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Application of RS & GIS in Estimation of Sub-Basin Runoff Potential using HEC-HMS

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Abstract
The objective of the study is to simulate the daily runoff depth using remote sensing data and geographic information system (GIS) technique. Hydrologic Modeling System (HMS) has been applied to simulate the runoff potential. The USDA Soil Conservation Services Curve Number (SCS-CN) loss model has been used for computing the daily runoff depth of Sheonath River upper sub-basin. The SCS-CN is a quantitative description of land use / land cover / soil complex characteristics of a basin. This model is a widely used hydrological model for estimating runoff using runoff and curve number (CN). Land use and hydrologic soil type were merged together in GIS to get the curve number grid of the sub-basin. Base map, soil map, land use / land cover map and other associated map of the study area have been prepared using Indian Remote Sensing LISS-III data and Survey of India (SOI) topographic sheets. Then, these maps were used to get the various characteristics of the sub-basin to be applied in HMS for runoff estimation.

Keywords: Runoff; Hydrological modeling; SCS-CN model; Remote Sensing; GIS; Digital Elevation Model.

Introduction
Rainfall is one of the important components of hydrological cycle. It is not possible to measure the rainfall amount accurately, as it varies from place to place, but we can measure precisely the amount of surface runoff in the form of discharge at the outlet of any hydrological unit. The runoff potential provides the knowledge of water availability in a river basin. Now days with the advent of remote sensing and GIS technology, it become easier to perform hydrological analysis analyze at basin level. There are number of approaches for estimating runoff. The Soil Conservation Service-Curve Number (SCS-CN) method developed by National Resources Conservation Service (NRSC), United States Department of Agriculture (USDA) in 1969, is simple, predictable and stable conceptual method for estimation of direct runoff depth based on storm rainfall depth[1]. This method is a quantitative description of land use / land cover / soilcomplex characteristics of a basin. These characteristics can be derived by applying remote sensing products to GIS. Because of the significance of spatial analysis in hydrological modelingGIS constitutes a powerful modeling tool [2]. ArcMap is being utilized for this purpose. The main objective of this study is to quantify the runoff using GIS based SCS Curve Number loss model simulated in HEC-HMS modeling environment.

HEC-HMS
HMS is a software system, developed by Hydrologic Engineering Centre (HEC) of the US Army Corps of Engineers, to model rainfall runoff processes in a basin or a region [2]. The physical characteristic of a basin is extracted by HEC-GeoHMS tool and these characteristics were imported to HEC-HMS for hydrological modeling to simulate runoff. The HEC-HMS can be used to simulate a single watershed or a system of multiple hydrological connected watersheds. The first step in the application of HEC-HMS is defining the basin area and sub-basins, a stream network, and diversions and junctions. Like any physically base hydrological model, HEC-HMS simulates most of the key hydrologic processes at watershed scale. The HEC-HMS model requires different database including a Digital Elevation Model (DEM), weather data, soil type, and land use. A detailed map of land surface elevation was obtained from ASTER with 30 m resolution.
The Geospatial Hydrologic Modeling System extension (HEC-GeoHMS), along with ArcHydro extension in ArcView, was used to delineate the physical properties from ASTER data and generate a stream network. HEC-GeoHMS was also used to create the input file in the form of sub-catchment boundaries, a meteorological model, etc. for use in HEC-HMS. HEC-HMS includes three main components:

1. Basin Model
2. Meteorological Model
3. Control Specification

The basin model stores the physical datasets describing the catchment properties and the hydrologic elements i.e. i.e. sub-basins, reaches, junctions, reservoirs, diversions, sink and sources. Meteorological model describes the rainfall event and evapotranspiration processes. The time span of a simulation is controlled by control specifications including a starting date and time, ending date and time, and computation time step.

SCS-CN Model

In this study loss from the basin was computed by the SCS-CN method. This model was developed by United States Department of Agriculture (USDA) Soil Conservation Services (SCS) in the year 1954 [3]. Curve number is essentially a coefficient that reduces total precipitation to runoff potential after losses i.e. evaporation, absorption, transpiration and surface storage. Basically, it is a quantitative descriptor of land use, soil characteristic and antecedent moisture condition. This method is based on two concepts:

- The ratio of actual amount of runoff to maximum potential runoff is equal to the ratio of actual infiltration to the potential maximum retention [3] and is expressed as

$$(P - I_a - R)/S = R/(P - I_a) \quad (1)$$

Where
P = precipitation in millimeters$(P \geq R)$;
R = runoff in millimeters;
S = potential maximum retention in mm;
I_a = Initial Abstraction;

- The second concept is that the amount of initial abstraction is some fraction of the potential maximum retention [3] and thus expressed as

$$I_a = \lambda S \quad (2)$$

for Indian conditions $\lambda = 0.3S$ [4]

$$S = 25400/CN - 254 \quad (3)$$

Solving equation (1) and (2) we get

$$R = (P - I_a)\text{^}2/(P - I_a + S)\text{for}$$

$$P \geq 0.3S \quad (4)$$

Equation (4) is the required equation for computing runoff potential of a basin.

Study Area Description

A portion of Upper Sheonath sub-basin was considered for this study. The study area extends between latitudes 20º25'00" N and 21º00'00" N, and longitudes 80º26'00" E and 80º55'00" E. The study area comprises of Durg (area= 93.52 km^2), Rajnandgaon (area= 991.83 km^2) Districts of Chhattisgarh state and Gondia (area= 13.15 km^2), Garchirolli (area= 297.39 km^2) districts of Maharashtra State. Total geographic area of the upper Sheonath basin considered is 1395.89 km^2. Study area was influenced by two raingauge stations namely AmabagarhChowki and Dongargaon. The study area map is shown in Figure 1. Satellite Imageries: The Indian Remote Sensing satellite with Linear Imaging Self Scanning sensors (IRS – LISS III) satellite data of scale 1:50000 were collected from Bhuvan portal of Indian Space and Research Organization (ISRO), to use land use/ land cover of the study area.Daily rainfall data (1993-2005) from AmbagarhChowki and Dongargaonraingauge station from Water Resources Department Chhattisgarh were used.The soil data from National Bureau of Soil Survey & Land Use Planning (NBSS & LUP).

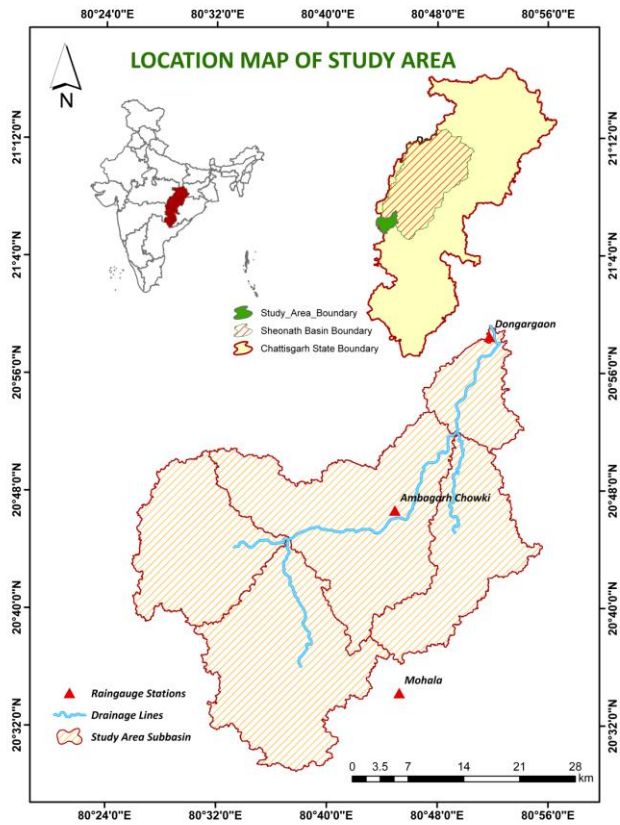


Fig.1. Location Map of the Study Area

Methodology

A. Demarcation of Study Area

The foremost task is to delineate the hydrological boundary of the upper Sheonath basin. This involves the application of 30m resolution Aster Global Digital Elevation Model (GDEM) [5] and the drainage lines digitized with the help of Topographic sheets in the scale 1:50000 procured from Survey of India (SOI). The following procedure is adopted to demarcate the sub-basin boundary:

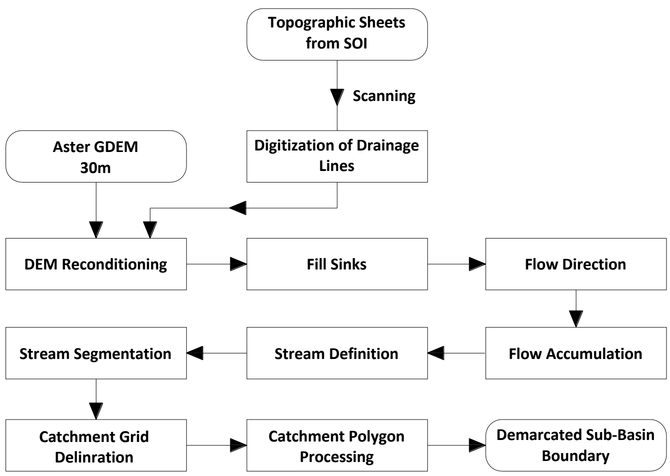


Fig.2. Flowchart for Demarcation of Sub-Basin Boundary

The flowchart shown in Figure 2 involves number of processing steps for demarcation, the same is briefly described as follows [6]; DEM reconditioning involves imposing of drainage lines over DEM so that it can be adjusted with drainage lines. Fill sink operation will fill the cell surrounded by higher elevation cell and lower the cell surrounded by lower elevation cell, so that flow will occur smoothly overland. Flow direction defines the direction of flow in each cell. Flow accumulation provides the total number of upstream cell draining to a given cell. Stream Definition classifies all the cells with flow accumulation greater than the user defined threshold belonging to stream network. Stream Segmentation divides the stream grid into segments, which are the sections of a stream that connects two successive junctions or outlets. Catchment grid delineation delineates a sub-basin for every stream segments. Finally, the Catchment polygon processing creates a vector layer of sub-basin created from the delineated grid. Thus, the study area boundary is demarcated. The study area is found to be divided into five sub-basins as shown in Figure 1.

B. Computation of Hydrologic Parameters of Sub-Basins

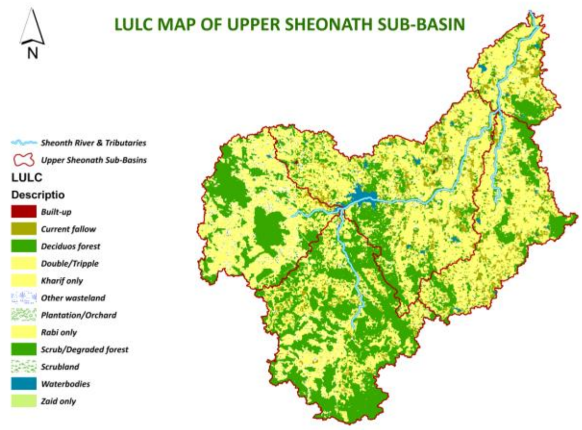
After demarcation of study area boundary various physical characteristics were derived using HEC-GeoHMS Extension. Basin characteristics like river length, river slope, basin slope, longest flow path, basin centroid, centroid elevation and centroidal longest flow path were derived and attributed. Among the different methods supported by HMS for runoff calculation SCS-CN has been applied as it relies on one parameter only i.e. Curve Number. An area weighted curve number for each sub-basin were estimated from curve number grid map using the LULC and soil data of the study area. Area weighted composite curve number for various conditions of land use and hydrologic soil conditions are computed as follows:

$$\mathrm{CN} = (\mathrm{CN}_1 \times \mathrm{A}_1) + (\mathrm{CN}_2 \times \mathrm{A}_2) + .. + (\mathrm{CN}_n \times \mathrm{A}_n)/\mathrm{A} \quad (5)$$

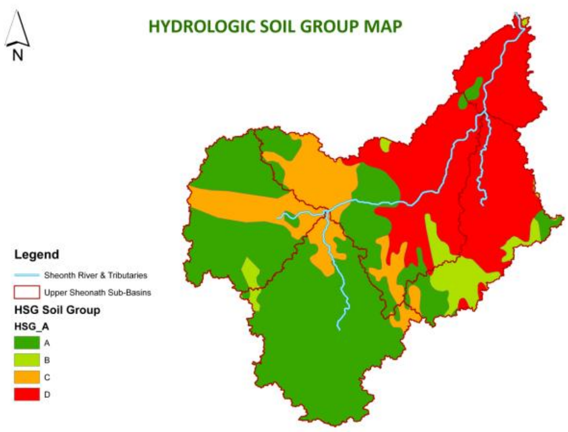
Where A_1, A_2, A_3, ….….,A_n represent areas of polygon having CN values CN_1, CN_2, CN_3,……...,CN_n respectively and A is the total area. Ministry of Agriculture has published a Curve Number lookup table which consists of recommended curve number values for different combinations of hydrologic soil group (HSG) and land use [7]. LULC map of the study area is shown in figure 3 (a). As per GIS Computation it was found that out total geographic area agriculture land 58.86 %, forest 34.32 %, wasteland 5.50 %, water bodies 1.28 %, plantation 0.01 % and build up area is 0.03 %. Figure 3 (b) shows the HSG A, B, C and D which is based on the infiltration rate, in which group A more permeable to infiltration whereas Group D is less permeable. It was found that area covered by HSG Group A = 658.39 km^2, Group B = 75.44 km^2, Group C = 197.36 km^2 and Group D = 463.53 km^2. HSG Soil Group intersected with land use polygons creates a map in which each resulting polygon is related to a unique combination of soil and land use [2]. For each polygon the curve number is obtained as weighted combination of curve numbers based on the percentage of each hydrologic soil group in the polygon. The curve number lookup table is used to extract the weighted curve number for five sub-basins of the study area. The curve number grid file is prepared and weighted curve numbers for each of the sub-basins were derived. Curve number grid is shown in Figure 3(c). Initial Abstraction is computed using equations (2) and (3) for each sub-basins. Impervious percentage is computed using land use map. Basin lag time is computed using the relation [6]:

$$L = \{l^{0.8}(S+1)\}/1900y^{0.5} \quad (6)$$

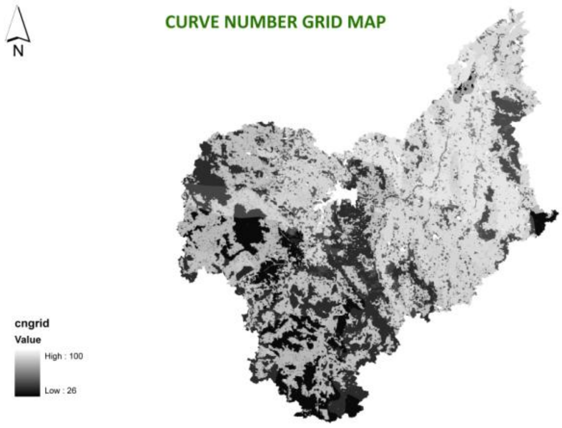
Where
L = Basin lag time in hour
l = longest flow length in ft
S = Max. Potential retention in inches=1000/CN- 100
y = Average watershed slope (%)



(a)



(b)



(c)

Fig.3. Upper Sheonath Sub-Basin (a) Landuse (b) HSG (c) Curve Number Grid

Geometric data of the sub-basins including area, curve number, basin lag time, longest flow length are listed in Table 1.

TABLE.1. Basin Model Parameter

Sub-BasinCode	Area(Km^2)	WeightedCN	*L*(minute)
W60	108.01	82.83231	4969.93836
W90	253.54	66.59077	3995.44602
W80	419.66	78.80985	4728.59118
W70	240.56	79.70237	4782.14220
W100	374.12	58.36600	3501.95526

The generated runoff is routed towards the junction and outlets by Muskingum routing method. There are two parameters for routing; travel time of wave through the river in hours (K) and weighting parameter (x) between inflows and outflows ranges from 0.0 – 0.5. The routing parameters are listed in Table 2.
The sub-basins and river codes are shown in Figure 4.

TABLE.2. Routing Parameter

ReachCode	Length of reach(km)	MuskingumK (hr)	Muskingumx
R10	17.51635	6.0821	0.2
R20	17.88601	6.2104	0.2
R30	32.64713	11.336	0.2
R40	8.891261	3.0872	0.2
R50	20.30759	7.0512	0.2

C. Computation of Meteorological Parameters of Sub-Basins

The meteorological model contains the rainfall data. In this study the user gauge weighting method has been selected. The number of rain gauges and their Theissen weights considered for the study is shown in Table 3.

TABLE.3. Rain Gauges and Their Weights

Sub-BasinCode	Rain Gauge	Theissen weight
W60	AmbagarhChowki	0.0038
	Dongargaon	0.9962
W90	AmbagarhChowki	1.0000
W80	AmbagarhChowki	0.9977
	Dongargaon	0.0023
W70	AmbagarhChowki	0.9957
	Dongargaon	0.0043
W100	AmbagarhChowki	1.0000

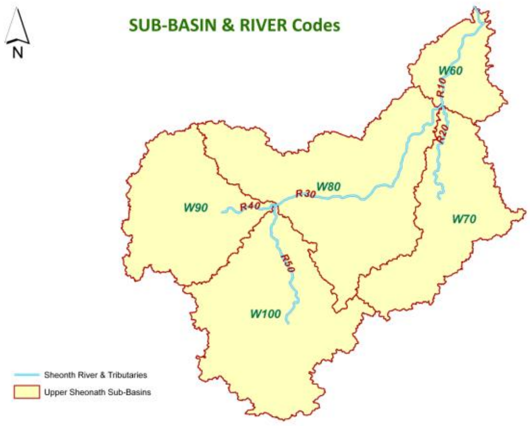


Fig.4. Upper Sheonath Sub-Basins River Codes

D. Control Specification

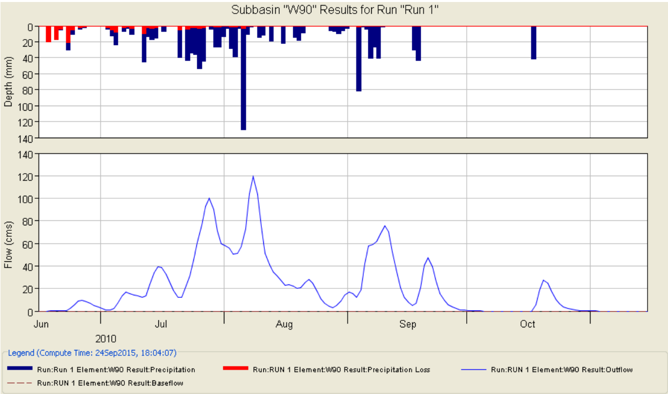
It contains all the simulation control information for the model including the start time and date, end time and date and the computational time step of the simulation. Rainfall data form the rain gauge stations namely AmbagarhChowki and Dongargaon are provided in the time series folder, data ranges from 1980 - 2012. Since we have used landuse cover of the year 2010, the simulation period starts from 15th June 2010 to 15th Nov. 2010.

Results

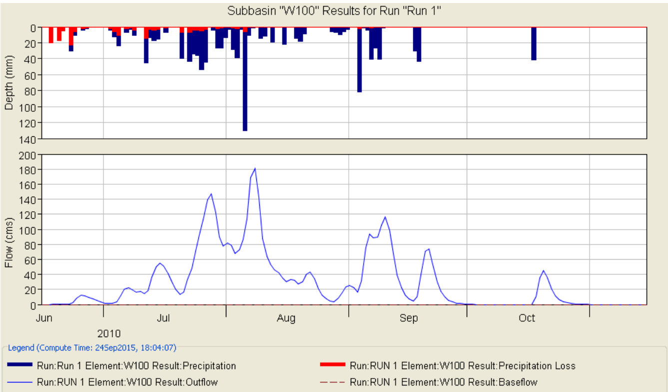
HMS parameters computed were applied for simulating the runoff in five sub-basins of the study area for the mentioned period of the year 2010. The resulted hydrographs were used to compute the runoff potential from the upper Sheonath sub-basin. The estimated runoff depth from the various sub-basins are tabulated in Table IV and presented in figure 5(a) to 5e)

TABLE.4. Estimated Runoff Depth for the Year 2010

Sub-BasinCode	Rainfall (mm)	Loss(mm)	Runoff Depth(mm)
W60	1117.96	80.42	1037.54
W90	1239.50	145.49	1094.01
W80	1239.22	94.86	1144.36
W70	1238.98	91.58	1147.40
W100	1239.50	187.77	1051.73



(a)



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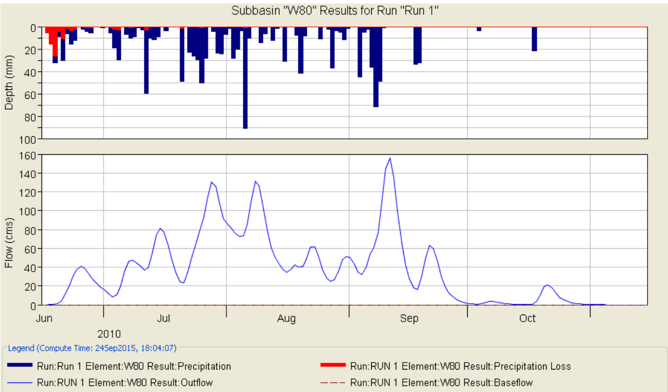

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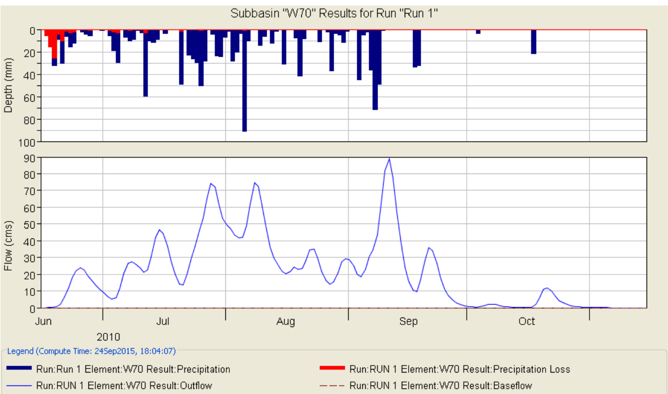

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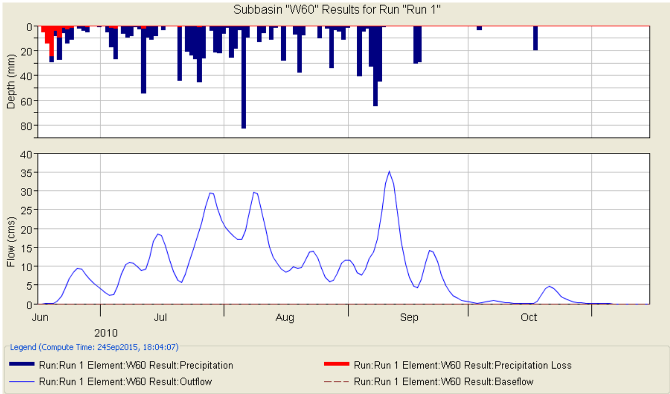

(e)

Fig.5. (a) W90 (b) W100 (c) W80 (d) W70 (e) W60 Simulation Result of the Five Sub-basins

Conclusion

The study demonstrates the utilization of HEC-HMS modeling in quantifying the water availability in river basins with the application of GIS based SCS-CN loss model. SCS-CN model proves to be simple, reliable and effective model for computing the runoff. The loss model is applied to Sheonath river upper sub-basin. In the present study the runoff is simulated for a period of six months. Finally, based on the information stored in the attribute tables, a basin model is developed and executed in HEC-HMS. The model can be applied for not only water availability study but also for studying the urban drainage, flood forecasting, future urbanization impact and many others.

Remote sensing and GIS with application of SCS-CN model proves to be a powerful tool for runoff estimation. Thus, land use planning and watershed management can be done effectively and efficiently using SCS-CN number method in GIS applied HMS modeling environment.

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