INTERNATIONAL JOURNAL OF ADVANCE RESEARCH, IDEAS AND INNOVATIONS IN TECHNOLOGY

ISSN: 2454-132X
Impact Factor: 6.078
(Volume 7, Issue 2 - V7I2-1280)
Available online at: https://www.ijariit.com

Extraction of flood hydrographs for a hilly terrain region using open source spatial data and meteorological parameters using hydrological modeling – A case study with HEC-HMS

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ABSTRACT

To estimate Rainfall-Runoff process popularly used watershed model is Hydrologic Engineering Centers–Hydrologic Modeling System (HEC-HMS), which is generally used to estimate the basin's hydrological phenomenon caused due to precipitation. It helps to predict the various hydrologic responses to watershed management and to have a best understanding of the effect of these practices. It is specific from the spacious study of the literature that the studies on relative assessment for hydrologic simulations are finite in developing countries including India. This case study dealt with hydrological modelling software of HEC-HMS is used to simulate Rainfall-Runoff process to derive hydrograph at the outlet of 'Karcham' catchment, Himachal Pradesh, India. In this study, SCS curve number method is applied to determine loss model as a major component in Rainfall-Runoff modeling. To enumerate runoff volume, peak runoff rate, and flow routing methods SCS-Curve Number, SCS-Unit Hydrograph, and Muskingum routing methods are choosen respectively. The simulated peak flood hydrograph obtained with open source spatial and meteorological data at the outlet of 'karcham' watershed was 5663.6 m³/s. The predicted discharge is lesser than by 1.4% to the simulated discharge. The results of the present study indicate that HEC-HMS is a tool applied to derive flood hydrographs with open source spatial and non-spatial data in absence of virtual data to achieving the various objectives.

Keywords: *Hydrograph, Runoff, Meteorological Model, Peak Discharge, Open Source Data*

1. INTRODUCTION

The Hydrologic Modeling System is designed to simulate intact hydrologic processes of watershed systems. It incorporates much traditional hydrologic analysis. In that cases, evapotranspiration, infiltration, percolation and other locomotion and storage should be tracked over long period of time and detailed accounting model is required. This model computes and reports the peak volume or the hydrograph of watershed runoff. The components which will predict runoff are represented in detail and other components are omitted. For example, in a common application, HEC-HMS omits any detailed accounting of movement of water vertically within the soil layer. Infiltration, unit hydrographs and hydrographic routing. It encloses procedures necessary for continues simulation including evapotranspiration, snow melt and soil moisture accounting. Forward capabilities are also provided for gridded runoff simulation using the linear cursory-distributed runoff transform. Supplemental analysis tools are provided for parameter estimation, depth area analysis, flow forecasting, erosion and sediment transport and nutrient water quality.

The flood damages will be increased over the years due to population growth and socio-economic development, and the climate change due to the global warming effect. Therefore, it is necessary to define methodology to predict the flash floods in this region, to protect the city against inundation. The widely used approach to determine flash flood occurrence and the relationships between rainfall and runoff data is the Hydrological Modelling which accommodate the hydrological process to estimate streamflow over river basins and assist forecasters in making a comparison between simulated streamflow and observed flooding, to predict and understand the hydrological process. Hydrological studies are often aimed at establishing Rainfall-Runoff relationships [1]. Rainfall-Runoff models can be categorized according to the model type. According to CLARKE (1973) [2] and AMBROSE (1998) [3], the hydrological models can be classified into four main categories: deterministic or stochastic, global or semi-distributed, kinematic or dynamic and finally empirical or conceptual. The selection of the model depends on the watershed and the objective of the hydrological forecast in the watershed. In this study, the conceptual approach is adopted for the hydrologic modelling, we use a semi-distributed hydrologic model of HEC-HMS (Hydrologic Engineering Center–Hydrologic Modelling System) was developed by US Army Corps of Engineers in order to investigate the rainfall-runoff interactions in the 'Karcham' watershed of Northern Ghats of Himachal Pradesh. It is applicable in diverse geographic areas for solving the widest possible problems. Many scientists have conducted important hydrologic studies using HEC-HMS model, which proved its ability to simulate and forecast streamflow. An example Sinthayehu (2015) [4] used HEC-HMS model employing Sinder Unit Hydrograph and Exponential Recession method to simulate the runoff of Upper Blue Nile River Basin. Norhan et al. (2016) [5] modelled rainfall-runoff relations using HEC-HMS in arid environment at Wadi Alaqiq, Madinah, Saudi Arabia. Sampath et al. (2015) [6] modelled the rainfall-runoff relations using HEC-HMS in tropical catchment in Sri Lanka. Meiling et al. (2016) [7] employed the HEC-HMS to simulate runoff in the semi-arid region of northwestern China. Laouacheria and Mansouri (2015) [8] used HEC-HMS model by employing frequency storm to simulate the runoff in a small urban catchment in the North-East of Algeria. Mokhtari et al. (2016) [9] modelled the rain-flow by HEC-HMS in watershed of Wadi Cheliff–Ghrib in the North of Algeria. Skhakhfa and Ouerdachi (2016) [10] used HEC-HMS for estimating floods of short duration in Wadi Ressoul watershed in the North-East of Algeria. Walega (2013) [11] reconstructed a flood event in an uncontrolled basin by using HEC-HMS model. This paper presents a methodology of deriving flood hydrograph using HEC-HMS program integrated with open source data. This open source data in the form of spatial and meteorological data. The spatial data in the form of DEM and meteorological parameter in the form of Rainfall utilized in semi-arid environment for a return periods of 500 years in 'Karcham' watershed situated in hilly terrain region of Himachal Pradesh, India.

2. MATERIALS AND APPLIED METHODOLOGY

The main material required in the form of spatial and non-spatial data to perform the model to achieve the object. The basic input data required to derive topographic characteristics of the watershed obtained in the form of spatial data of Digital Elevation Model (DEM). The other topographic spatial data is LandUse/LandCover (LU/LC) map and soil map. These two spatial maps required to estimate various hydraulic parameters in basin models of HEC-HMS modelling. These basin models used to estimate the losses in the sub-basins. To make ready of meteorological model, the other point data of rainfall data is required to perform the simulation. The brief description of materials used and its corresponding pictorial representation as follows at Kinnaur district of Himachal Pradesh.

2.1 Spatial Data - Digital Elevation Model (DEM)

The Advanced Land Observing Satellite (ALOS) was launched on January 24, 2006 by the Japan Aerospace and Exploration Agency (JAXA) and was operational until May 12, 2011.The satellite provided high quality, Earth observation data for topographical mapping, disaster and environmental monitoring and climate change studies. The Phased Array type L-band Synthetic Aperture Radar (PALSAR) is an active microwave sensor using L-band frequency to achieve cloud-free and day-and-night land observation. The development of the PALSAR is a joint project between JAXA and the Japan Resources Observation System Organization (JAROS). An ALOS PALSAR searchable data archive is maintained at the US Geological Survey Earth Resources Observation Science (EROS) Center [12]. Data may be downloaded by USGS personnel after registering with the Americas ALOS Data Node (AADN) located at the Alaskan Satellite Facility (ASF). In this study the ALOS-PASAR DEM of 12.5 m resolution data downloaded, processed and clipped to the area of extent as shown in Fig.1

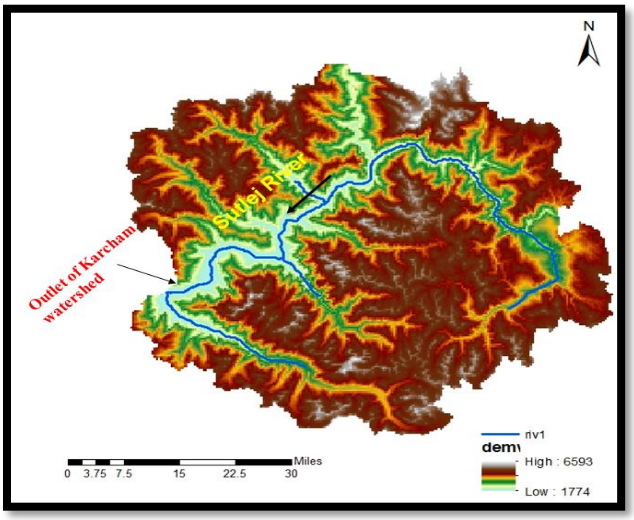


Fig. 1: Digital Elevation Model of 'Karcham' catchment

The first and foremost data required to derive catchment and its characteristics using DEM. The DEM derived sub-basins are useful to incorporate all spatial and meteorological parameters to proceed further modelling aspects with hydrological modelling. The maximum elevation value is 6593 m and minimum elevation of 1774 m occurred at the outlet of catchment as shown in figure 1.

2.2 Spatial data- LandUse/LandCover & Soil Maps

The LandUse/LandCover (LU/LC) data was download from SWAT datasets for India [13]. The total area of the 'Karcham' watershed covers about 5800 km2. The main dominant lands in the basin are the snow (56%) the forest land (26%) grassland/shrubs/woodlands (14%) barren/waste land/built-up (4%) as shown in Fig-2(a). The other major factor influence losses of the basin property are the soil type. The main object of Landuse/Landcover map and soil maps are to found Curve Numbers of the watershed. The Hydrological Soil Groups (HSG) were categorized to different Landuse/Landcover maps based on the soil verities covered in the basin. The HSG by overlaying the soil and Landuse/Landcover map. The area with a particular soil type and land use are ascribed a CN, then it is multiplied by the area it covers and its weighted value is found out. The weighted Curve Number was generated using Landuse/Landcover map, Hydrological Soil Group map and standard curve number for Indian conditions. The individual CN values are computed for all the sub-basins of 'Karcham' watershed and used for computation of the hydrologic parameters.

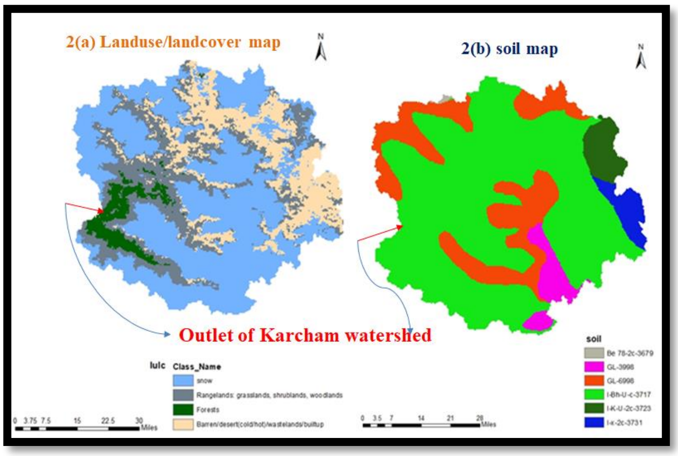


Fig. 2: Landuse/Landcover Map (2a) and soil map (2b) of 'Karcham' Watershed

For this study, FAO/UNESCO soil data were used with projection based on Universal Transverse Mercator (UTM) and 90 × 90 m resolution. The FAO digital soil map of the world is the digitized version of the FAO-UNESCO soil map of the world [14]. There are 6 verities of soils distributed in the 'karcham' watershed. The major soil units are Humic Cambisols of 67% which are belongs to Loamy texture of hilly terrain slope type soils. The other major type covered Glaciers of 23% of the catchment. Eutric Cambisols are the least verity of soils of medium texture loam soil covered in hilly terrain region of the catchment. Lithosols and Haplic Kastanozems are other kind of soils covered in the 'Karcham' catchment. All the soil having Loam texture of medium texture covered in hilly region. Soil types and their distribution are extremely related to the nature of geomorphic unites.

The combination of these spatial data sets of LandUse/LandCover (LU/LC) map and soil maps are important to derive non-spatial data of Curve Numbers (CN). This CN values are used as input data in SCS-CN loss model to estimate losses in each sub-basin of 'Karcham' watershed.

2.3 Non-Spatial Data-Point Rainfall

Daily Rainfall data collected from NASA-POWER web portal [15] at each sub-basin about 36 years from 1985-2020. The time series data and flow data not available from different open source web sites for validation of the flow volume. The details of the rainfall data collected in 4 sub-basin locations are shown in Table 1.

Table 1: Rainfall-Data locations and details

Station Name	Longitude	Latitude	Elevation	Selected Period
Sub-basin 1	78.750	31.690	4675.97	1985-2020
Sub-basin 3	78.437	31.691	4333.18	1985-2020
Sub-basin 4	78.715	31.379	4379.96	1985-2020
Sub-basin 6	78.475	31.397	3412.69	1985-2020

The region is characterized by a semi-arid climate with dry and hot summers where rainfall is almost absent and with high evaporation. Winters are cool and sometimes very cold, with often rain intensities in autumn. The series of data available from 1985-2020 in the watershed sub-basins. The average and mean annual rainfall data plotted for the entire period of 36 years as shown in figure 3.

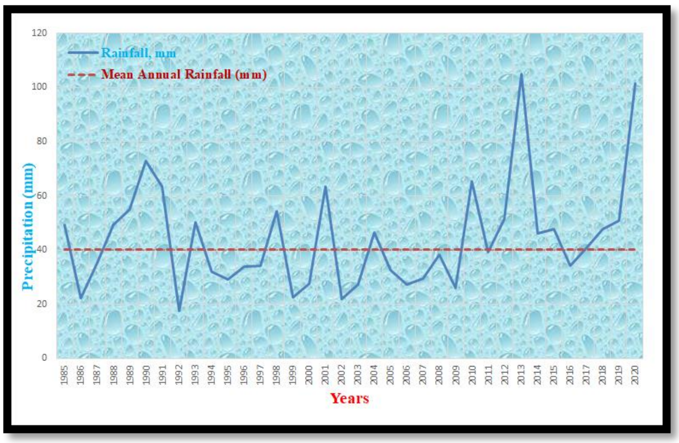


Fig. 3: The total annual rainfall depth at the rain gauge of 'Karcham' watershed

2.4 Study Area
The study area of 'Karcham' catchment situated at village name 'karcham' in Kinnaur district of Himachal Pradesh. The derived 'Karcham' watershed has an area of 5800 km^2, it is situated in the South West of Himachal Pradesh in the region called Karcham mountains on Sutlej river. The catchment outlet is located between longitudes 78.10 and 31.51 latitudes. The watershed is as a landlocked basin surrounded by mountains as shown in Fig.4

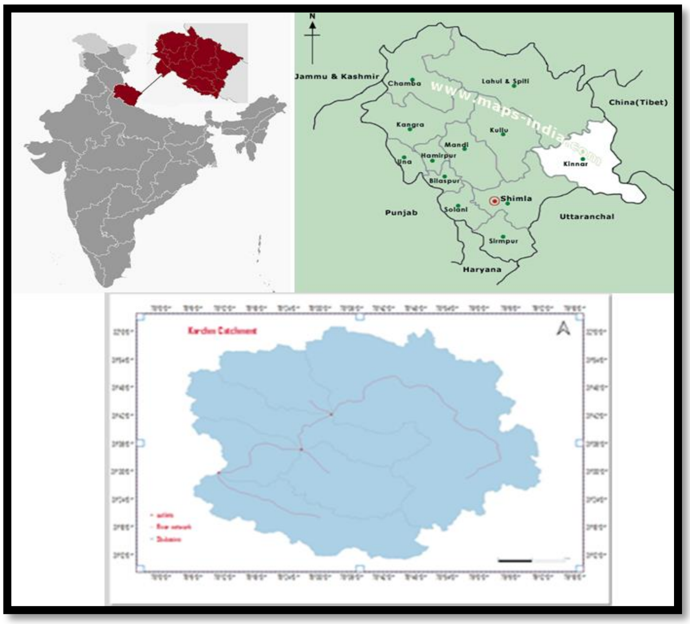


Fig. 4: Location of 'Karcham' watershed in Kinnaur district of Himachal Pradesh

2.5 Methodology
Our objective is to examine the rainfall-runoff relationship in 'Karcham' watershed, and develop a hydrograph using open source data in order to propose effective solutions to protect the built-up areas and properties against inundations. The methodology is based on meteorological and physical data processing in the geospatial environment and on data editing using Remote Sensing and GIS techniques. Our methodology can be separated into six main stages:

- Description and geographic location of the study area
- Download spatial and non-spatial data
- DEM processing: defining stream network, topography and watershed characteristics
- Precipitation data processing into return periods
- Importing the catchment physical characteristics data to HEC-HMS model
- Simulation and run the model

The location of this study selected in Kinnaur district of Himachal Pradesh. The selected watershed outlet located just before 'karcham' dam, which is the outlet point of to derive catchment. The DEM processed and utilized to derive watershed and its sub-basins. In each sub-basin the required input hydraulic and physical parameters derived from landuse/land cover map along with soil characteristics. The processed rainfall data used as input data to the meteorological model of the HEC-HMS. The brief description of methodology explained in the form of flow-chart as shown in figure 5.

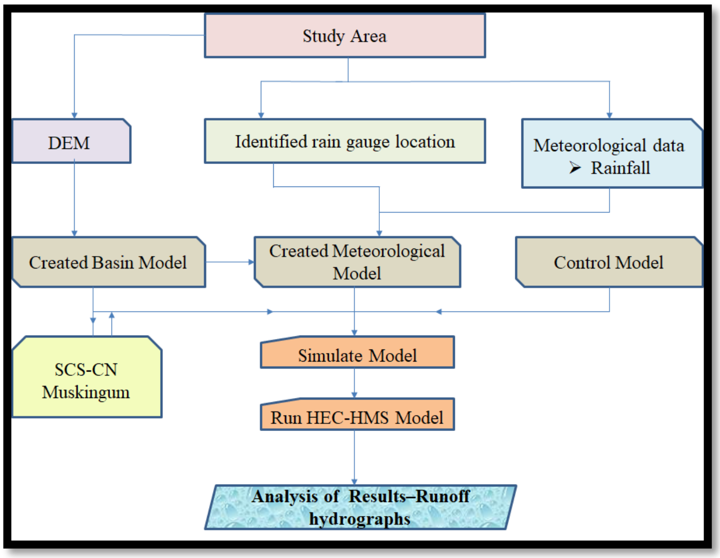


Fig. 5: Methodology of Flow Chart

3. HEC-HMS MODEL

The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) is designed to simulate the precipitation-runoff processes of dendritic watershed system. It is designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems [16]. Hydrographs produced by the program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and system operation. HEC-HMS model setup consists of four main model components, basin model, meteorological model, control specifications, and input data (time series, paired data, and gridded data). An assortment of different methods is available to simulate infiltration losses (deficit and constant, exponential, Green and Ampt, initial and constant, SCS-Curve Number, Smith Parlange and Soil Moisture Accounting–SMA. Seven methods are included for transforming excess precipitation into surface runoff are listed as Clark unit hydrograph, Kinematic wave, ModClark, SCS unit hydrograph, Synder unit hydrograph, user specified graph. Six methods are included for routing model these are Kinematic wave routing, lag routing, modified plus routing, Muskingum routing, Muskingum-Cunge routing and saddle Stagger routing. For the meteorological model eight methods are included like Frequency storm, gage weights, gridded precipitation, inverse distance, HMR-52, SCS storm, specified hyetograph, standard project storm.

3.1 Model Structure

HEC-HMS software has 3 main model structures. The first one is Basin model, which divides the entire watershed into sub-basins. In basin model, SCS curve number (CN) loss method will be used to determine the hydrologic loss rate, the SCS unit hydrograph (HU) method will be used to calculate the runoff rate. The second model structure is meteorological model in which simulating process is done by using frequency storm. The third important structure is control specifications, in which the simulation period of time is given to run the model. The following paragraphs explains the model structure in detail.

3.2 Basin Model

The basin model represents the physical visualization of the watershed. In order to increase for better performance of modelling, the catchment is sub-divided into 6 sub-basins to use the model as semi-distributed. The representation of these sub-catchments within the watershed is shown in Fig.6. The sub-basins connected with 4 reaches from sub-basin 1 to sub-basin 6. These reaches contain 4 junctions to store the discharges from sub-basins and carry to the next junction. The schematic diagram represents the structure of the 'karcham' catchment as shown below.

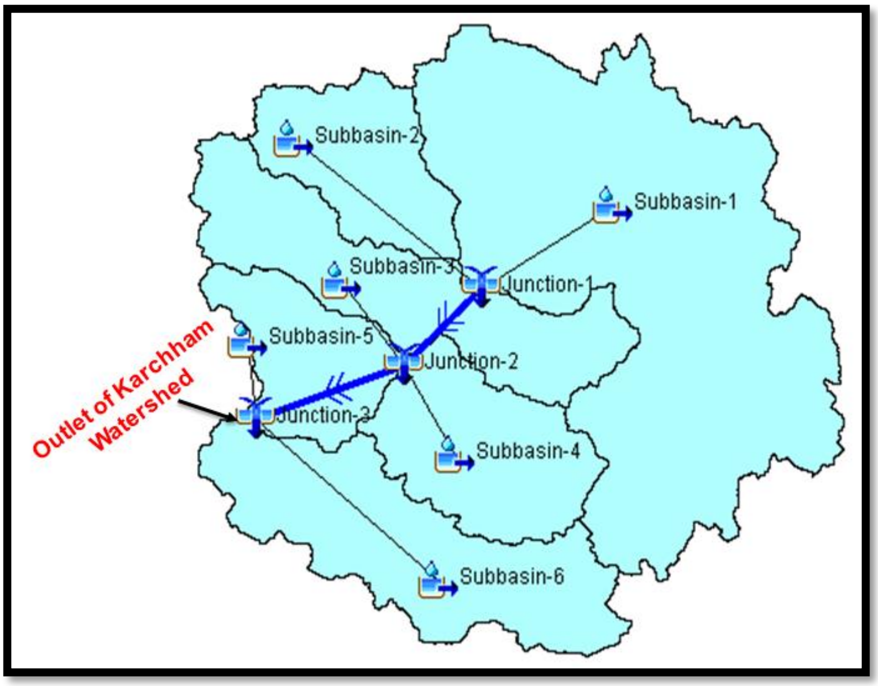


Fig. 6: The schematic representation of Karcham watershed extracted by HEC- HMS

In each sub-basin, losses are computed using loss method, the excess precipitation to runoff computation parameters are given in the transform method. The precipitation data is used in storm frequency method which is embedded in meteorological model. All these model structures are explained in detail in the following paragraphs under separate headings. The hydrological parameters of sub-basins of 'Karcham' watershed are shown in Table-2

Table 2: Details of Sub-basin parameters

Sub-basin No's	Area, km^2	Perimeter, km	Channel slope,%	Stream length, km
Sub-basin 1	3052.624	495.85	1.362	103.189
Sub-basin 2	574.573	161.15	2.905	10.225
Sub-basin 3	965.926	298.075	0.6905	21.576
Sub-basin 4	719.895	178.275	6.645	14.069
Sub-basin 5	1099.788	147.4	1.308	35.078
Sub-basin 6	494.786	301.975	4.238	41.685

3.3 Loss Method

In this study, SCS-Curve Number (CN) loss method is used to determine the hydrologic loss rate. The Soil Conservation Services Curve Number (SCS-CN) method implements the curve number methodology for incremental losses originally, the methodology was intended to calculate total infiltration during a storm. The curve number for a watershed can be estimated as a function of land use, soil type, and antecedent soil moisture, using tables published by the SCS-CN values range from 100 (for water bodies) to approximately 30 for permeable soils with high infiltration rates [17]. The SCS-CN model is given by equation (1)

$$Q = \frac{(P-Ia)^2}{(P-Ia+S)} \text{..............................eq}^n \text{ (1)}$$

where Q = runoff value (mm), P= precipitation (mm), Ia = initial abstraction (mm), S = potential maximum retention is given by Equation (2)

$$S = 25400 - \frac{254}{CN} \quad \text{........................eq}^n \text{ (2)}$$

$$Ia = 0.2\ S \text{.................................. .eq}^n \text{ (3)}$$

The runoff Curve Number (CN) is a function of LandUse/LandCover (LU/LC) treatment and condition, infiltration characteristics of the soils, and antecedent moisture condition. Mocuen (1982) [18] discusses the use of the SCS runoff model in detail. The hydrological soil classification system developed by the Soil Conservation Service was used for classifying soils into different hydrological soil groups. In this classification system, soils are classified as A, B, C or D Hydrologic Soil Group (HSG) depending on their properties: Soil group 'A' has low runoff potential and high infiltration. Soil group 'B' has low to moderate runoff. Soil group 'C' have flat infiltration rate, so the runoff is quite higher. Soils group 'D' has high runoff potential and very low infiltration rate [19]. For this purpose, the hydrologic soil groups were defined based on the geological map of Karcham watershed. The CN value compute Potential Maximum Retention(S) as per eq^n (2) and Initial abstraction (Ia) could be estimated for Indian conditions. Ultimately, the runoff volume predicted as per the eq^n (1) based on these parameter equations (2) and (3).

3.4 Transform Method

In this paper, the translation of excess precipitation to runoff is accomplished using the user-specified S-graph transform method. The SCS unit hydrograph method requires only one parameter for each sub-basin "The Lag-time". The standard lag is defined as the length of time between the centroid of precipitation mass and the peak discharges of resulting hydrograph [20]. The transform method requires a lag time determination as an input. The SCS developed a relationship between the time of concentration (T_c) and the lag time (T_{lag}) given by equation (4). The time of concentration is calculated by Giandotti's formula given by Equation (5) [21]. The time of concentration and lag time values for the 'Karcham' sub-catchments are listed in table-3.

$$T_{lag} = 0.6\ T_c \text{ ....eq}^n \text{ (4)}$$

$$Tc = \frac{4\sqrt{A}+1.5L}{0.8\sqrt{H}} \text{.........................eq}^n \text{ (5)}$$

where T_{lag} = the lag time, Tc the time of concentration, A = the watershed area (km^2), L = the length of the main channel (km), H= the difference between the mean basin elevation and outlet the outlet elevation (m)

Table 3: The time of concentration and lag times of Karcham sub-basins

Sub-basin No's	T_c, min	T_{lag}, min	T_c, h	T_{lag}, h
Sub-basin-1	1179	412.57	19.65	6.876
Sub-basin-2	575.4	201.42	9.59	3.357
Sub-basin-3	681.6	238.50	11.36	3.975
Sub-basin-4	569.4	199.26	9.49	3.321
Sub-basin-5	571.8	200.05	9.53	3.334
Sub-basin-6	995.4	348.33	16.59	5.805

t_{lag} = the lag time, T_c = the time of concentration

3.5 Meteorological Model

In this study, frequency storm data are used for the HEC-HMS model. The frequency storm method is designed to produce a synthetic storm from statistical precipitation data. This method is designed to use precipitation data collected from the different sources along with other information to compute a hyetograph for each sub-basin, and to accept partial or annual duration precipitation depth-duration data. The records from 'Karcham' watershed rainfall stations were obtained and analyzed to establish the Intensity-Duration-Frequency (IDF) curves based on extreme value, in order to evaluate the watershed reaction to a given rainfall event. In this study, it is assumed that the entire watershed would receive the same amount of design rainfall. The rainfall IDF results adopted for the area for various storm duration The storm duration of 30 minutes is used in the simulations.

4. RESULTS AND DISCUSSIONS

The selected historical event for the control was flood measured by the 'Karcham' Dam authority which records maximum peak discharge (6744 m^3/s) and that represent the flood of 500-year recurrence interval according to the frequency analysis with the statistical Gumbel method. The HEC-HMS simulated results reveals that the peak discharge of 5663.6 m^3/s obtained after 20 hrs. of the simulation period. The resultant flood hydrograph at the outlet of 'karcham; watershed as shown in gig.7. After run the model the simulated hydrograph at the out let of the catchment as shown in Fig.5. The peak discharge obtained after 20 hrs. of the simulation of the model.

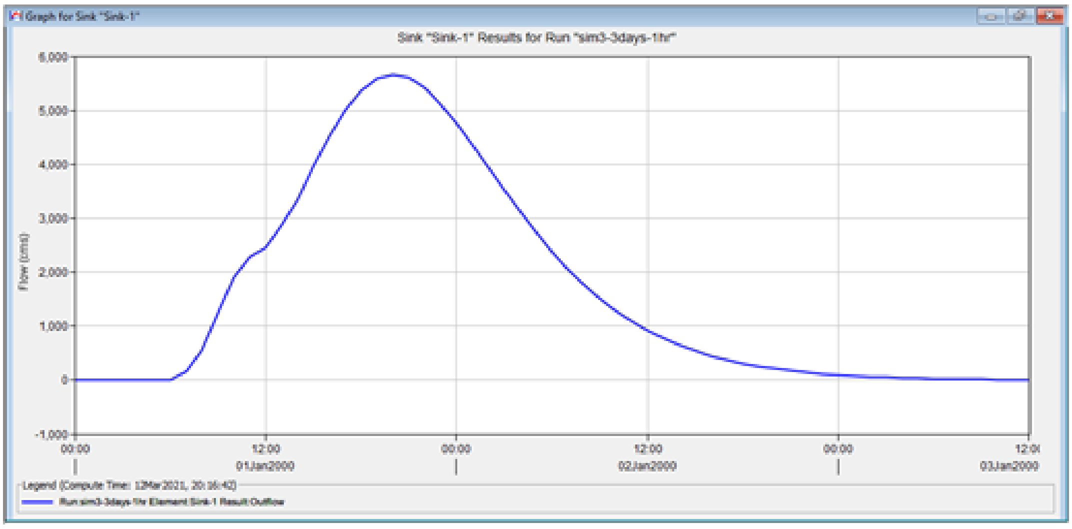
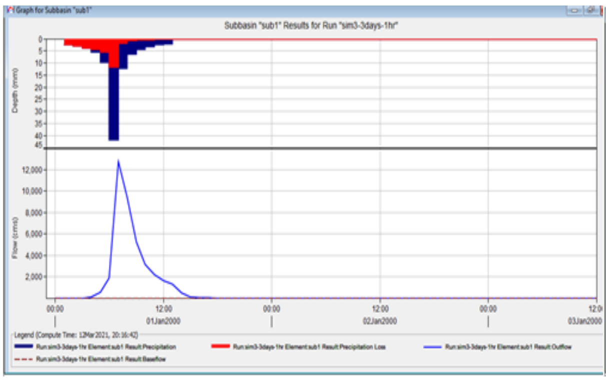


Fig. 7: Simulated hydrographs for Karcham watershed in HEC-HMS

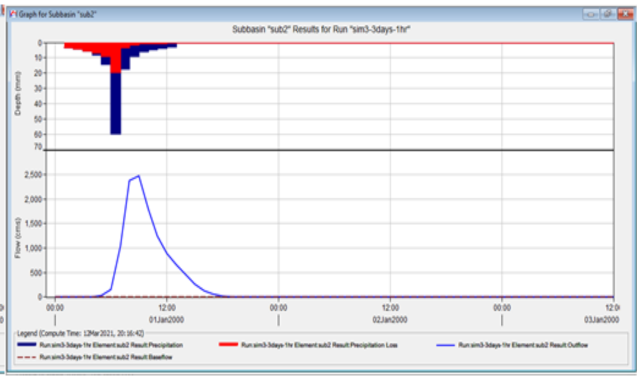
However, the observed peak discharge at 'karcham' dam location is higher than predicted peak discharge. This indicates that the simulated hydrograph underestimates to the observed peak discharge by 1.4%. This small amount of difference in peak discharge may under tolerable limit to consider for utilization of different objectives. This amount of difference in due condition of watershed topography and the precipitation used from satellite derived one. The HEC-HMS model also used to estimate direct runoff volume of 61.47 MM at the time of 20:00 hrs. after commencement of the model run at the recurrence interval 500 years. The peak discharges (m^3/s) and discharge volumes (mm) for the 6 sub-basins of 'karcham' watershed are listed in Table 4. The precipitation, precipitation loss and peak discharge of each sub-basin and the corresponding figures of each sub-basin are shown in Fig.8.

Table 4: Peak discharge and discharge volume–basin wise

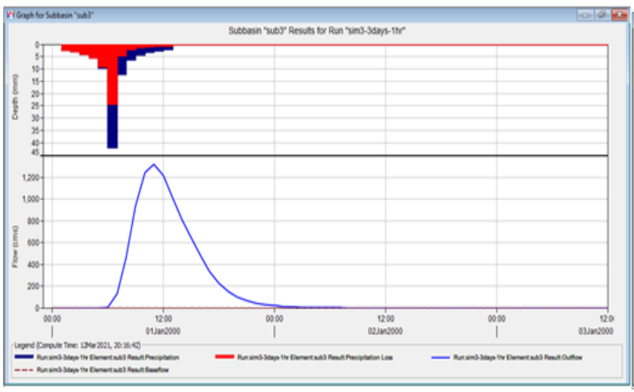
Return period years	parameter	Sub-basin 1	Sub-basin 2	Sub-basin-3	Sub-basin-4	Sub-basin-5	Sub-basin-6
500	Peak discharge cum/s	12788.2	2476.8	1322.8	2429.8	90.0	2371.9
	Volume, MM	62.0	84.11	39.06	68.19	35.67	56.42



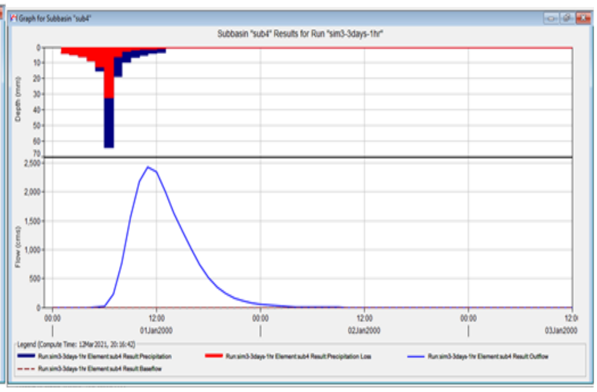
Sub-basin 1



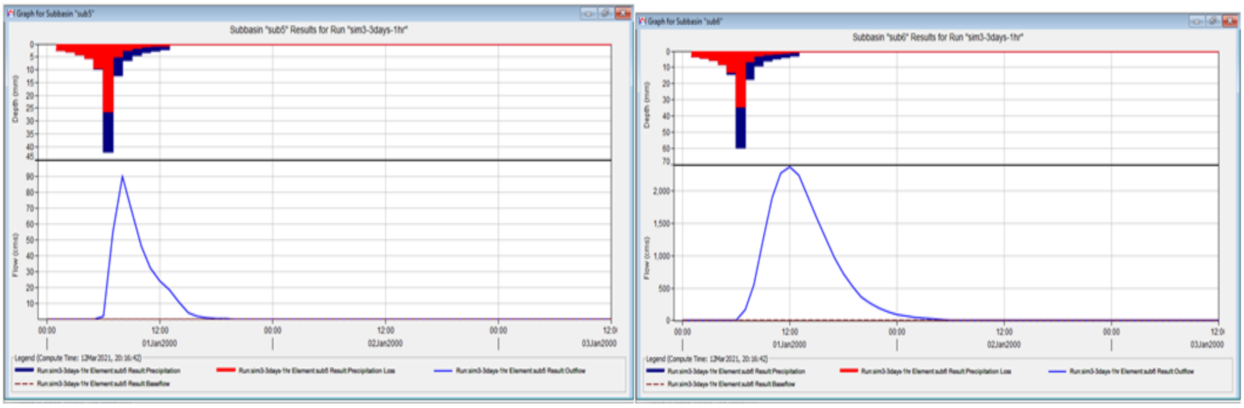
Sub-basin 2



Sub-basin 3



Sub-basin 4



Sub-Sub-basin 5 Sub-basin 6

Fig. 8: Simulated hydrographs of sub-basins of 'Karcham' watershed

The peak discharges and volumes for the sub-basins 1 and 2 are 32 and 393, 35.4 and 15.5 million m3 respectively. This difference due mostly to topography condition and the catchment area (sub-catchment 1 area 579 km^2, sub-catchment 2 area 1334 km^2).

5. CONCLUSION

The objective of this study is to utilize open source data to derive hydrograph at the outlet of the 'karcham' watershed in Kinnaur district of Himachal Pradesh. One of the open source data is Digital Elevation Model (DEM) of 12.5 m resolution was used for Karcham watershed delineation and catchment characteristics using HEC-HMS. This software which derive all topographical parameters of watershed similar to ArcHydro tools available in other softwares. The other open source data is Landuse/Landcover map obtained from SWAT web portal. Also another open source data is soil map, which is obtained from FAO-USGS web portal. This geological data used to well-understand the nature of watershed. The important meteorological parameter of rainfall data obtained from open source web portal of NASA-POWER for about 36 years. This data used for the preparation of meteorological model as input for HEC-HMS software. The HEC-HMS hydrologic modelling software was applied to Karcham watershed located in southwestern Himachal Pradesh to predict flood hydrograph using open source data at the outlet of watershed. The SCS Curve Number loss method was used to determine the hydrologic losses from the study area and SCS unit hydrograph method was used for effective rainfall transformation. As there are plenty of ungauged rivers located in the semi-arid zone in HP, the presented methodology could be allowed an acceptable estimation of the flood hydrograph in area with similar conditions. The results reveals that the predicted peak flood is lesser than by 1.4% to the observed discharge at the outlet of the 'Karcham' watershed. This is evident, that the open source spatial and non-spatial data could be used to derive flood hydrographs with immense care to prepare the input parameters to apply with open source software of HEC-HMS. The results could be utilized for flood management during non-availability of the virtual data in such hilly terrain regions.

6. ACKNOWLEDGEMENT

The author express deep gratitude to the agencies like 'SWAT data sets for India' for make availability of LandUse/LandCover map, NASA-POWER to make availability of point precipitation data, make availability of world digital soil map by FAO-UNESCO, and the digital elevation model from Alaska Satellite Facility (ASF) web portal making available of data for public domain to utilize for my research work.

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