Rainfall-Runoff Estimation in the North-Eastern Region of Bangladesh Using SCS-CN Method

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ABSTRACT: Measuring discharge in a developing nation like Bangladesh is very important for flood prediction, land management, and sustainable development. Rainfall-induced runoff is a part of the cycle of hydrology and is required for efficient water resource planning. The most significant debatable procedure in hydrology is calculating and determining catchment surface runoff. The study aims to estimate runoff using the GIS-based Soil Conservation Service-Curve Number method (SCS – CN) method, where this hydrological model has a physical foundation and spatial distribution, and the curve number plays a key role in this model's runoff computation. The Hydrologic Soil Group (HSG) present in the study area and the land use pattern are used to find the Curve Number (CN). The calculated weighted CN for Antecedent Moisture Condition (AMC) I, II, and III for the study area was roughly 74.78, 87.12, and 94.06 respectively with the incorporation of Land use and land cover (LULC) and HSG. For total average rainfall of 35163.8mm, the SCS-CN approach determined the total average runoff 16077.55 mm for the period of 2009-2018. With a correlation coefficient of 0.966, the average rainfall and SCS-CN discharge have a significant linear relationship. The runoff regulates the amount of water that enters stream systems and returns extra precipitation to the ocean benefitting the hydrological cycle. With this runoff estimation, the quality and amount of water resources can be better understood, managed, and tracked.

Keywords: Rainfall-Runoff Estimation; Hydrological Model; Land use Pattern; Remote Sensing; Soil Conservation Service-Curve Number method (SCS – CN); North-Eastern Region of Bangladesh

INTRODUCTION

Bangladesh is a South-Asian country that is most sensitive to the detrimental effects of climate change due to its tropical monsoon with heavy seasonal rainfall, high temperatures, and high humidity (Akter et al., 2019; Akter Mitu et al., 2018). It is referred to as a riverine country because of its abundance of national and international rivers that change frequently due to the force of natural and anthropogenic influences (Akter et al., 2019). Bangladesh's agriculture is highly dependent on these rivers' flow and discharge (Uddin et al., 2018). According to the prediction, the temperature and rainfall pattern of Bangladesh will change due to climate change. It is anticipated that the main rivers' stream flows will alter as the pattern of rainfall changes (Akter et al., 2019). River discharge and variations in rainfall characteristics are the two most important hydrological factors that influence the amount of water in rivers and the most important effects of climate change. Bangladesh's average annual rainfall has significantly increased, but Sylhet has experienced a declining pattern (Uddin et al., 2018). During periods of intense rainfall in the uplands, water quickly travels through a number of rivers and tributaries and into the haor-featured basin, where it creates flooding. As a result, haor areas in the northeast of the country (Netrokona, Sherpur, Sunamganj, Sylhet, Moulvi Bazar. and Habiganj) experience flash floods which cause damages in those areas (Basir et al., 2020).

The northeastern region of Bangladesh is comprised of hilly areas, which causes the terrain of this region to sunken below the surrounding areas (Basir et al., 2020). Numerous haors and low-lying parts of northeast Bangladesh have experienced early flooding as a result of heavy rainfalls and runoff from India's upstream hills (Ali and Rahman, 2017). The country experiences widespread flooding as a result of monsoon rainfall and inadequate drainage systems. The west to northeast regions of Bangladesh sees significant monsoon rainfalls from June to October, with an annual average rainfall ranging from 1200 mm to 5800 mm. The amount of water that enters outlet waterways following a downpour depends on catchment features. River features and nearby infrastructure influence the

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economic, social and environmental effects of flooding. Therefore, analyzing flood episodes and the catchment's response to high rainfall is important (Basir et al., 2020).

There are some studies on flow distribution and sediment transport in the Ganges-Brahmaputra-Meghna (GBM) basin, studies on the Brahmaputra basin that has used an established linear regression model between rainfall and stream flow to predict changes in future flow, studies on the effects on the peak flow of Meghna River basin due to climate change (Basir et al., 2016; Akter et al., 2019). Hydrological modeling and the detection and quantification of spatial-temporal trends and changing patterns of rainfall are crucial for planning and managing water resources, forecasting floods, and many other uses (Thakural et al., 2019). Due to the ability to simulate water management system, hydrological models are an effective tool for determining how well human and environmental needs are balanced (Setegn et al., 2015**.** However, this requires a huge amount of data. Hydrological modeling faces several challenges arising from data limitations, model constraints, and other factors. In terms of data, the reliance on extensive datasets for precipitation, streamflow, and groundwater levels introduces vulnerabilities to incomplete or inaccurate information, potentially yielding unreliable predictions (Beven, 2001). The precision may be limited by the spatial and temporal resolution of the available data (Sivapalan et al., 2005). It is also difficult to validate and calibrate the models due to its scale dependency (Sivapalan et al., 2003) and several uncertainties (Beven & Young, 2013), which highly affect the performance of the model in a variety of scenarios. Also, simplification of the complex natural processes, such as evapotranspiration, through simplified equations, potentially leading to inaccuracies, especially in extreme events (Abbott et al., 2017). Additionally, hydrological models often overlook human impacts like water withdrawals and land use changes, potentially resulting in inadequate simulations of future scenarios (Hrachowitz et al., 2015). However, the most significant contestable procedure in hydrology is the determination of catchment surface runoff (Viji et al., 2015) which can be estimated using conceptual rainfall-runoff models, data-driven models and SCS-CN curve. Conceptual rainfall-runoff models offer a physically based representation with adaptability but demand extensive data and resources for calibration (Beven, 2001). Data-driven models, while flexible and potentially accurate, have a black-box nature, an overfitting risk, and are highly dependent on the quality of training data (Hrachowitz et al., 2015). However, the Soil Conservation Service-Curve Number method is still the most widely accepted, successful, and practical approach. It is widely used because of its simplicity and accessibility. A crucial component of the SCS-CN approach is the runoff curve number (CN), which depends on the soil type, antecedent soil moisture, and land use/land cover (LULC) (KUMAR & GK, 2017). Different parameters, such as land use and land cover, hydrological soil characteristics, rainfall data, weighted curve number, etc. that are required inputs to the SCS model, have either been derived from available remote sensing data or from in-situ data which is highly expensive and difficult to access (Sharma Suresh Gyan Vihar & Kanga, 2020; Viji et al., 2015)the SCS-CN method still remains the most popular, fruitful and frequently used method. Runoff curve number (CN.

The SCS-CN (Soil Conservation Service Curve Number) method plays a vital role in estimating surface runoff in Bangladesh, a country highly vulnerable to floods and water scarcity. In flood management, the method contributes to forecasting, early warning systems, and the design of flood control infrastructure. It also aids in identifying flood-prone areas, supporting floodplain management strategies. In sustainable water resource planning, the SCS-CN method assists in water harvesting, groundwater recharge assessment, and land-use management for sustainable agriculture. Additionally, it can be adapted to assess climate change impacts on water resources. Challenges include the need for accurate data, local calibration, and integration with other tools and knowledge. Community engagement is crucial for effective flood management and sustainable water resource planning. In conclusion, the SCS-CN method, when adapted to local conditions and combined with other tools, offers valuable insights for policymaking in Bangladesh, contributing to flood resilience, water security, and sustainable water management practices. However, there aren't many studies that used SCS-CN method to estimate the rainfall-runoff, therefore, rainfall-runoff is estimated for the northeastern region of Bangladesh using SCS-CN method.

STUDY AREA

Bangladesh is a country which is known for its heavy rains lies in the South Asia in the northeastern region of the Indian subcontinent that is situated in the

Ganges-Brahmaputra-Meghna River system delta. Northeastern Bangladesh experiences the highest average precipitation, often exceeding 4000 mm per year, due to its location immediately south of the foothills of the Himalayas, when monsoon winds veer west and northwest.

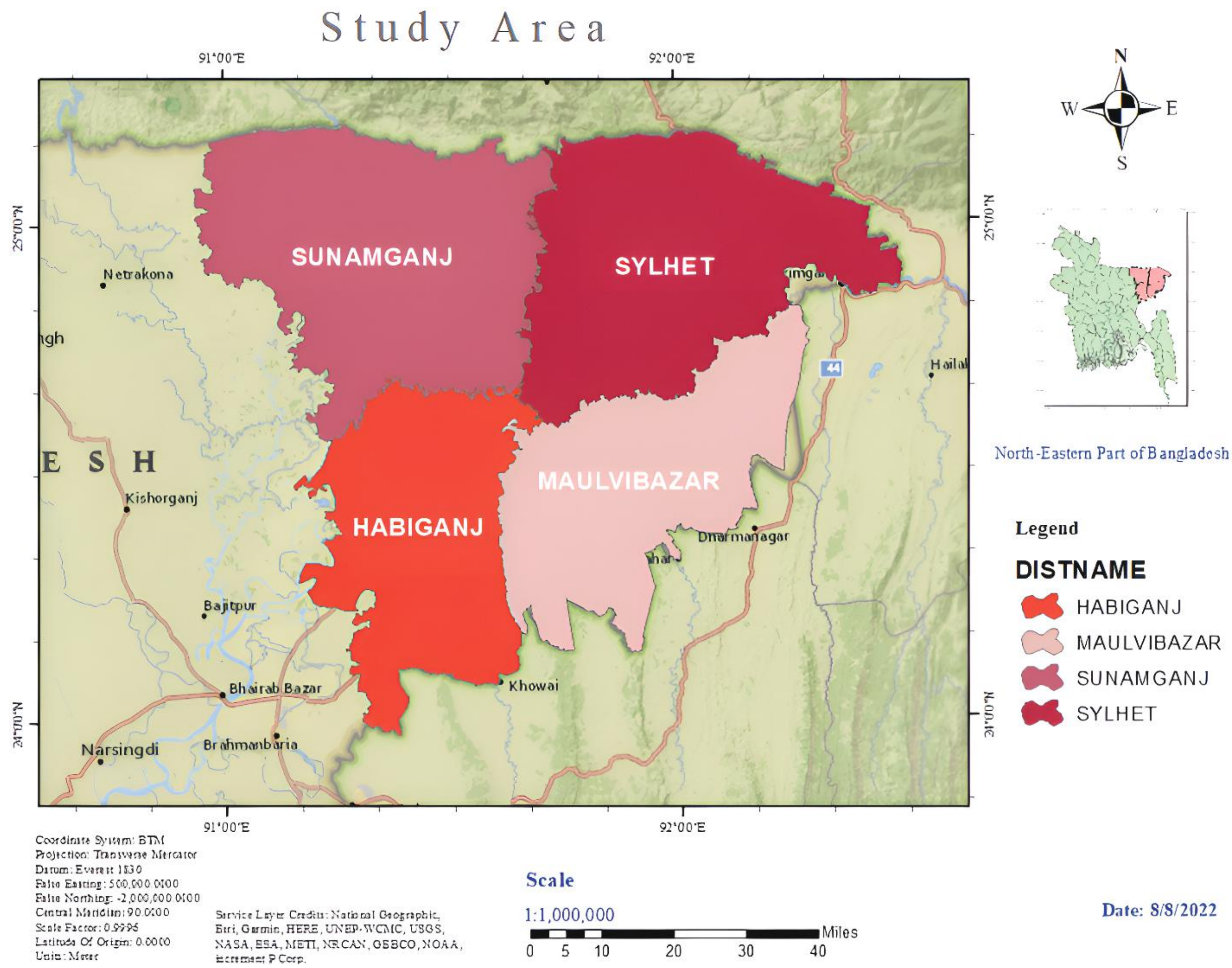


Figure 1: North-Eastern Region of Bangladesh

The earth's groundwater is restocked by a portion of the precipitation but most of it runs off in a downward direction. Runoff is crucial because it not only maintains the level of rivers and lakes but also alters the environment due to erosion. One of the most prevalent and pervasive severe weather risks that impact Sylhet is heavy rainfall. As Sylhet is a hilly area, current state of this natural drainage is not feasible causing frequent occurrence of water logging. Due to the significant amount of rain, many areas of Sylhet are experiencing serious inundation issues. This is why, it is necessary to estimate the runoff due to rainfall for this region.

MATERIALS AND METHODS

The daily runoff was estimated for the period of 2009-2018 using SCS-CN method. To estimate the rainfall-runoff, spatial datasets (landuse/landcover map, soil map) and meteorological dataset (rainfall) were used. Then SCS-CN runoff simulation was done finalizing the input for the method.

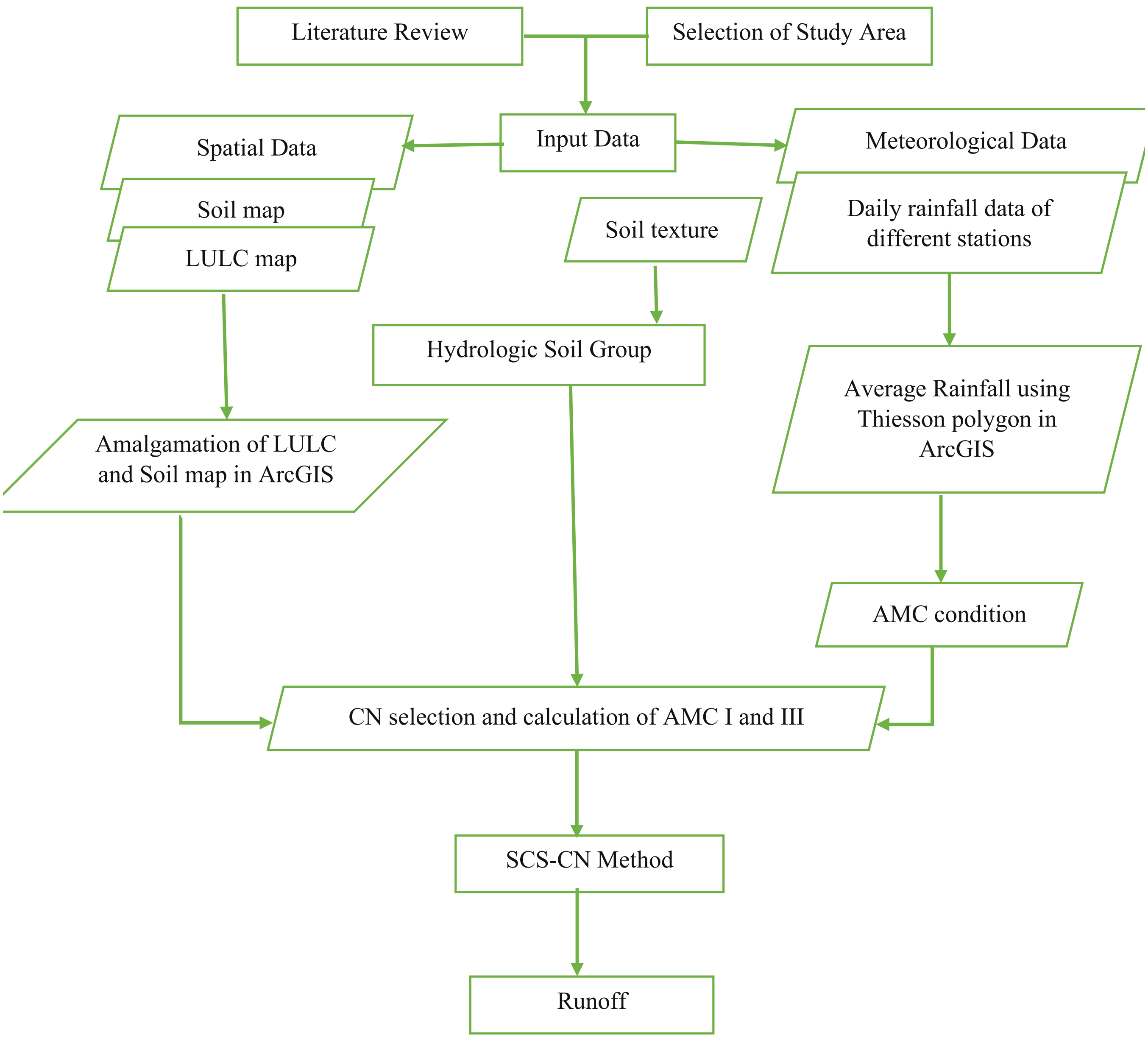


Figure 2: Methodological Framework of the Study

SCS-CN Method

The SCS-CN method is a simple, popular, and useful method to estimate how much runoff due to rainfall will occur. The approach can be scaled to determine average yearly runoff values even if it is meant to be used for a single event (Sharma Suresh Gyan Vihar & Kanga, 2020). The water balance equation serves as the foundation for the SCS-CN approach. After deriving equations, the main equation to estimate the runoff is as follows-

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

where,

Q = Actual runoff in mm

P = Average rainfall in mm

Ia = Initial abstraction representing all the losses before the runoff begins and is given by the empirical equation.

$$Ia = 0.2S \qquad (2)$$

After substituting the eq. (1) becomes

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

For, P>Ia (0.2S)

which is otherwise Q = 0

S = Potential infiltration after the runoff given by following equation-

$$S = \frac{25400}{CN} - 254$$

The only statistics needed for this procedure are the amount of rainfall and the curve number. A table based on land-cover, HSG, and AMC is used to determine the CN (dimensionless number between 0 and 100).

Hydrologic Soil Group (HSG)

In the methods of estimating runoff, soil characteristics affect the creation of runoff following rainfall. The classification of different soils into hydrologic soil groups was done using a soil map created by the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP) and a soil report of the study region. When classifying soils into various hydrologic soil groups, the SCS-CN soil classification method was used. According to their characteristics, soils are categorized into the A, B, C, or D hydrologic soil groups in this categorization system according to *USDA-SCS Soil Classification*.

Antecedent Soil Moisture Condition (AMC)

Antecedent Moisture Condition (AMC) describes how much water is in the soil at any one period. It is a crucial aspect in figuring out the actual CN value. According to the characteristics of the soil and the maximum allowable rainfall for the dormant and growing seasons, SCS constructed three antecedent soil-moisture situations and designated them as I, II, and III.

Table 1: Classification of Antecedent Soil Moisture Condition

AMC class	Soil characteristics	Total 5day antecedent rainfall (mm)	
		Dormant season	Growing season
AMC-I	Dry condition	< 13 mm	< 36 mm
AMC-II	Average condition	13-28 mm	36-53 mm
AMC-III	Wet condition	> 28 mm	> 53 mm

(Source: Handbook of Hydrology, 1972)

For different land conditions, there is a variation of the curve number under AMC (II) termed CN(II). The equation is given below-

$$CN_w = \frac{\sum(CN_i * A_i)}{A}$$

Where, CN_w = Weighted curve number

CN_i = Curve number from 1 to any number

A_i = Area with curve number CN_i

A = Total area

The hydrological equations are used to determine the surface runoff based on the amount of rainfall (P) and watershed storage (S), which are determined from the adjusted CN. As a result, it is necessary to determine S for AMC. The polygons representing the land use-soil group within the watershed were used to determine the area-weighting that produced the weighted curve number.

Landuse and Landcover Map

Since LULC gives information on present land use and patterning. With the aid of USGS-obtained Landsat-8 ETM satellite image with a 30m resolution, the LULC map of the research area was created. The study area was divided into various LULC classes. The cluster was identified by its spectral characteristics. This map is important because different landuse have different infiltration rate. If there is more built-up area, the runoff of that area will be more. Moreover, curve number values are different for different landuse as per the soil texture which is a crucial element in estimating runoff using SCS-CN method.

Soil Texture Map

For figuring out the HSG, the soil's texture is crucial. It is a fundamental variable to investigate the relationship between soil and its hydraulic properties and soil. According to various soil fractions, soil textures are divided into several main categories (sand, silt, and clay). Some areas soil has mixed type of textures including sandy loam, sandy clay, silty clay and combination of these etc. Soil texture map is important for SCS-CN approach because the CN values change depending on this texture.

Rainfall Data

Rainfall data is the most important parameter in this method. There were two stations (Sylhet and Srimangal) in the study area by balancing the impact of the area in the shape of the polygon closest to the station, rainfall data from the two stations in the study area are converted into average rainfall using the Thiesson Polygon tool in ArcGIS. As a result, it seeks to account for any errors brought on by the uneven distribution of rain gauges. The area's typical annual precipitation is provided by-

$$P = (P1B1 + P2B2 + \cdots + PnBn)/ (B1 + B2+. . . +Bn)$$

where, B1, B2…., Bn =Areas of the Thiesson polygon representing the stations 1, 2….,n.

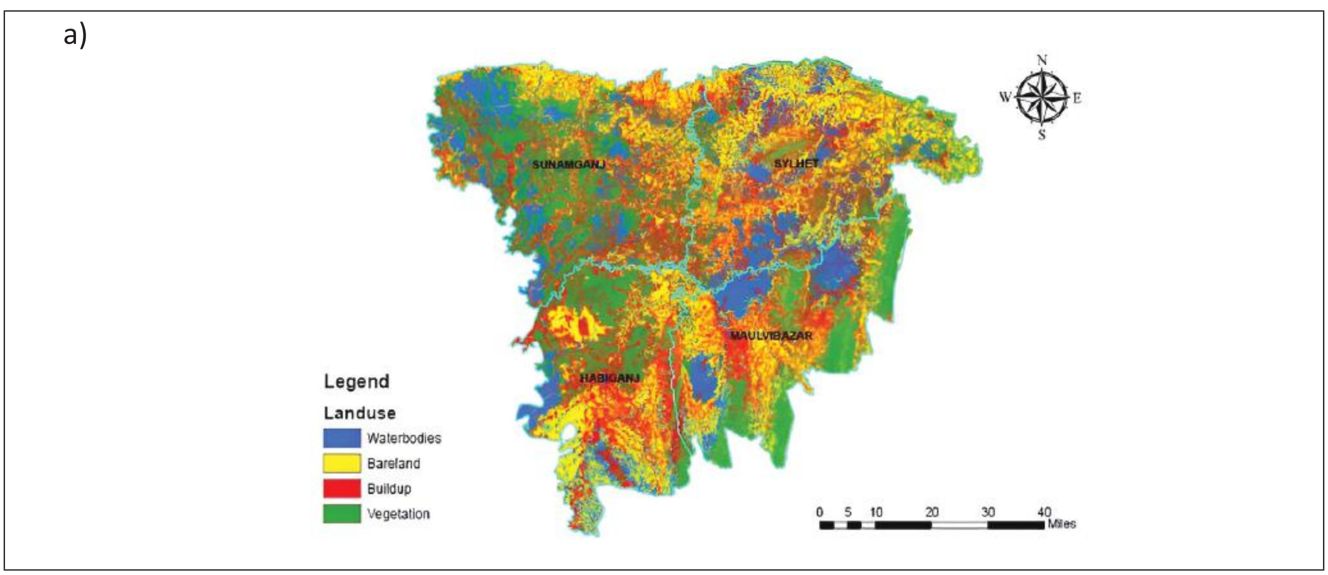
P1, P2, …., Pn= Precipitations of corresponding stations.

A= Total area of the catchment.

RESULTS AND DISCUSSIONS

Factor Maps

Landuse Map: The LULC maps (Fig. 3) were developed only considering four main classes including waterbodies, bareland, vegetation and buildup areas. The map shows that the area for different landuse mostly waterbodies are changing frequently over time. The vegetation areas are decreasing day by day whereas buildup areas are increasing. An accuracy assessment was carried out which shows that the accuracy of each of the classification were 87.54%, 89.5%, 84.37% and 91.2% for the year of 2015, 2016, 2017 and 2018 respectively.



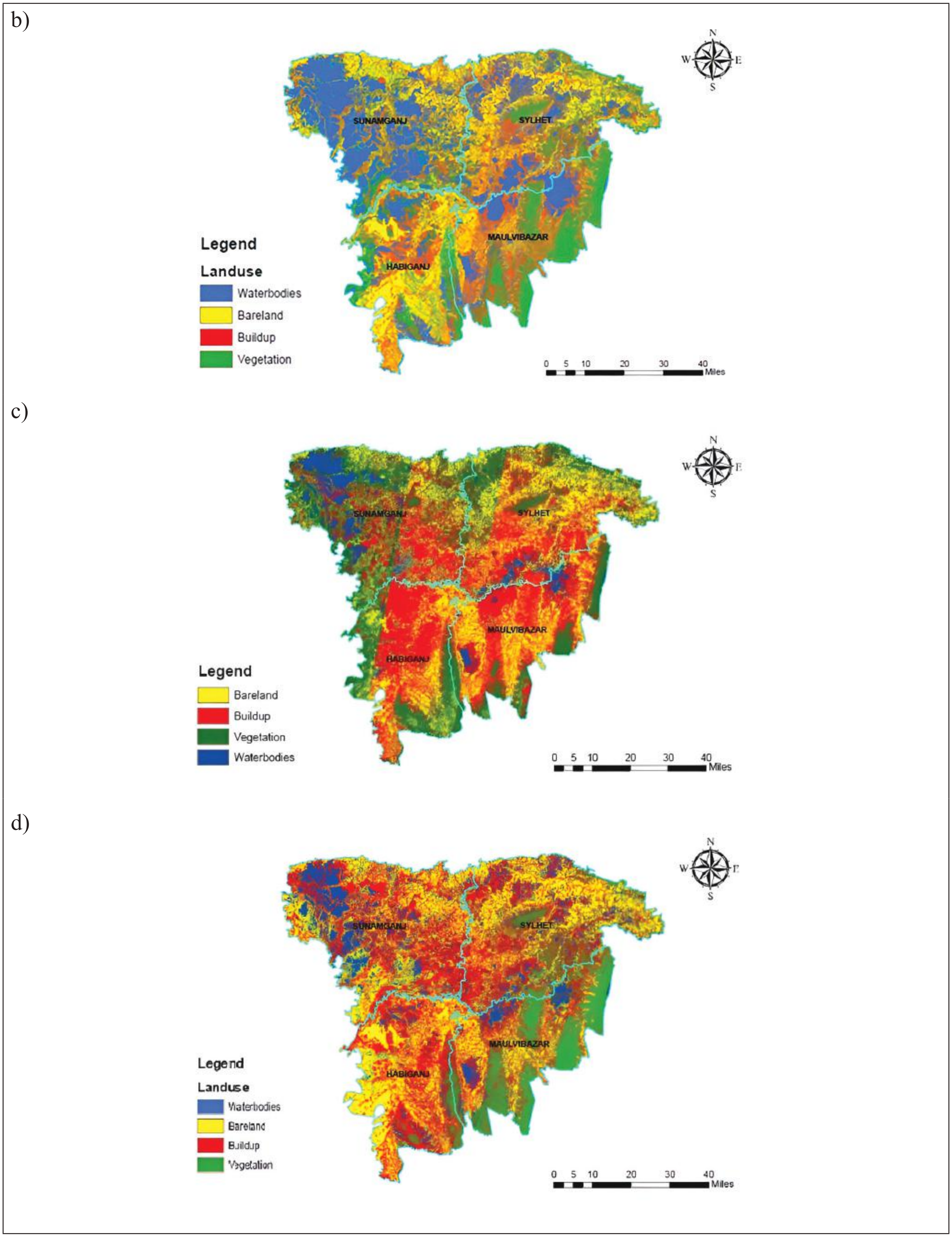


Figure 3: Landuse Classification Map of a) 2015; b) 2016; c) 2017; d) 2018

Soil Texture: Four different kinds of soil texture, namely silty loam, sandy loam, mixed silty clay loam and clay loam, mixed silty clay and silty clay loam (Fig. 5) were found in the study region after generalizing the map. The percentage area of each of the class was 29.71%, 20.23%, 26.8% and 23.26% respectively. Silty loam is characterized by moderate infiltration rate, sandy loam is characterized by low infiltration rate, mixed silty clay loam and clay loam as well as mixed silty clay and silty clay loam soil have a high infiltration rate. If the infiltration rate is high, the runoff automatically becomes low. In most of the cases, forest or vegetation areas have silty clay or silty clay loam type soil textures resulting in high infiltration rate. As a result, the runoff is less in the forest areas.

Hydrologic Soil Group: There are mainly 4 different classes of HSG including class A, B, C and D. In the study area, there were no landuse class or soil texture that belonged to class C. very few percent of area belonged to class D as there was less vegetation in that area. Most of the area belonged to the class D. The percentage of each of the HSG class A, B and D were 14.23%, 33.8% and 51.97 respectively. From the study area, it can be said that, Sunamganj area have class B and D of hydrologic soil group. All the other three areas have all the three class within them. As most of the classes belonged to class D, it can be said that Sylhet district is made up on silty clay type soil mostly.

Curve Number, Weighted Curve Number and Antecedent Soil Moisture Content: Using ArcGIS, the various layers were sequentially layered to produce a new attribute table. The result was utilized to determine the research area's total weighted CN and compute the CN (II). The other weighted CN were calculated from CN(II) and then computed according to the equation. The AMC condition has then been approximated for each rainfall data set. The percentage area for the CN 98, 86 and 77 were 19.26%, 67.51% and 13.23%. The weighted CN were 74.78, 87.12 and 94.06 respectively.

CN values are the most significant parameter in SCS-CN method. It is a primary input for the method. If the CN value is low, it represents low runoff potential as the soil is thought of more permeable. This CN value changes as per the factor maps.

Table 2: Classification of Different Landuse and Landcover and Their Weighted Curve Number

Class	% Area	HSG	CN	% Area * CN	Weighted Curve Number
Waterbodies	19.26	D	98	1887.48	Weighted CN I = 74.78 Weighted CN II = 87.12 Weighted CN III = 94.06
Bareland	31.8	B	86	2734.8	
Vegetation	13.23	A	77	1018.71	
Buildup	35.71	D	86	3071.06	
Total	100			8712.05	

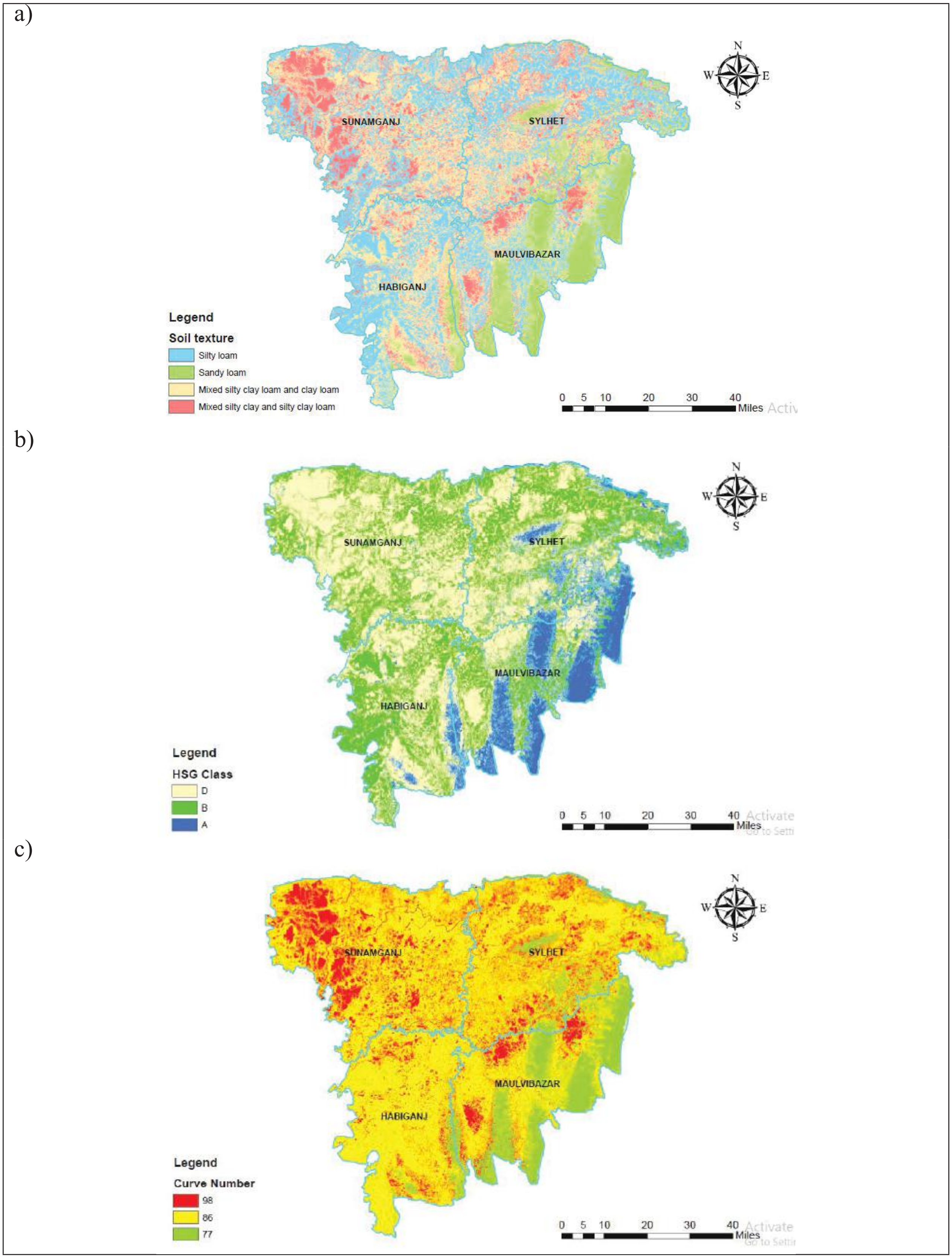


Figure 4. The Following Maps are (a) Soil Texture (b) Hydrologic Soil Group and (c) Curve Number

Assessment of Average Rainfall by Thiessen Polygon Tool

Runoff is estimated from two raingauge stations from the study area through theissen polygon method to remove the error due to varying rainfall distribution of stations. The stations that were used to find the weighted area are Sylhet station and Srimangal station of Sylhet region. The weighted areas of the polygons were 0.63 and 0.37 respectively.

Rainfall-Runoff Estimation

Daily precipitation data for the years 2009 to 2018 has been used. According to the SCS Curve number, the region's highest rainfall occurred in the year of 2017 which was 5155.53mm. It is the average rainfall that had been calculated through Theissen polygon. The lowest rainfall occurred in the year of 2011 which was 2712.13mm. From the Figure 5, it can be said that most of the years experienced more than 3000mm average annual rainfall. The amount of average rainfall for each of the years were 2978.05mm, 3958.87mm, 2712.13mm, 3617.29mm, 3279.99mm, 2968.7mm, 3779.89mm, 3648.5mm, 5155.53mm and 3064.85mm respectively from the year of 2009 to 2018. The total average rainfall that the area experienced was 35163.8mm.

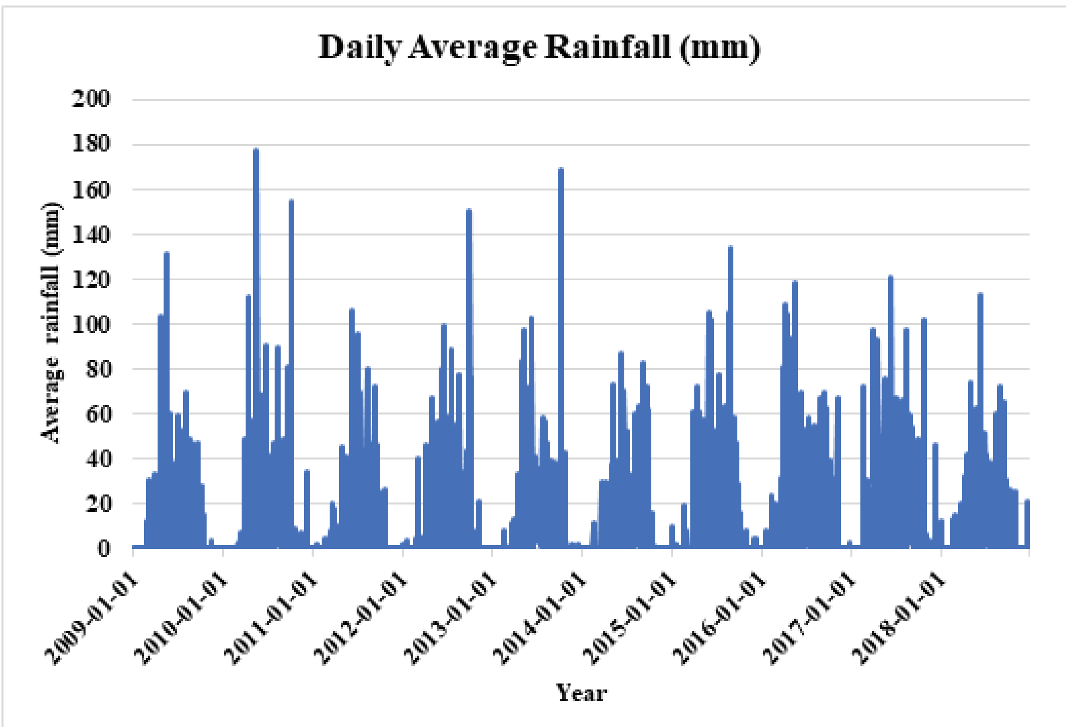


Figure 5: Daily Average Rainfall Variation

Runoff Calculation using SCS Method

Daily runoff for the years 2009 to 2018 has been calculated. According to the SCS Curve number, the region's highest runoff occurred in the year of 2017 which was 2761.51mm. It is the average runoff that had been calculated from the average rainfall data. The lowest runoff occurred in the year of 2011 which was 1051.12mm. From the graph, it can be said that most of the years experienced more than 1500mm average annual runoff. The total average runoff that the area experienced was 16077.57mm.

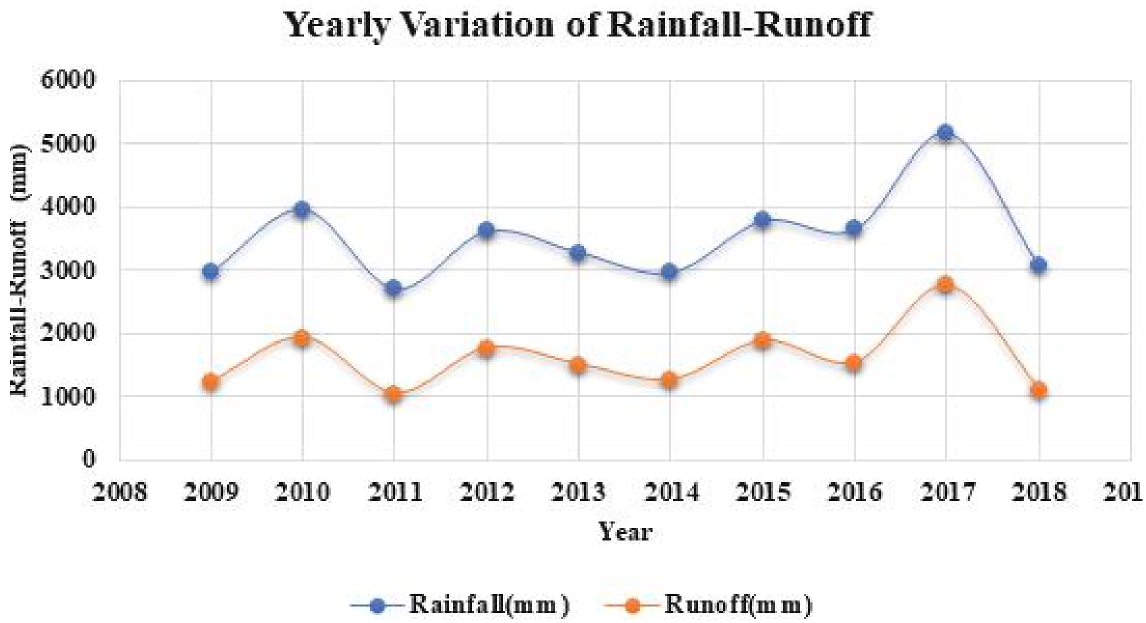


Figure 6: Annual Rainfall and Simulated Runoff by SCS-CN Method

Simulated runoff is almost linear to the average rainfall. When there is more rainfall, there is more runoff. The runoff fluctuates from 1051.12–2761.505 mm (2009–2018) and the rainfall fluctuates between 2712.13 to 5155.53 mm.

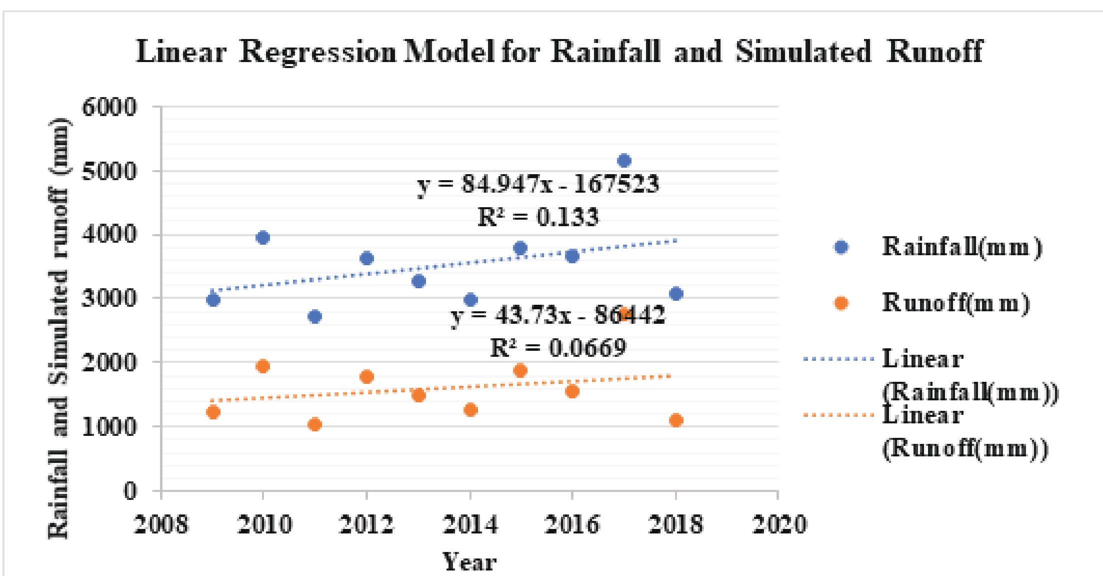


Figure 7: Comparison between Linear Regression Model of Average Rainfall and Simulated Runoff (SCS-CN Method)

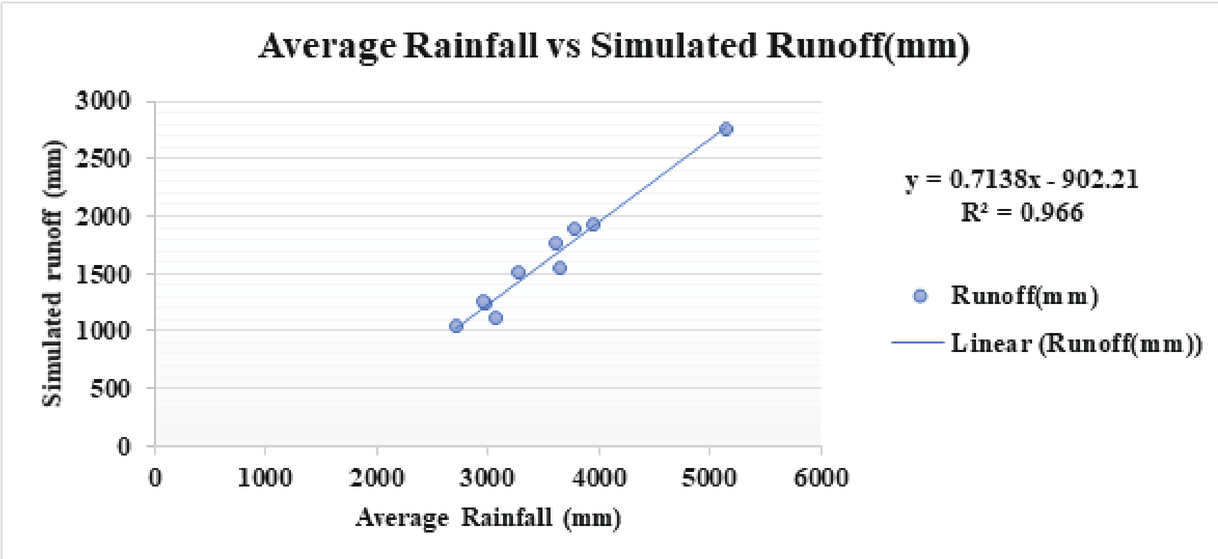


Figure 8: Average Rainfall -Simulated Runoff Correlation

With a correlation coefficient of 0.966, the scatter-plot represents a significant graphical association between the average rainfall and the calculated runoff. The magnitude of the area's response to runoff generation may be usefully revealed by this coefficient. From the R2 value, the relationship between rainfall and runoff can be understood.

The SCS-CN method used precipitation data from 2009-2018 of two stations. The average rainfall has been calculated using Thiessen polygon method in ArcGIS. According to the SCS Curve number, the region had maximum runoff in 2017 of 2761.51mm and minimum runoff of 1051.12mm in 2011. The range of the runoff is 1051.12-2761.505 mm (2009–2018), and the average rainfall ranges from 2712.13 to 5155.53 mm. The average rainfall is linearly related to the simulated runoff. The scatter-plot demonstrates a substantial linear link between the average rainfall and runoff with a correlation coefficient of 0.966. The area's reaction to runoff generation may be inferred from this coefficient.

CONCLUSION

GIS-based SCS-CN methodology is useful for estimating runoff requiring less time and with the capability of handling huge data as well as a larger area structures and may also be efficiently used in watershed management.

In this study, LULC and soil texture map from ArcGIS were used together with the SCS-CN method. Ae the CN number varies depending on the soil, it is important to consider the soil's antecedent moisture status while using the SCN Curve number approach to estimate runoff. The LULC map of the study area was created considering four main classes including waterbodies, bare land, vegetation and buildup areas. The runoff is more for higher CN values and less for lower CN values. The thick forest's great infiltration capacity caused the runoff to be low in the dense forest and high in the built-up land's hard surface. The water body receives all of the rainfall as runoff.

Even though the SCS-CN approach is frequently applied to estimate runoff, further adjustment is required before it can be used in the tropics as the climatic conditions, soil types, and land use cover differ from temperate areas. Developing the curve number for the landuse is necessary and crucial to improve runoff estimation for improved basin area management. However, calibrating and validating takes a lot of time, resources, and money but it is a useful tool as it offers information on runoff potential, erosion risk, and the effects of changing land use on the water cycle.

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