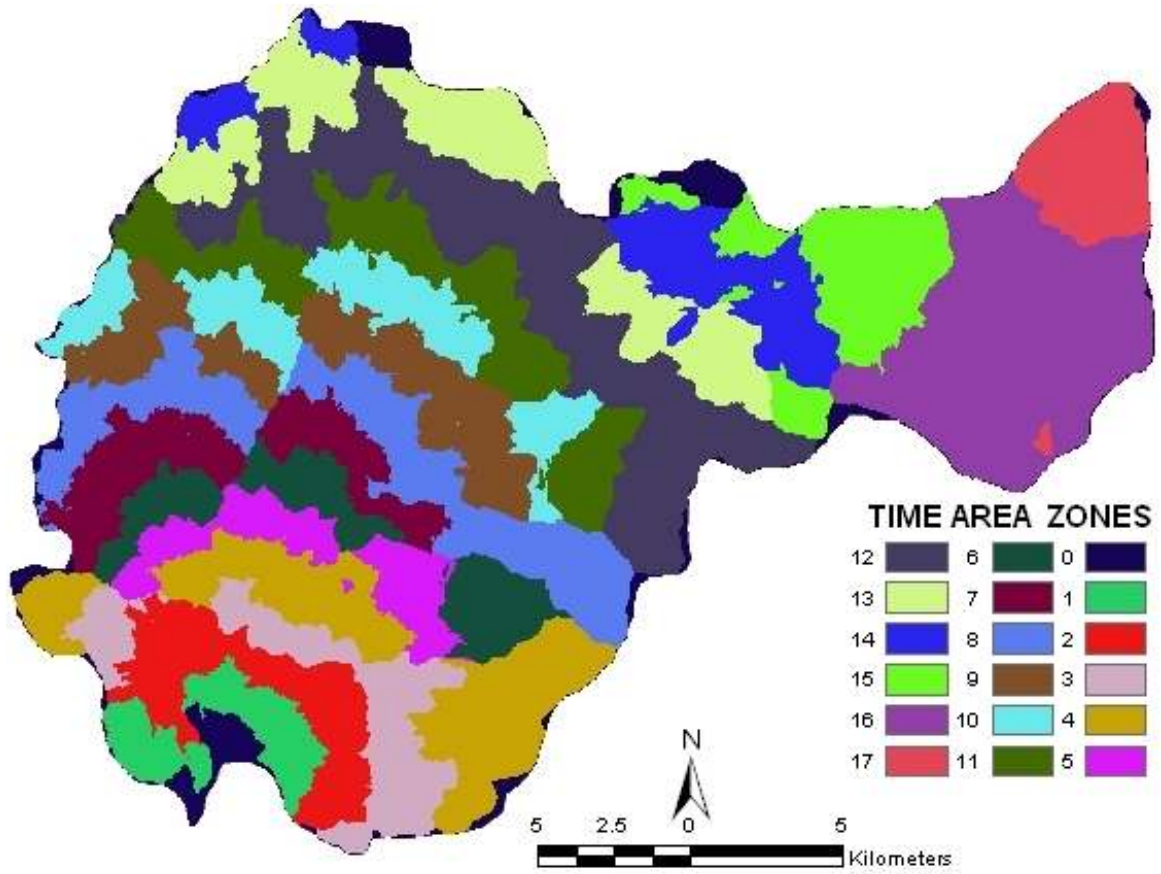


Fig 4: Time-area zones with intervals of 1 hour

Table 1: Hourly rainfall intensities deduced from records obtained from gauge J218 for , Holy Mosque, Makkah (KSA Ministry of Public Works and Housing, 2002)

Date of Storm A.D.	10 min duration mm/hr	20 min duration mm/hr	30 min duration mm/hr	1 hour duration mm/hr	2 hour duration mm/hr	Daily rainfall mm
22.11.69	108.0	77.4	56.0	28.6	--	30.4
17.10.70	42.0	26.4	20.0	17.6	10.0	20.6
11.12.70	27.26	18.6	12.8	7.2	3.8	13.2
21.01.71	43.2	28.8	21.2	11.0	--	11.0
13.02.71	84.0	69.0	50.0	29.8	--	30.8
17.09.71	39.6	21.6	--	--	--	7.2
07.12.71	50.4	25.8	17.6	10.0	--	10.2
07.01.72	14.4	7.8	6.4	4.2	2.6	5.8
25.08.72	24.0	15.6	11.2	--	--	5.6
21.09.72	26.4	13.2	9.2	--	--	4.6
29.10.72	4.8	3.6	3.2	2.8	2.2	5.0

4.3 Runoff generation

Since the catchment is composed of massive crystalline and metamorphic rocks, the infiltration into hillslope rock units is assumed to be negligible, and the initial infiltration rate into channel alluvium will be very high. The flow routing is based on the following assumptions:

- 1- The rainfall excess generated in each cell flows out in one direction along the steepest slope (D-8 algorithm).
- 2- The routed cell flow does not interact or affect any flows from other cells sharing the same flow path. Therefore, the calculated flow velocity at a given location will be constant as it is based on a fixed hydraulic radius at a given cross section.
- 3- The rainfall component of the model is computed according to the biggest storm event reported in table 1 having 30 mm/h intensity, a spatially uniform

distribution over the whole catchment and a duration of 1 hour.

Therefore, the potential discharge (D) generated at each time-area zone will be given by the equation;

$$D \text{ (m}^3\text{/s)} = \text{area (ha)} \times \text{rainfall intensity (mm/h)} / 360$$

A time-discharge diagram has been created to show the cumulative drainage area flowing to the outlet within a specified time of travel (Fig 5). It is constructed by summing up the travel time zones draining to the outlet. According to this figure the peak discharge of more than 500 m³/s would be expected to arrive at the outlet 12 hours after the start of the rainstorm.

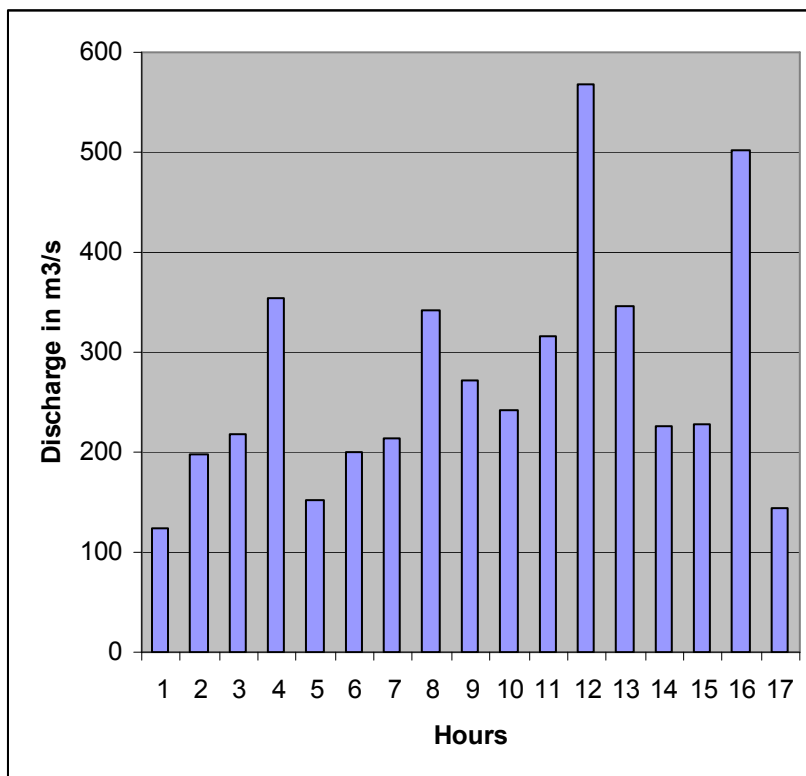


Fig. 5: Time-discharge diagram

According to the findings of the report on the Aranah Watershed (KSA Ministry of Public Works and Housing, 2002) a discharge of this volume would lead to a depth of flood water in the channel passing the bridge of road no. 8 in Arafat of 1.25 m. As the channel of the wadi has been deepened to more than 4 m such a discharge would not cause any problem at this point. However, if the furthest point in the Aranah Watershed requires only 3 hours for its discharge to reach the outlet as suggested in KSA Ministry of Public Works and Housing (2002) and a shift of the peak discharge cause by transmission loss would be taken into consideration as well the picture might change.

5 DISCUSSION

This work is based on a deterministic approach. Although literature available for this special location has been studied no field work has been carried out yet. Instead, field data of a survey in a very similar environment (Egypt) have been used. Fieldwork that is planned to be carried out should cover precipitation patterns in the watershed and runoff parameters.

Naturally, any analysis cannot be more accurate than the data it is based on. Although no metadata for the 10 m grid was available most likely it was produced by interpolating digitized contour lines. This became obvious after slope had been computed: Especially, in very flat areas sudden changes in the slope angles occurred letting the original contour lines "shine through". This led to unrealistic high velocity values for some of the channel areas. Compared with the whole study area, areas with such spots having wrong values are relatively small. Therefore, the impact onto the computation of the overall discharge at the outlet of the watershed should not have been too high.

Especially, in the valleys many structures like dams, elevated roads, etc. are man made. In order to take these structures into account while working on hydrologic modeling highly accurate and up-to-date digital elevation models (DEM) are needed. The model used in this study (10 m spacing) certainly does not meet such criteria. As more accurate models are currently not available ways to improve this situation have to be found.

A weakness of this study is the missing integration of spatially and temporally variable transmission loss as channel velocity had not been computed separately. Transmission loss depends on the active channel cross sectional area, and the physical characteristics of the alluvium, and hence, the infiltration rate. At the beginning of a flow, only a fractional portion of the total bankfull channel cross section is conveying flow. Then at bankfull stage, the complete cross-section is inundated. Following the peak flow, the active cross sectional area is reduced. Thus, the active channel cross-sections have to be considered spatially and temporally variable over the catchment.

6 Conclusions

In this paper a methodology has been presented to compute discharge for watersheds with reasonable amount of resources. Although field work is required comparison with one reference indicates that the results presented in this paper are realistic.

Future works should focus on the production and processing of DEM with higher precision and accuracy. Furthermore, transmission losses in channels have to be integrated into the computation of the total discharge of a watershed. Then, flood risk planning based on GIS techniques will be much more precise than traditional methods using methods that do not take into account the spatial variability of hydrological parameters.

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