Modeling of Hill Torrent Using HEC Geo-HMS and HEC- HMS Models: A Case Study of Mithawan Watershed

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Abstract

A hydrological model using HEC Geo-HM and HEC-HMS was created for Mithawan watershed in Punjab province of Pakistan. A watershed model delineated using DEM's and HEC-Geo HMS was exported into the HEC-HMS model for estimation of run-off. One of the major sources of water is the Hill Torrents which emerges from the mountains and diverted towards Agriculture fields for irrigation. Rain fall run-off model of Mithawan catchment developed using HEC-HMS model at different return periods by using frequency analysis. The 170 Cumecs discharge of Kachhi Canal (passes through catchment of Mithawan) is beneficial for the agriculture of Baluchistan province only if exact estimation is ensured by using different techniques. Result of the study revealed that peak discharge of Mithawan at Darraha was 2238, 2653, 3060 Cumecs at 25, 50 and 100 years return period respectively. It is concluded that this study will be helpful in developing the Agro based community in the Hill torrents affected areas and for the design of cross drainage structures & storage reservoir at different locations. The same methodology has been adopted for other water shed in hill torrent affected areas to save the entire community from the damages of floods as well as to upgrade the living standard of entire humanity.

Key Words: HEC Geo-HMS, HEC-HMS, Arc-GIS, Hydrograph, Hyetograph, hill torrents, rainfall, Digital Elevation Model (DEM), Frequency Analysis.

Introduction

Hill Torrents contributes about 65% (517,461 Sq. Km) area of Pakistan and almost entire area of Baluchistan province (Nawaz and Han 2006). The pattern of rain fall in D.G. Khan hill torrent areas is very erratic as during a year with heavy rain fall in the catchment, generating intense run-off may be followed by a drought year with low or no rainfall. This zone falls in arid to semi arid region as average annual rain fall is of the order of 400 mm.

Mithawan Hill Torrent leaves the mountains near village ChotiBala and fans out in pachad area into a number of branches. These are Northern Branch, Southern Branch and Ganahar Branch. After the utilization of sufficient amount of flood water for irrigation from these branches, the remaining flows in Kachhi Canal. Some damages scenarios of Kachhi canal because of Mithawan hill torrent is shown in Figure 1, taken from Google Earth.

Figure 1: Damages of Kachhi Canal due to Mithawan hill torrent flow.

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Kachhi Canal is a project of National interest to supply 170 Cumecs water to Baluchistan province for irrigation purposes. Management of flood during low flows is not an issue as this water easily being consumed in pachad area. The real problem starts during high flows as these flows are above the bearing capacity of pachad area. Being a contour channel, the Kachhi canal irrigates its left side. D.G. Khan Canal also has its command area on the left side. Whereas, no arrangement is available or proposed to irrigate the right bank side. The hill torrents also emerge from the right bank side of the canal, passes through canal and fall in the Indus River.

The storm hyetograph can be developed by using hourly rainfall data, in case of non availability of hourly data the synthetic storm hyetograph can be developed as the U.S department of agriculture, Soil Conservation Service SCS (1986) uses 6 hours and 24 hours duration storm for the development of synthetic storm hyetographs for United States. There are four 24-hour duration storms, called Types I, IA, II and III and they also give the geographic location within the United States where they should be applied.

WirasatUllah Khan (1986) analyzed the daily rainfall record for a large number of stations in Balochistan Pakistan. He carried out separate analyses on 1 hour rainfall records at Quetta, which was the only station with at least ten years of record. He developed depth-duration-Frequency DDF relationship in two steps. Depth-frequency relationship was established with daily recorded historic data by taking average for frequency rainfall of required return period.

The alternating block method (Chow et al, 1988) is a simple way of developing a design hyetograph from an intensity-duration-frequency curve. The design hyetograph produced by this method specifies the precipitation depth occurring in n successive time intervals of duration Δt over a total duration $T_d = n\,\Delta t$. After selecting the design return period, the intensity is read from IDF curve for each of duration's Δt, $2\Delta t$, $3\Delta t$…, and the corresponding precipitation depth found as the product of intensity and duration. These increments, or blocks, are reordered into a time sequence with the maximum intensity occurring at the center of the required duration Td and remaining blocks arranged in descending order alternately to the right and left of the central block to form the design hyetograph.

Physically based hydrological model using GIS software package is the recent development of HEC-Geo HMS by the US Army corps of Engineers Hydrological Engineering Centre (HEC).Digital Elevation Model (DEM) can be easily download and used in HEC- Geo HMS package for watershed delineation based on topographic data. HEC-Geo HMS and HEC-HMS collectively used for the prediction of runoff from available rain fall data. Hoblit and Curtis (2001) concluded that the HEC-Geo HMS and HEC-HMS could be used to create hydrological models for most of the watershed in the United States. These models required physical data as input which were freely available in USA.

Alemaw et.al, (2003) mentioned that GIS has the capability of handling large amounts of spatially detailed information derived from various sources such as remote sensing and ground surveys. With the advent of increasing computing power and GIS techniques, physical-based hydrologic modeling has become important in contemporary hydrology for assessing the impact of human intervention and/or possible climatic change on basin hydrology and water resources.

Hashmi (2005) used HEC Geo-HMS and HEC-HMS for rainfall-runoff modeling for Kaha Hill Torrent watershed D.G.Khan district. Calibration of HEC-HMS model carried out using daily historic rainfall data of Murange rain gauge station compared well with observed flood peak at Darraha gauging station.

Nawaz and Han (2006) concluded that if the proper storage facility and modernized structures are provided in hill torrent affected areas then not only the flood is controlled but also the drought conditions can be mitigated and the crops yield can be enhanced. Roy et al (2013) concluded that the stream flow simulation performed well with calibrated HEC-HMS model in different watersheds of Subarnarekha river basin and other hydro meteorologically similar river basin.

Estimation of peak flood has been carried out by using HEC Geo-HMS, HEC-HMS by extracting the data from Arc-GIS for the management of flood water in Mithawan Catchment. By using better management techniques not only save the entire community from the damages of floods but also manage the water for productive use.

Methodology

The Study Area

Mithawan hill torrent situated in District Dera Ghazi Khan of Punjab Province of Pakistan between longitudes 69^o 10' E to 70^o 49' E and latitudes 28^o 27' N to 31^o 20' N, have almost polygonal shape watershed, drains from an area of 710 square kilometer from an elevation of 2107 meter above mean sea level (AMSL). The study area map of Mithawan Watershed prepared in Arc-GIS is shown in Figure 2. Kachhi Canal off-takes from Taunsa barrage in the river Indus in Punjab Province and irrigate about 713,000 acres of cultivable command area in Kachhi plain of Baluchistan province of Pakistan. Highly silted water of Mithawan directly hit Kachhi canal, breach its banks and enter in canal, disturb canal supply, damage infrastructure, roads, crops and effect live stock and humans also. The safe drainage of Mithawan hill torrent flow at Kachhi canal is necessary for efficient use of canal water.

Data Utilized

Rainfall Data and Discharge Data

Hydro-meteorological and physiographic data for the Mithawan Hill Torrent was collected and analyzed using HEC Geo-HMS and was used as an input to the HEC-HMS. Hourly Rain fall data of Barkhan Rain Gauge station (longitudes 69^o 50' E and latitudes 28^o 90' N) was collected from PMD , Stream flow data of Mithawan Stream Gauge at Darraha was collected from Irrigation Department Govt. of Punjab.

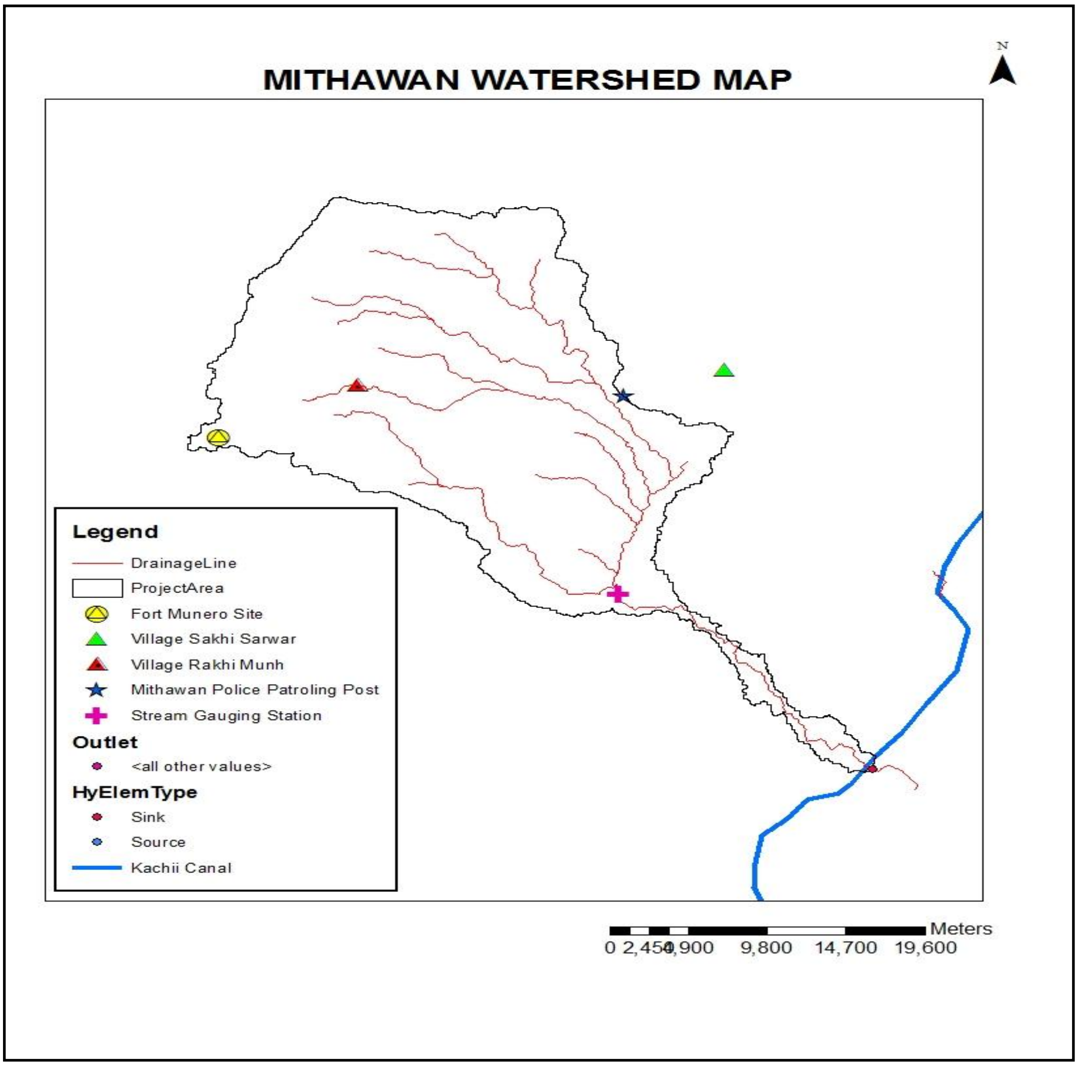

Figure 2: Location map and Catchment area of Mithawan hill torrent.

Digital Elevation Model

The Shuttle Radar Topography Mission (SRTM) is a project of National Aeronautics and Space Administration (NASA). The SRTM maintained Digital Elevation Data (DEM) on a near-global scale is collected to generate the most complete high-resolution digital topographic database of earth. These will cover digital topographic data for 80% of the earth's land surface, with data points located every 90 x 90 meters on a latitude / longitude grid. 30 x 30 meters DEM is also freely available but this data set does not verify the stream network of Mithawan Watershed. Therefore, 90 x 90 meters dataset have downloaded from internet and use in this study.

Terrain Pre Processing

The terrain preprocessing (TPr) is the first step in using HEC Geo-HMS. A terrain model is used as an input device that describe the drainage patterns of the watershed with eight additional data sets, that allows for stream and sub-basin delineation. These eight additional data sets are Fill Sinks, Flow Direction, Flow Accumulation, Stream Delineation, Stream Segmentation, Catchment Grid Delineation, Catchment Polygon Processing, and Drainage line processing. The working of Geo-HMS and HEC-HMS in pictorial form has been shown in Figure 3 (a) and Figure3 (b). The results acquired after Geo-HMS are the catchment area of each sub-basin, slope of each sub-basin, flow length, which will help us for the calculation of "Time of Concentration". Nine sub basins, four reaches, four junctions and one outlet have been finalized in Geo-HMS analysis.

Cross Section Value from Geo-HMS for Four Reaches

There are four reaches in study area i.e. R1, R2, R3 and R4 as shown in Figure3 (b), whereas at least one cross section is required as an input for HEC-HMS. The procedure includes click on "line tool" in Arc GIS and drawing a line from left to right perpendicular to river reach. Observe the graph between distance on X-axis and raster value on Y-axis and this data may be extracted in Excel format for analysis. In the next step insert graph of the cross section and adjust it in "eight points" (as per requirement of HEC-HMS model) i.e. one point each on X-axis and Y-axis in such a way that its original shape remain unchanged, as there are more than eight values of each cross section. Similarly four cross sections, one from each reach needs to be extracted and adjusted. These cross sections are then used in HEC- HMS software as input for model.

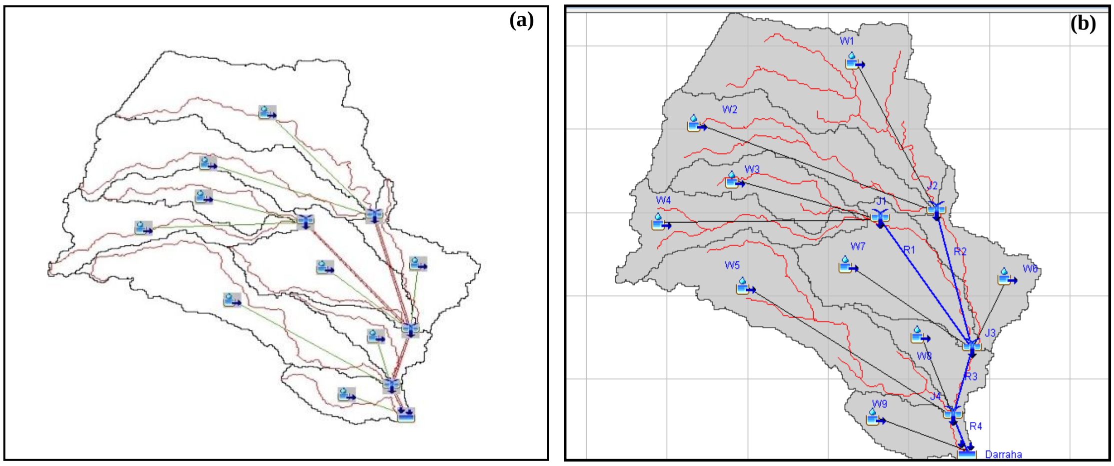

Figure 3:(a) Final Shape of HEC Geo-HMS**(b)** HEC-HMS extracted from Geo-HMS.

Frequency Analysis

One day annual maximum rain fall data of 81 years at Barkhan rain gauge station for the period (1911-1940, 1963-2013) has been used to carry out frequency analysis. Gumble's extreme value Type-I distribution has been used for this analysis. Plotting position has been computed by Weibull's formula as mention below in Equation (1).

$$T_r = \frac{1+n}{m} \qquad \text{---------------------------- (1)}$$

Where "Tr" is the Return Period, "n" is total number of events and "m" is the rank of rainfall event.

The steps involved in carrying out frequency analysis by using worksheet are given below.

i) The daily rainfall data of the required rain gauge station is collected and the maximum value of rainfall for each year is selected to put in the column no.1 of the said worksheet.

ii) In the second column of the worksheet, the annual maximum rainfall values are arranged in the descending order.

iii) In the third column, the ranking of the data is made by giving a number to each value up to no of years of records.

iv) The return periods to be computed are given in the fourth column, which contains Weibull formula. For annual maximum series, Weibull formula (Equation 1).

v) Gumble's Constant factor 'K' in the fifth column is computed by the formula given in equation 2 mentioned below.

vi) $K_T = -\frac{\sqrt{6}}{\pi}\left[0.5772 + \ell n\left\{\ell n\left(\frac{T}{T-1}\right)\right\}\right]$ ----------------------(2)

vii) The regression analysis is carried out by using the worksheet option of regression. The following is the flow diagram of regression analysis.

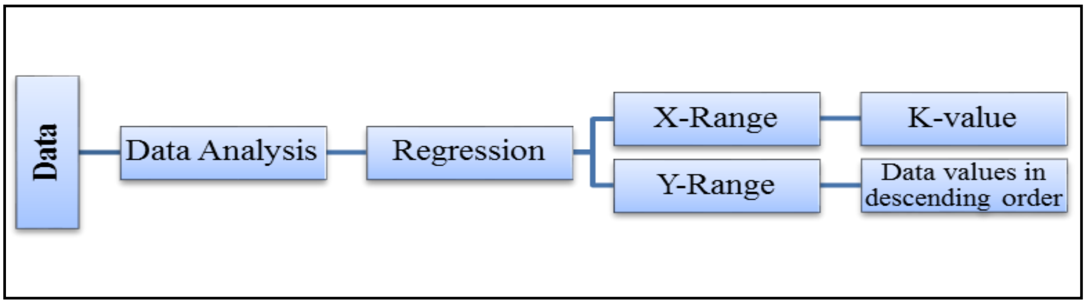

Figure 4: Flow Diagram for Regression Analysis

The summary output of regression analysis gives the coefficient of correlation R2. After regression analysis an extrapolated representative line of data predict the required return period values by taking 'K' values of data along x-axis and rainfall values at Y-axis over a graph paper, which is also a part of worksheet.

vii) The rainfall value against the required return period is computed in the sixth column by formula mentioned below in the form of equation 3.

y = mx + C ----------------------------(3)

Where,

Y = magnitude of hydrologic event x = x-variable

m = Frequency Factor c = Intercept

HEC-HMS Model

Methods used to compute and model the floods in the HEC-HMS software are discussed here. Open HEC-HMS and import data from Geo-HMS. The HEC-HMS will showing all the sub-basins, junctions, reaches. Rename all the sub-basins, junctions and reaches conveniently as shown in Figure3 (b) above.

Time Distribution of Design Storm

Total storm rainfall determines the magnitude of flood, while its pattern (estimated on hourly rainfall) gives the shape of hydrograph. The relationship between time and rainfall in Equation 4 is used.

$$P_t = \left(\frac{t}{24}\right)^n \qquad \text{------------------------------(4)}$$

Where "Pt" is ratio of rainfall at time "t" with 24 hr rainfall, "t" is time in hours and "n" is an exponent depending on hourly rainfall pattern.

A detail study regarding selection of Design storm pattern for design flood estimation in Baluchistan has been carried out by WirasatUllah Khan 1980 . For the study WirasatUllah Khan used the hourly data of whole Baluchistan and estimated an 'n' value of 0.2 for Baluchistan. The 55% drainage area of Dera Ghazi Khan Hill Torrents is in Baluchistan. So, it found appropriate to apply the '0.2' value of 'n' for design storm pattern.

Loss Method Selection

Excess rain fall can be estimated by using loss method. In HEC-HMS model loss methods, initial constant, SCS curve number, gridded SCS curve number, exponential, Green Ampt, one-layer deficit constant method and smith parlange can be used to compute excess rainfall. The SCS curve no method was selected as a loss method for computations of excess rainfall. This is the latest method for loss calculation and is widely used in USA and Pakistan. This model has been updated by panel of experts on yearly basis whereas other models do not have such facility.

Selection of US SCS Curve No. (CN)

The Soil Conservation Services SCS curve number (CN) model estimates precipitation excess as a function of cumulative precipitation, soil cover, land use and antecedent moisture using following equation 5.

$$P_e = \frac{(P-I_e)^2}{P-I_a+S} \qquad \text{------------------------------(5)}$$

Pe = Accumulated Precipitation, P= Actual rainfall depth,

S= Potential maximum retention, Ia = The initial abstraction

Direct run-off has been computed by using SCS procedure of curve number i.e. Single storm has been selected to compute the direct run-off. Curve Number has been estimated using the curves which were prepared for different soil cover combinations. The curve number of Mithawan hill torrent has been estimated as 82 for AMC II condition. If five days antecedent rain fall is over 1.1 inches in dormant season, it will be considered as AMC-III conditions. Mithawan catchment has been analyzed as AMC-III condition after viewing all rain fall events of about 80 years and the curve number of 91 has been estimated.

Selection of Soil Type

SCS divides soil types into four major hydrological soil groups denoted by the letters A through D. The soil of the Mithawan catchment area to be assessed as a mixture of soil C (40%) and soil D (60%). Same procedure has been adopted by V. Chow (1964).

Transform Method

Following Seven different models were used for transforming excess precipitation into surface runoff.

1. User Specified Unit Hydrograph model,
2. Parametric and Synder unit hydrograph model,
3. Synder Unit Hydro graph model,

4. SCS unit hydrograph model,
5. Clark unit hydrograph model,
6. Modclark model,
7. Kinematic Wave Model

SCS unit hydrograph model has been selected as transform method. The parameters required for transformation are discussed as under:

Lag Time

The time from center of mass of excess rainfall to the hydrograph peak is the lag time, which is also referred to as basin lag is computed using Equation 6.

Lag time = 0.6 Tc minutes ------------------------------(6)

whereTc = Time of Concentration

Time of Concentration

This is a time required for a rainfall drop to reach from the remotest point in a watershed to the outlet. From the hydrograph it may be accessed as the time from the end of rainfall to the inflection point of a recession curve.

Chow and US Soil Conservation services 1973 have confirmed Kirpich formula the most authenticated for the calculation of "Time of Concentration" which is written in Equation 7

$$T_c = \frac{L^{0.77}}{7700xS^{0.385}} \quad \text{----------------------------- (7)}$$

Where

Tc = Time of concentration (hours),
L = Length of the longest stream (meters)
S = Slope of the longest hydraulic length (m/m)

Muskingum Cunge Method

Muskingum model is very common for channel routing and easy to use but it includes parameters that are not physically based and thus difficult to estimate. An extension of Muskingum-Cung model overcomes these difficulties. The model is based on the following form of continuity equation No. 8 (q_L is the lateral inflow).

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial X} = q_L \quad \text{------------------------------(8)}$$

Calibration of Model

HEC-HMS model has been calibrated with Mithawan at Darraha stream gauging station. The peak discharge on 28 June 2011 was 8395 cfs. The specified hyetograph method of metrological model has been used. In the model component time series data, create all rainfall gauges used in study. Incorporate hourly rainfall data of 28 June 2011 (total one day 34mm) of Barkhan rain gauge in the model. Now in the metrological model component assign Barkhan rain gauge to each sub basin. Compute the model at Run-1 and the resultant peak at Darraha is 8,994 cfs. These results are within the permissible limit.

Add all the data in the model as explained earlier except "Time series data", in this case the actual rainfall of 28 June, 2011 synthetically analyzed on hourly basis will be used. The results will be compared with the actual discharge measured at MithawanDarraha.

Resultsand Discussion

The results of pre processing of terrain data are shown in Figures 5 (a) and 5 (b). The resultant Raw DEM of Mithawan is shown in Figure 6 (a) and Slope in percent of the study area is shown in Figure 6 (b).

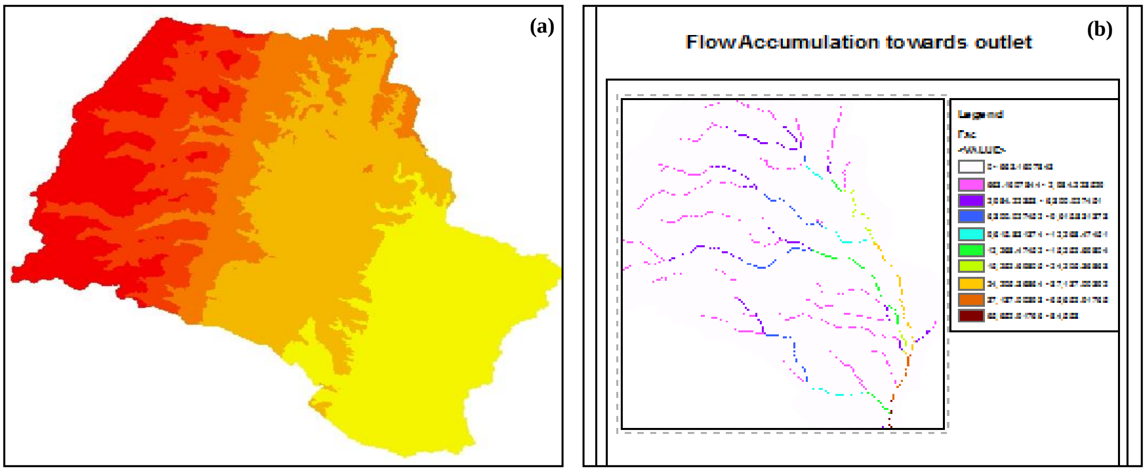

Figure 5:(a) Fill Sinks **(b)** Flow Accumulation

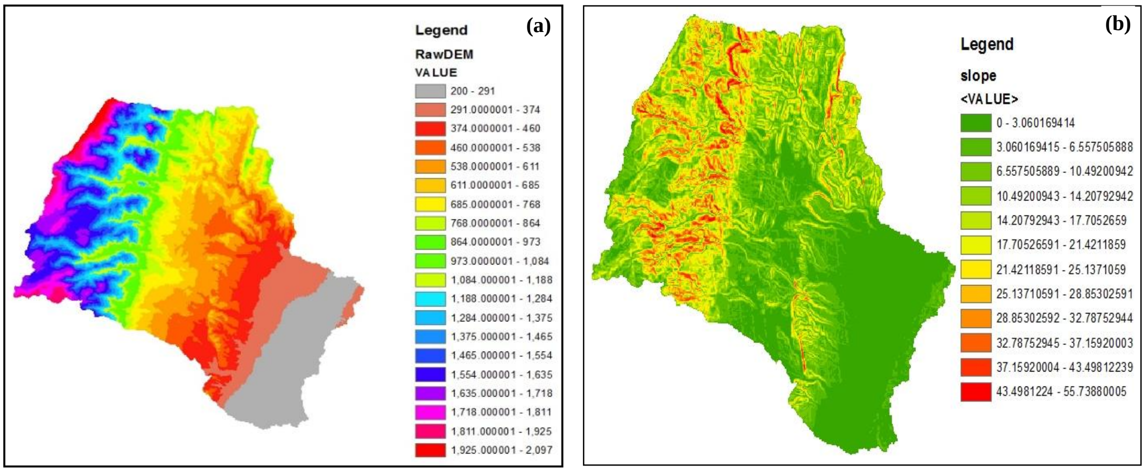

Figure 6:(a) Raw DEM and Elevations**(b)** Slope Difference of catchment

The specifications of each sub basin extracted by using HEC Geo-HMS are shown in table-1, which clearly indicates that total catchment area of Mithawan is about 271 Sq. Miles whereas, NESPAK (1998) mentioned that total catchment area of Mithawan hill torrent is 274 Sq. Miles.

Table 1: Specification of Sub-Basins

Sr. No.	Sub Basin Name	Catchment Area (Miles²)	Lag Time (minutes)	Time of Concentration (hrs)
1	W-1	54.61	141.04	3.92
2	W-2	35.88	120.03	3.33
3	W-3	17.07	73.83	2.05
4	W-4	22.24	97.57	2.71
5	W-5	41.90	154.95	4.30
6	W-6	41.89	115.18	3.20
7	W-7	12.20	109.49	3.04
8	W-8	31.80	102.73	2.85
9	W-9	13.05	13.055	3.44

Frequency Analysis

The results of frequency analysis using Gumbel Extreme value Type-1 distribution have been shown in Figure 7. The rain fall estimated at 25 year return period at Barkhan rain gauge station was 98 mm. The rain fall event of 194 mm in the year 1982 has been treated as outlier in the data set and not include in the analysis.

Hydrograph

The resultant hydrograph at 25 year return period is shown in Figure 8. Peak discharge calculated with HEC-HMS at 25 year return period is 2238 Cumecs. This result is very close to the findings of NESPAK (1992) which concluded that peak discharge is 2208 Cumecs. Result of HEC-HMS at different return periods is shown in table 2.

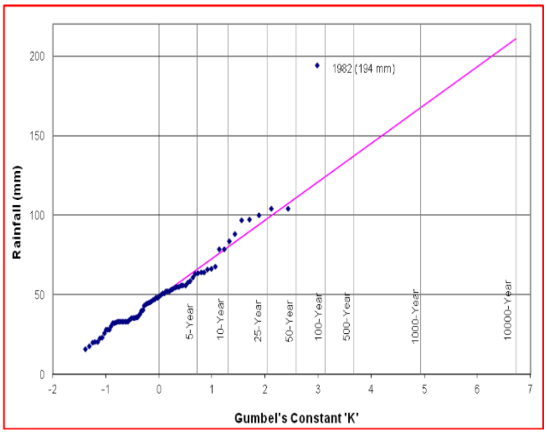

Figure 7: Frequency Analysis rainfall data

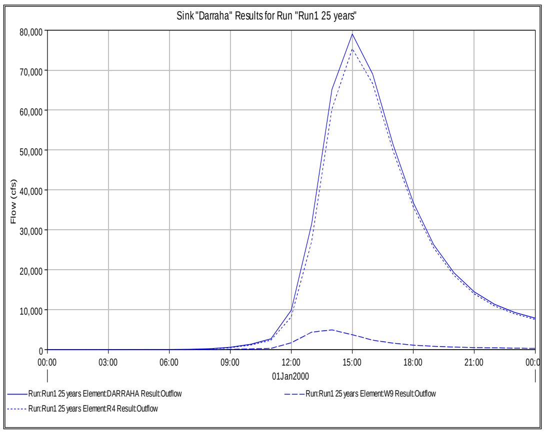

Figure 8: Resultant Hydrograph at 25 year Return Period.

Table 2: Results of HEC-HMS at Different Return Period.

Return Period	Rainfall (mm)	Discharge (Cfs)
200	137	121,704
100	124	108,068
50	111	93,707
25	98	79,045

Calibration of Model

Rainfall data of 28 June 2011 have been used for calibration (34 mm). The results are within the permissible limit as compared the actual 8395 cfs. Same procedure has been adopted by Hashmi in 2005 for kaha hill torrent in D.G. Khan District of Pakistan and D. Roy et al. while studying Subarnarekha river basin. The results of observed Discharges at Darraha and Computed discharges with model are shown in Figure 9.

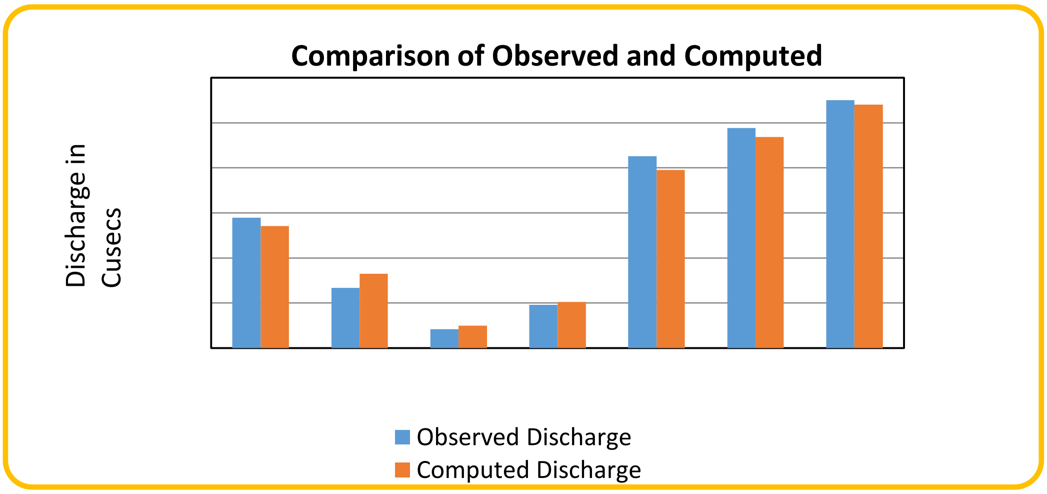

Figure 9: Comparison of Computed and Observed Dishcarges.

Conclusion

Arc GIS is a very sophisticated and time saving tool to extract raster values and for hydrological analysis of any catchment. The combination of HEC Geo-HMS and HEC-HMS use for the better estimation of run-off from rainfall data of Mithawan Watershed. Peak discharges available at Darraha at 25, 50 and 100 years return periods were estimated as 79,045 Cusecs, 93,707 Cusecs and 108,068 Cusecs respectively using GIS, HEC Geo-HMS and HEC-HMS. The accuracy of model is very effective as results of the peak discharges are within the permissible limit i.e 7-10 %, which is acceptable. HEC-HMS uses a finite difference scheme that ensures accuracy and stability. Accuracy refers to the procedure to reproduce the terms of differential equation without introducing minor errors. The range of feasible, acceptable parameters is limited. For example a Muskingum “X” parameter that is less than 0.0 or greater than 0.5 is un-acceptable, no matter how good the resulting fit might be. Further added, the performance of the model regarding current scenario is very effective and also recommended for other hill torrents in D.G. Khan zone having same catchment characteristics.

Recommendations

Topographic survey of the area must be conducted before the final strategy for the exact estimation of different parameters. At least 4-5 rain gauges must be installed in Mithawan Catchment to meet the international standards and at least one rain gauge must provide to estimate hourly rain fall data.

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