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A GIS-Based Hydrological Assessment of Urban Runoff in Shimla Using the SCS-CN Method

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ABSTRACT

Urbanization in hilly regions like Shimla has significantly altered natural hydrological processes, leading to increased surface runoff and flood risks. This study presents a GIS-based hydrological assessment of urban runoff in the Shimla urban area using the Soil Conservation Service-Curve Number (SCS-CN) method. The research integrates remote sensing data, land use/land cover (LULC) classification, soil maps, and rainfall data to estimate runoff potential across the city. GIS tools were employed to spatially analyze and map hydrological parameters, enabling the generation of Curve Number values based on hydrologic soil groups and land use characteristics. The study reveals spatial variations in runoff potential, highlighting areas vulnerable to high runoff and surface flooding. Results indicate a strong correlation between increasing impervious surfaces and elevated runoff coefficients. This methodology provides a cost-effective and efficient approach for urban watershed management, offering critical insights for sustainable urban planning, storm water management, and climate resilience in mountainous urban environments.

INTRODUCTION

The estimation of runoff is crucial for effective urban water management and infrastructure planning. There are generalized physically based and spatially distributed hydrologic computer models of catchments that are able to compute sequences of runoff generation for a given rainfall event. The main advantage of these models is the accuracy of their predictions. Their major disadvantage is that they require considerable expertise, time, and effort to be used effectively. In between the extremes there are methods like the SCS-CN (Soil Conservation Service curve number) method that are relatively easy to use and yield satisfactory results (Schulze et al. 1992). The Soil Conservation Service curve number (SCS- CN) method (SCS, 1956, 1964, 1971, 1985)

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is one of the most popular methods for computing the volume of surface runoff for a given rainfall event from small agricultural, forest and urban watersheds.

Urban areas situated in mountainous regions, such as Shimla, face unique challenges related to runoff management due to their complex topography and rapid urbanization. The intricate interplay of steep slopes, varying land uses, and intense precipitation events significantly influences the hydrological dynamics and poses several critical issues: such as Flash Flooding and Infrastructure Vulnerability, Water Scarcity and Supply Reliability, Environmental Impact and Ecological Balance and Climate Change Resilience. Runoff estimation in mountainous urban areas like Shimla is essential for sustainable urban development, environmental protection, and resilience against natural hazards. It provides valuable insights for informed decision-making and infrastructure planning to ensure the well-being and safety of urban populations and the preservation of Himalayan ecosystems.

REVIEW OFLITERATURE

Urban areas located in mountainous regions present unique challenges and opportunities for runoff estimation and management. Shimla, situated in the foothills of the Himalayas, exemplifies such a setting where the interaction of steep terrain, varying land uses, and climatic factors influences hydrological processes significantly. In this paper, the Soil Conservation Service Curve Number (SCS-CN) method was employed to calculate runoff in the Shimla Municipal Corporation. ArcGIS, a powerful geographic information system (GIS) software, was utilized for spatial analysis and modeling.

Ponce and Hawkins (1996) reported as possible sources of this variability the effect of the temporal and spatial variability of storm and watershed properties, the quality of the measured data, and the effect of antecedent rainfall and associated soil moisture. **Soulis et al. (2009)** and **Steenhuis et al. (1995)** also noted that the variation of CN value, according to AMC category alone, cannot justify the observed CN values variability in every case

Mishra and Singh (1999, 2002a) derived the method from the **Mockus (1949)** method and from linear and non-linear concepts, respectively. With a discussion of advantages and limitations of available approaches, Mishra and Singh (2002a) extended the method for long term hydrologic simulation incorporating evapo-transpiration. Mishra and Singh (in press) described its behavior using the initial abstraction, provided a criterion for its applicability, and extended it for computation of infiltration and runoff rates.

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OBJECTIVESOFTHE STUDY

The present study is aimed at investigating the following objectives;

1. Apply the SCS-CN method to estimate runoff in Shimla MC area.
2. Utilize ArcGIS for spatial data analysis and visualization.

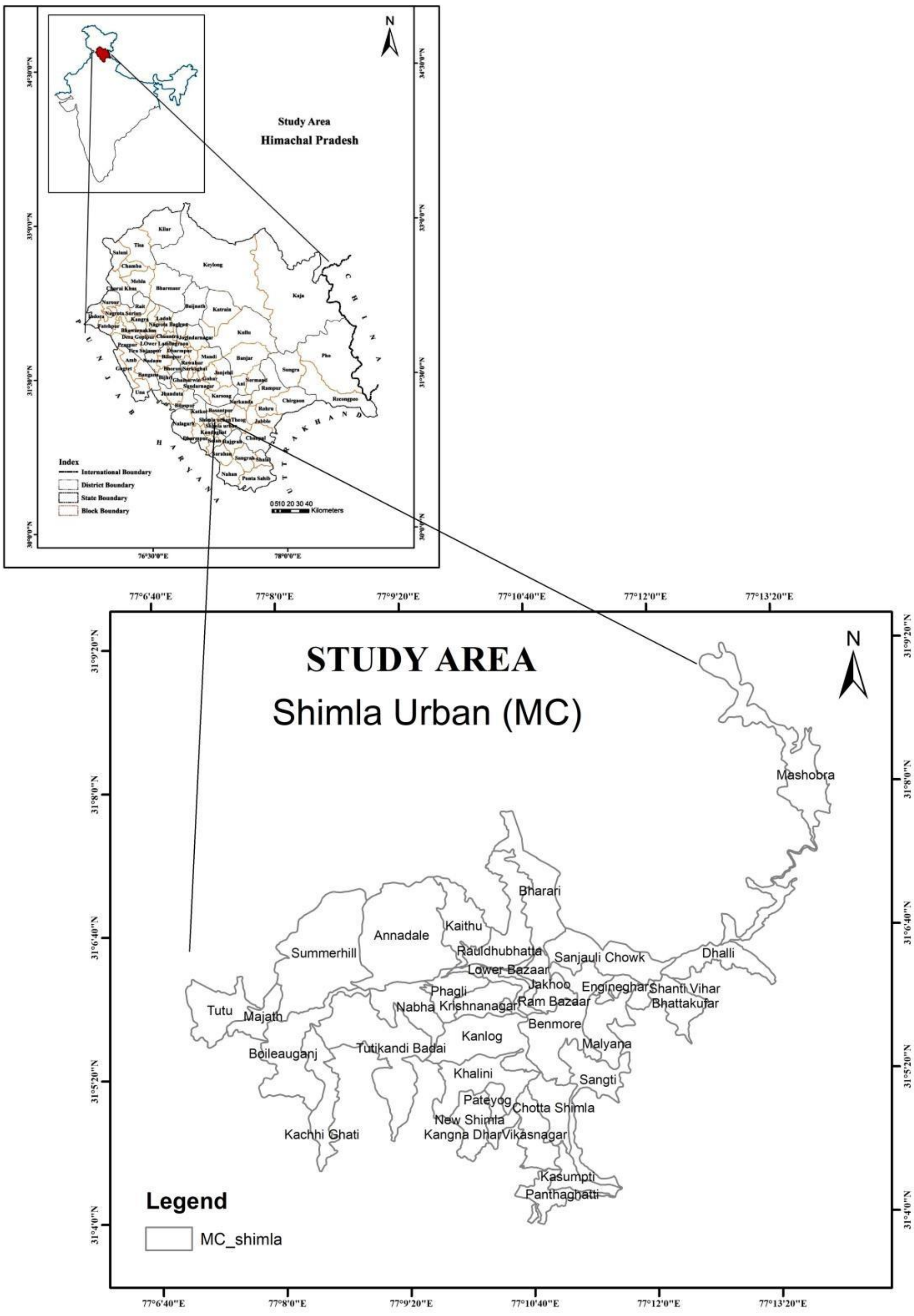
STUDYAREA

Municipal Corporation Shimla (MC Shimla) is the administrative body governing the city of Shimla, the capital of Himachal Pradesh, India. Located in the northwestern Himalayas, Shimla is one of India's prominent hill stations and a rapidly urbanizing city. Shimla is situated between latitude 31°04'N to 31°10'N and longitude 77°05'E to 77°15'E, at an average elevation of approximately 2,200 meters (7,200 feet) above mean sea level. The city spans an area of around 35.34 square kilometers, though the urban agglomeration is expanding beyond these limits due to increasing population and urban sprawl. Shimla lies on a ridge and is characterized by a series of steep hills, narrow valleys, and undulating terrain, making it highly susceptible to surface runoff and erosion. The city is spread across several hills, including Jakhoo Hill (the highest point at 2,455 meters), Prospect Hill, Summer Hill, and Elysium Hill. This varied topography influences both the flow of water and the pattern of urban development.

The soil composition in the region mainly includes sandy loam and silty loam, classified into different Hydrologic Soil Groups (HSGs) based on infiltration rates, which play a critical role in runoff modeling using the SCS-CN method. Shimla experiences a subtropical highland climate (Cwb) under the Köppen climate classification. The city receives an average annual rainfall of about 1,500 to 1,800 mm, with the majority occurring during the monsoon season (July to September). Snowfall is also common in winter months, further affecting runoff and drainage dynamics.

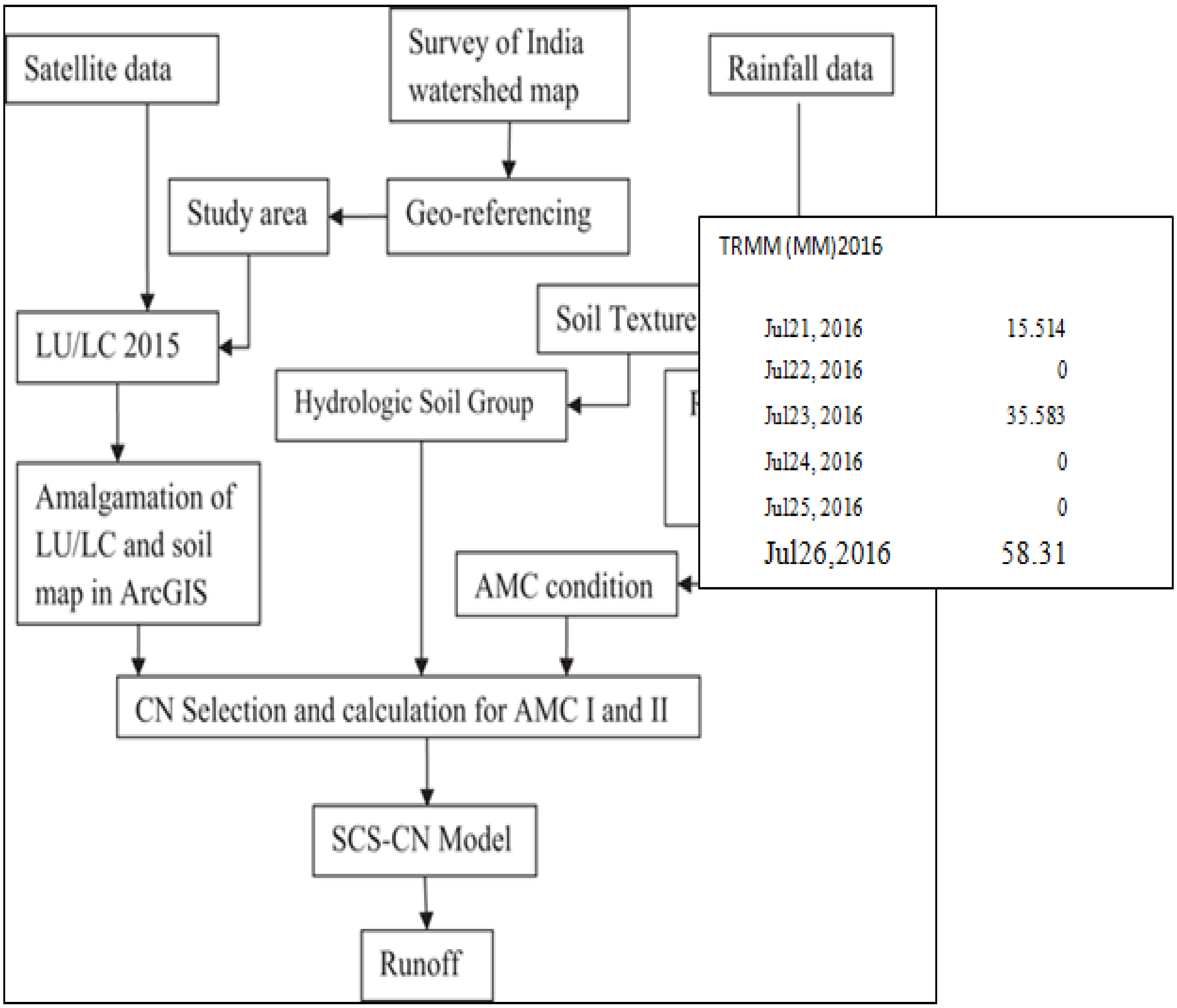
With increasing urbanization, natural vegetation and open spaces are being replaced by impervious surfaces such as roads, buildings, and pavements. This transformation reduces infiltration and significantly increases surface runoff, making hydrological assessments crucial for sustainable urban planning and flood risk mitigation.

Fig. 1: Location Map of Study Area



Research Methodology

Fig. 2



METHODSOFTHE STUDY

The SCS curve number method is a simple, widely used and efficient method for determining the approximate amount of runoff from a rainfall even in a particular area. Although the method is designed for a single storm event, it can be scaled to find average annual runoff values. The stat requirements for this method are very low, rainfall amount and curve number. The curve number is based on the area's hydrologic soil group, land use, treatment and hydrologic condition.

The general equation for the SCS curve number method is as follows:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad (1)$$

Q = runoff (in)
P = rainfall (in)
S = potential maximum retention after runoff begins
I_a = initial abstratctions

$$I_a = 0.2\,S \quad (2)$$

$$Q = \frac{(P - 0.2\,S)^2}{(P + 0.8\,S)} \quad (3)$$

$$S = \frac{1000}{CN} - 10 \quad (4)$$

The initial equation (1) is based on trends observed in data from collected sites; therefore it is an empirical equation instead of a physically based equation. After further empirical evaluation of the trends in the data base, the initial abstractions, I_a, could be defined as a percentage of S (2). With this assumption, the equation (3) could be written in a more simplified form with only 3 variables. The parameter CN is a transformation of S, and it is used to make interpolating, averaging, and weighting operations more linear (4).

With the following chart, the amount of runoff can be found if the rainfall amount (in inches) and curve number is known.

Land Use Description on Input Screen	**DescriptionandCurveNumbersfromTR-55**					
	Cover Description		**Curve Number for Hydrologic Soil Group**			
	Cover Type and Hydrologic Condition	% Impervious Areas	A	B	C	D
Agricultural	Row Crops - Straight Rows + Crop Residue Cover-Good Condition(1)		64	75	82	85
Forest	Woods(2)- Good Condition		30	55	70	77

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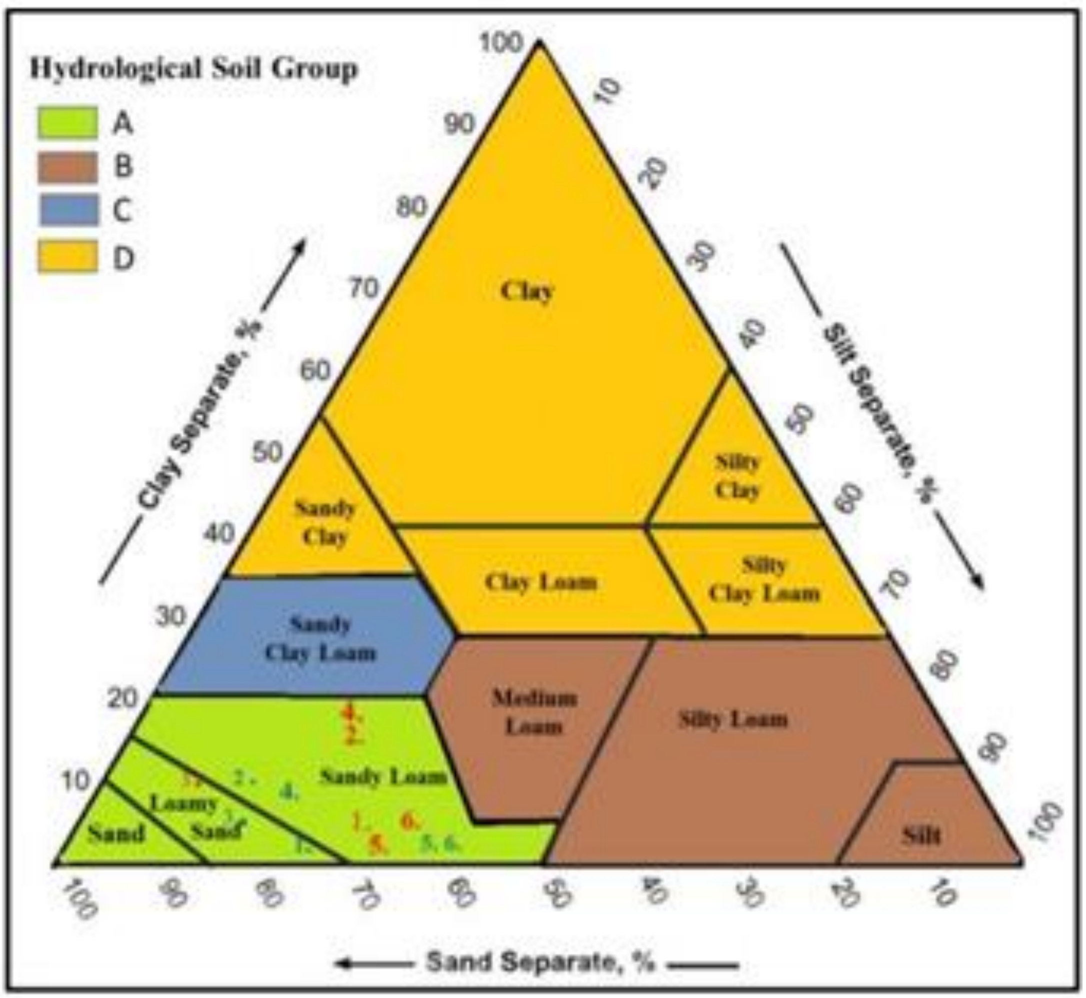
Grass/Pasture	Pasture, Grassland, or Range(3)-Good Condition		39	61	74	80
Residential1/8 acre	Residential districts by average lot size: 1/8 acre or less	65	77	85	90	92
Residential1/4 acre	Residential districts by average lot size: 1/4 acre	38	61	75	83	87
Residential1/3 acre	Residential districts by average lot size: 1/3 acre	30	57	72	81	86
Residential1/2 acre	Residential districts by average lot size: 1/2 acre	25	54	70	80	85

Fig 3



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AMCCONDITIONS

Antecedent Moisture Condition (AMC)	Total 5 days antecedent rainfal	
	Dry season	Growing
I	<12.7	< 35
II	12.7 – 27.9	35.6 –
III	> 27.9	> 53

Source: National Engineering Handbook (Mockus, 1964)

AMC group	Soil characteristics	Five-day antecedent rainfall (mm)	
		Dormant season	Growing season
I	Wet condition	<13	<36
II	Average condition	13-28	36-53
III	Heavy rainfall condition	>28	>53

Curve numbers (CNI and CNIII) can be calculated from average Antecedent (AMC II) conditions using equation (3 and 4).

$$CN(I) = \frac{CN(II)}{2.281 - 0.0128CN(II)} \tag{3}$$

$$CN(III) = \frac{CN(II)}{0.427 - 0.00573CN(II)} \tag{4}$$

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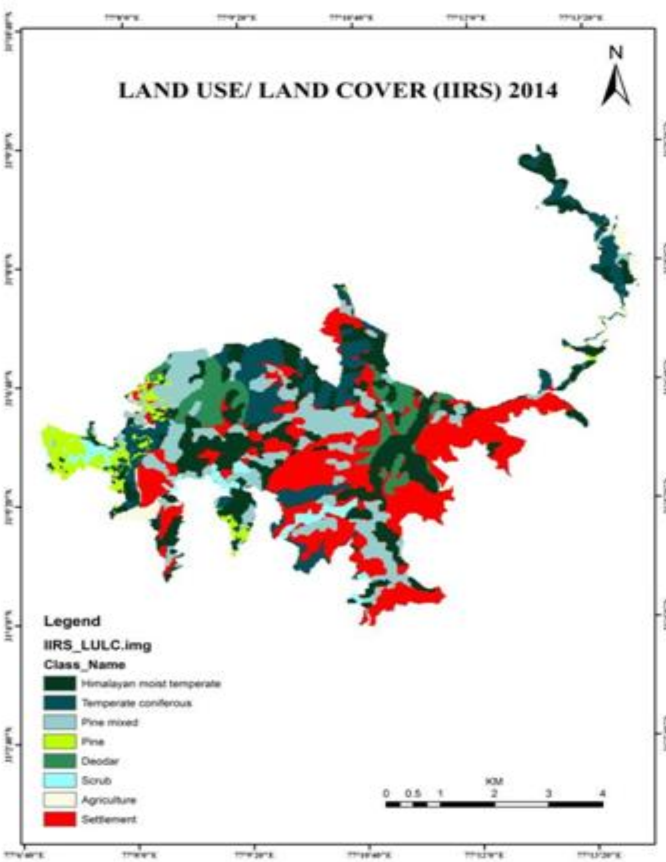
Results and Discussions

LANDUSE/LANDCOVER

Fig. 4 **Fig. 5**



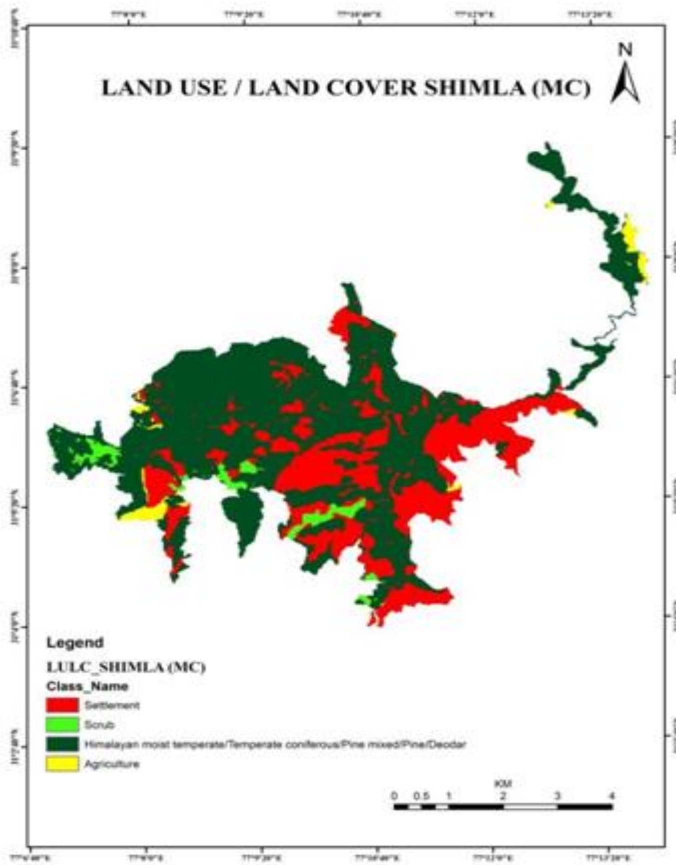


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Fig 6 SOIL MAP

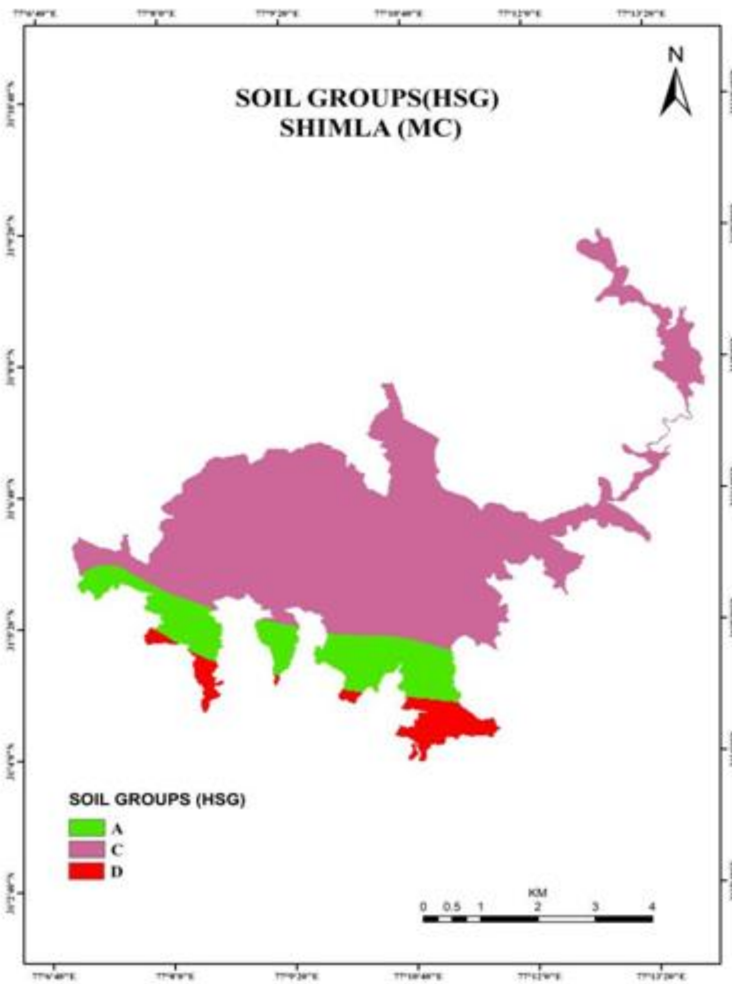

Fig 7 SLOPE MAP

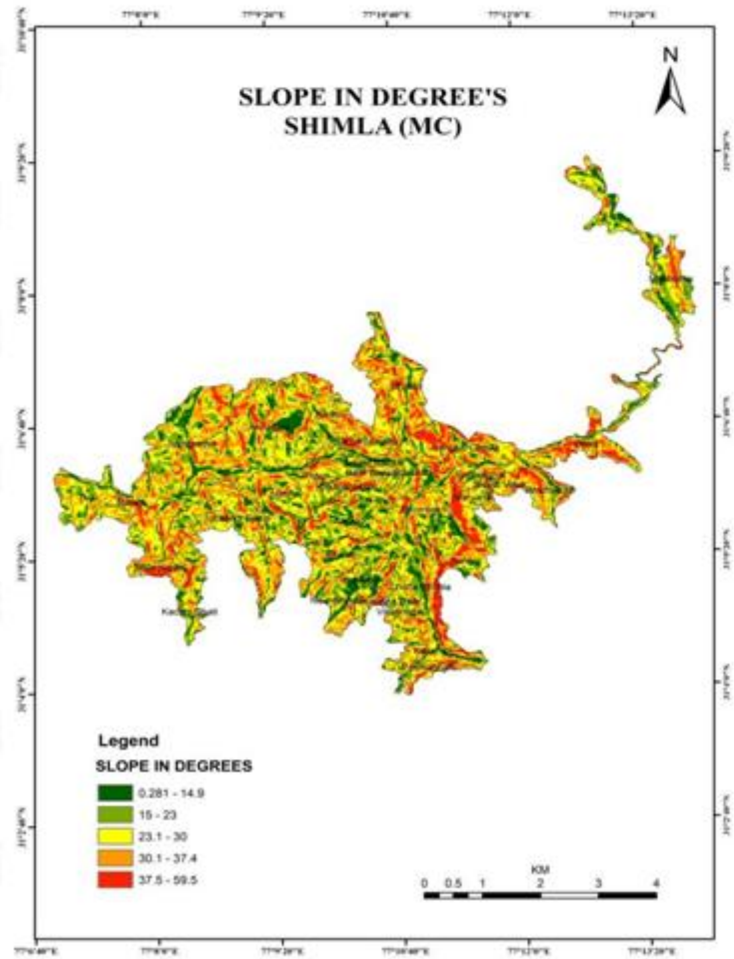

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Fig 8 CN I MAP

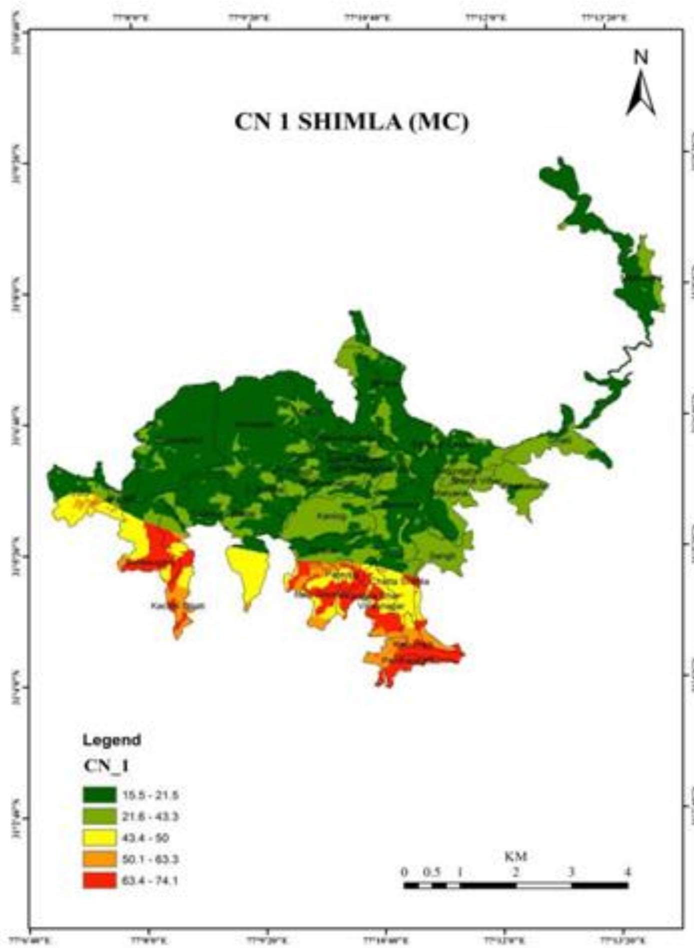

Fig 9 CN III MAP

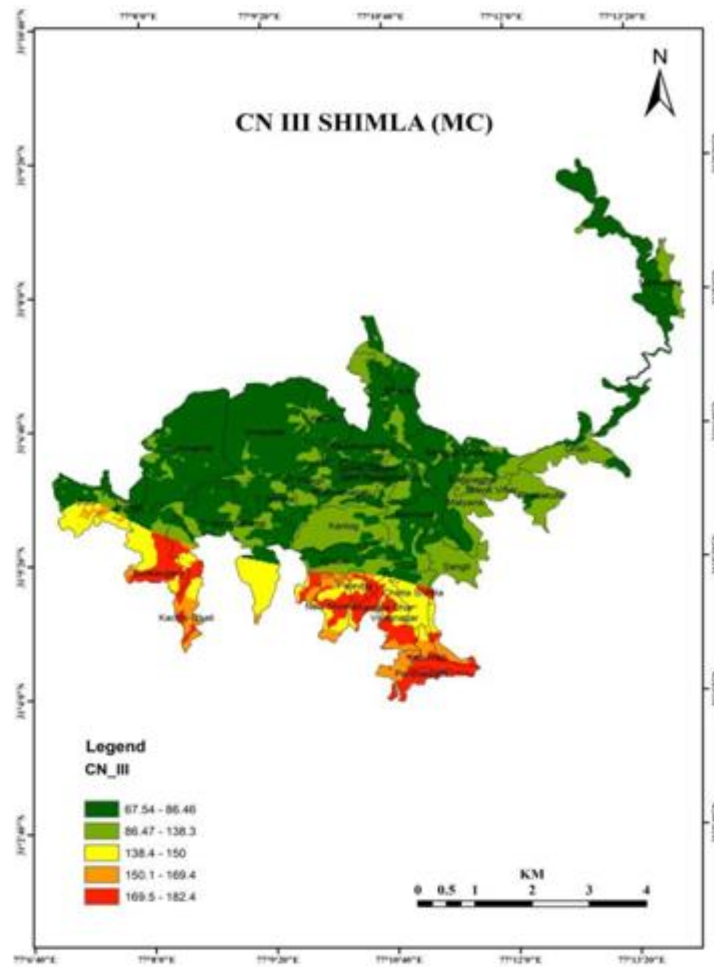

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Fig 10 Potential maximum retention(s)

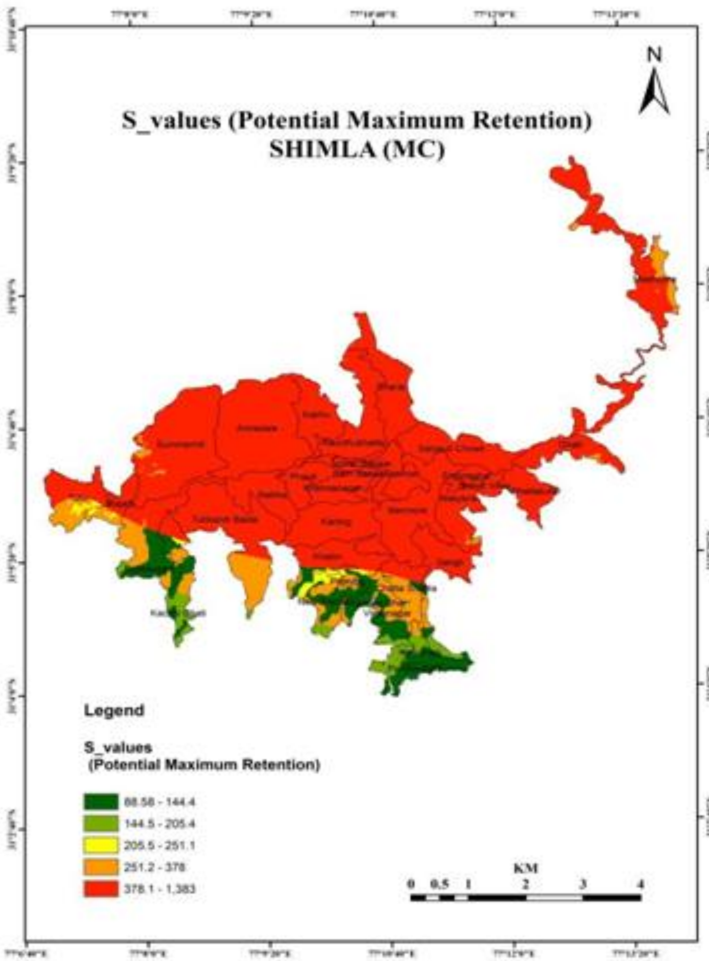

Fig 11 WATERSHED

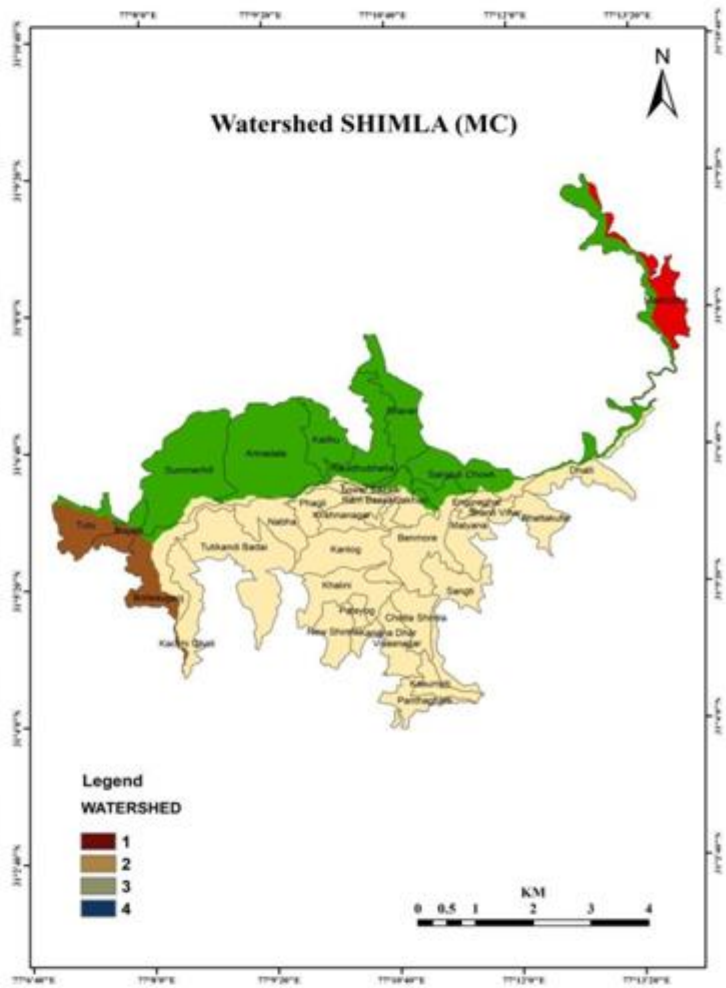

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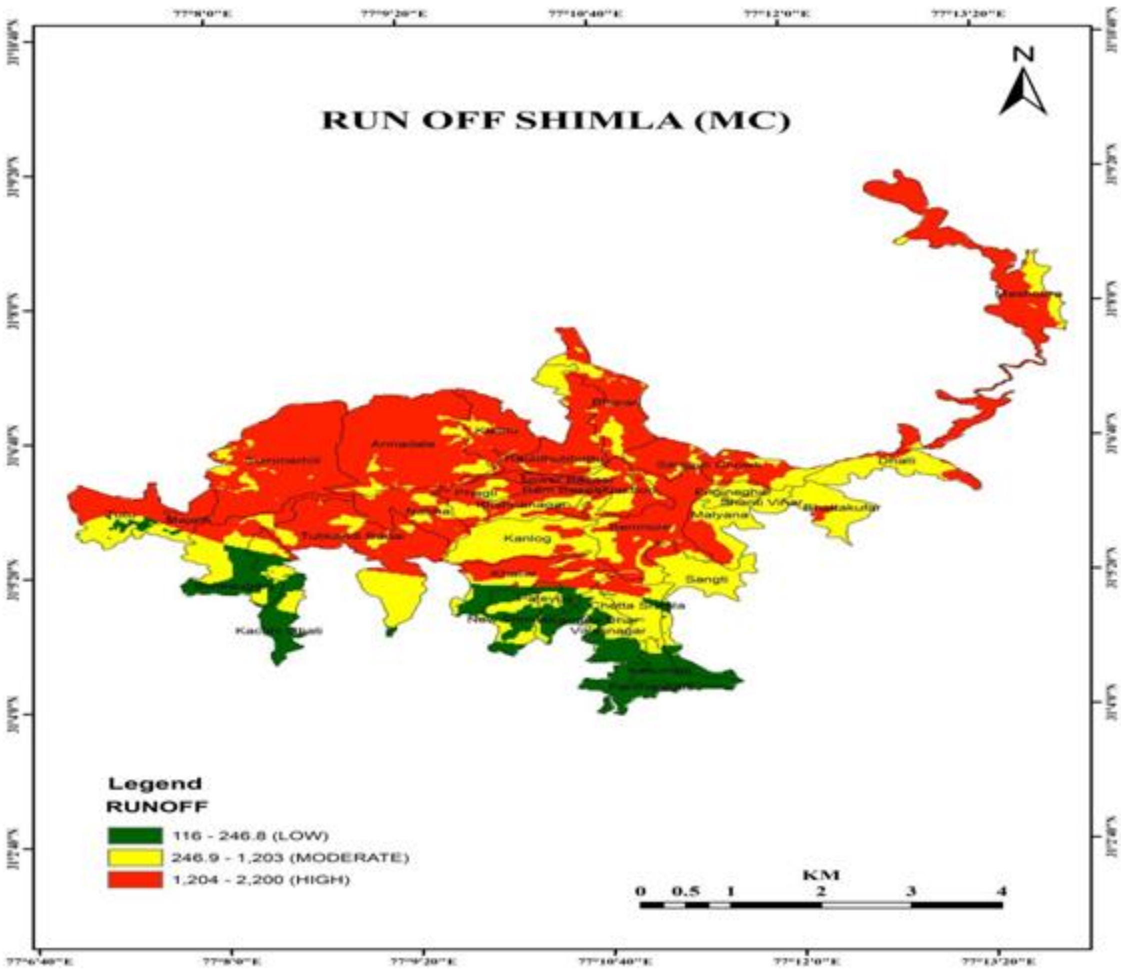
Fig12 RUNOFF MAP



Conclusion

Soil Conservation service and Curve Number model have been utilized in the present work by land use map and soil map described in ArcGIS, as input. The monthly rainfall runoff simulation found good in the watershed. The methodology for the tenacity of runoff utilizing GIS and SCS approach could be applied in other watersheds for orchestrating of sundry conservation measures. The study is conducted for Shimla urban which is a very small area of a watershed and it is found that runoff in the Himalayan region like Shimla is more dependent upon slope as compare to the soil type. It is found that northern part of Shimla has high runoff estimation then the south due to the slope and type c category of soil as mentioned in the HSG group of soils. The good soil and water conservation measures need be planned and implemented in the study area which is classified as high followed by moderately for controlling runoff and soil loss. In

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SCN Curve number method Antecedent moisture condition of the soil plays a very consequential role because the CN number varies according to the soil and that is considered while estimating runoff depth.

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