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Rainfall Runoff Estimation Using GIS and SCS-CN Method for Awash River Basin, Ethiopia

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Abstract

Understanding hydrological behavior is an important part of effective watershed management and planning. Runoff resulted from rainfall is a component of hydrological behavior that is needed for efficient water resource planning. In this paper, GIS based SCS-CN runoff simulation model was applied to estimate rainfall runoff in Awash river basin. Global Curve Number (GCN250), Maximum Soil Water Retention (S) and Rainfall was used as an input for SCS-CN runoff simulation model. The final surface runoff values for the Awash river basin were generated on the basis of total annual rainfall and maximum soil water retention potential (S) of the year 2020. Accordingly, a runoff variation that range from 83.95 mm/year to a maximum of 1,416.75 mm/year were observed in the study region. Conversely, recently developed Global Curve Number (GCN250) data was tested with Pearson correlation coefficient to be used as an input for SCS-CN runoff simulation model. The results of validation show that, predicted runoff was well correlated with observed runoff with correlation coefficient of 0.9253. Furthermore, correlation analysis was performed to explain the relationship between mean annual rainfall and surface runoff. The relationship between these two variables indicates a strong linear relationship with correlation coefficient of 0.9873.

Keywords: Global Curve Number (GCN250); Soil Conservation Service-Curve Number (SCS-CN) Maximum Soil Water Retention (S); Runoff ; Geographic Information System (GIS)

Introduction

Surface runoff at watershed scale significantly affects agriculture, environment and the availability of flood potential (Patil et al., 2008). Watershed runoff determines the hydraulic properties, soil erosion condition and even the potential yield of water resources within a given watershed [1]. Runoff from a watershed can be measured daily, monthly or annually depending on rainfall, infiltration rate and the characteristics of watershed [2]. Accurate estimation of surface runoff helps in designing irrigation schema, waterways, water harvesting and ground water resource management [3]. Accurate estimation of surface runoff can be achieved using hydrological modeling that takes into account the impacts of climate and land use on surface water balance [4]. Understanding rainfall and runoff is essential for the assessment of water availability. Correct runoff assessment is done for useful control and improvement of water resources [5]. Evaluation of water availability with the aid of an understanding of rainfall and runoff is vital. Hydro meteorological and hydrological statistics are an important position within the evaluation of supply water accessibility for the making plans and layout of synthetic recharge systems [6]. Surface runoff modeling is used to understand water availability, catchment yield and change over time in a given hydrological unit. Although rainfall runoff understanding is essential in hydrological applications, modeling surface rainfall runoff is difficult [7]. Numerous methods to compute runoff from a rainfall event have been developed. One of the most famous methods for predicting the surface runoff extent from a small watershed due to a rainstorm is the soil conservation service curve number (SCS-CN) method, now called the Natural Resource Conservation Service (NRCS)-CN method developed by the USDA-soil conservation service. The SCS-CN simulation model combines the parameters of the watershed with the climatic elements in a single entity referred to as the curve number (CN). A high CN shows low infiltration and excessive runoff, at the same time as a low CN implies excessive infiltration and low runoff. The SCS-N technique presents adequate consequences without the use of complicated statistics [8,9]. Supporting this statement, employed the SCS-CN approach for simulating the once-a-year depth of runoff over an ungauged catchment of Vindhyachal region. They revealed that the SCS-CN approach can be used efficiently to estimate the depth of runoff when there's no good enough hydrological data[10]. In addition, computed the runoff over a watershed inside the loess plateau of china with the SCS-CN approach and stated that the SCS-CN is a powerful and successful approach for estimating runoff. Runoff information at watershed scale is essential for the development of watershed planning for natural resource conservation. A number of hydrological models has been developed and used over years to predict the runoff information in different hydrological units. In recent years, SCS-CN number method has been widely used model to estimate runoff from spatial data. This method requires the property of soil permeability, [11]land use, and Antecedent soil moisture condition prior to the storm event. Although SCS-CN method can simulate rainfall runoff from soil, land use, and Antecedent soil moisture condition effectively, curve number (CN) generation from land use and hydrological soil group at basin scale requires intensive computational tasks. However, produced Global Curve Number (GCN250) with a spatial resolution of 250m at global scale[12]. This product can resolve intensive computational tasks in generating curve number at basin level. Therefore, the focus of this research work was testing GCN250 data to be used as an input for SCS-CN runoff simulation model at basin scale.

Study area

Awash River Basin is one of the most utilized basin on the basis of Awash river relative to the rest of twelve main basins of Ethiopia [13]. The geographic location of the Awash River basin is between 7°- 10°N latitudes and 38°- 41°E of longitudes. The river basin elevation ranges from 250m at Afar depression to 3000m of Addis Ababa highlands above mean sea level [14]. According to [13] Wabeshebele. Awash River basin covers an area of 112,000 KM^2 and the water volume of the River

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basin was estimated at around 4.9 billion cubic meters [15] (Figure 1).

Dataset

CHIRPS Rainfall data: Climate Hazard Group Infrared Precipitation (CHIRPS) data is a long-term temporal coverage data (1981 to present). It provides precipitation data at global scale with 0.05 x 0.05 degrees which is approximately five kilometers (5km) [16]. For this research work, CHIRPS data of the year 2020 was downloaded from (https://earlywarning.usgs.gov/fews) site freely. CHIRPS data archive provides rainfall data on daily, monthly and annual basis. For this study, the rainfall data of the twelve months was downloaded and processed to obtain the total annual rainfall of the year 2020.

Global Curve Number (GCN) data: Global Curve Number (GCN) is valuable data for rainfall runoff modelling. The first grided curve number data at global scale was created by [12]. The data was generated from ESA land cover map onward 2015 and Hydrological soil group data based on USDA curve number. The GCN data represent the curve number under wet, dry, and average conditions with 250m spatial resolution. For this project work, GCN with 250m spatial resolution was downloaded from (https://figshare.com/) website and clipped with study area extent.

Methods

SCS-CN runoff simulation Mode

SCS-CN model has been widely used model over years for runoff simulation [9]. The model is compatible with remote sensing data such as land use and soil type. Curve number (CN) quantifies the impact of soil and land use on rainfall runoff process. The SCS runoff model is based on the CN information and the model equation is given in equation (1).

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

Where, Q is direct runoff, P is total rainfall, λ is initial abstraction, and S is maximum soil water retention .Initial abstraction coefficient (λ) in equation (1) takes into account the infiltration, interception, and canopy content during early rainfall event [17]. Indicated that initial abstraction coefficient (λ) can vary between zero and infinity (0 and ∞). However, (Mockus, 1965) noted that initial abstraction coefficient (λ) is 0.2 for the general use of runoff simulation. Maximum soil water retention potential (S) can be calculated from dimensionless curve number (CN) as shown in equation (2).

$$S = \frac{25400}{CN} - 254 \tag{2}$$

Where, CN represents runoff potential which is determined by Antecedent Soil Moisture (AMC) condition. AMC describes pre-storm condition of the basin wetness and soil storage capacity. Three levels of AMC are identified, AMC I for wet condition, AMC II for normal (average) condition and AMC III for heavy rainfall condition. For rainfall runoff modelling purpose, CN value derived as a function AMC II for average condition (water) was applied for this project work. The following table (Table 1) depicts Antecedent soil moisture class for five-day rainfall.

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

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

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

Validation

The effectiveness of GCN250 data for rainfall runoff simulation was tested and quantified with Pearson correlation coefficient (R). The relationship between predicted runoff from GCN250 using SCS-CN simulation model was correlated with observed runoff obtained from station gauges of Awash river basin. The following equation

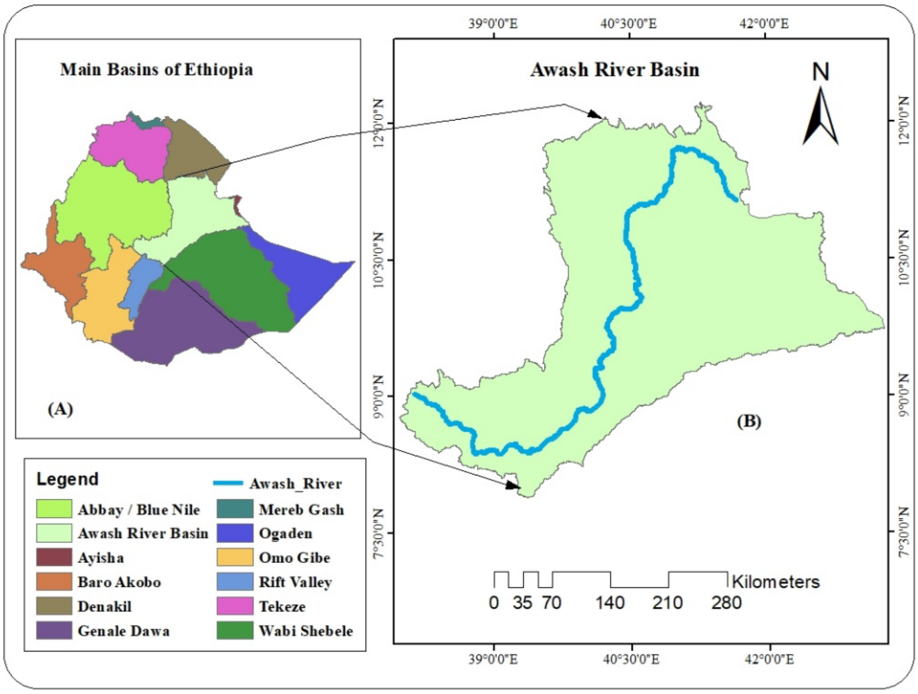

Figure 1: Geographic location.

Table 1: Five-day Antecedent Moisture Conditions.

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

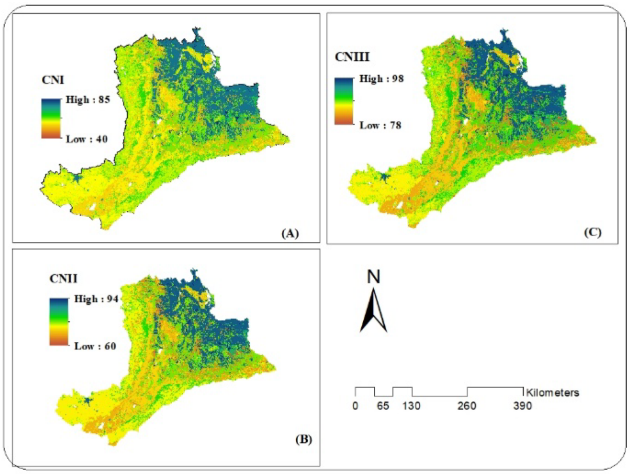

Figure 2: Curve Numbers.

(equation 6) can be applied to calculate coefficient of determination (R).

$$R = \frac{N\sum(P_o P_p) - \sum P_o \sum P_p}{\left[N\left(\sum\left(P_p{}^2 - \left(\sum(P_p)^2\right)\right)\right)\right]\left[N\left(\sum\left(P_o{}^2 - \left(\sum(P_p)^2\right)\right)\right)\right]} \quad (5)$$

Soil conservation service curve number (SCS-CN)

Curve number (CN) values for each cell was obtained from Global Curve Number which was developed on the basis of Average Antecedent Moisture Condition (AMC II), hydrological soil group, and land use land cover. As indicate in (Figure 2 B) the values of CN II ranges from 60 in the basin highland areas to 94 in flat regions of Afar. Furthermore, CNI and CNIII are calculated from AMC II as shown in equation (3 and 4). As shown in (Figure 2 A and C) the lowest CN values are 40 and 85, whereas the highest CN values were 85 and 98 for CNI and CNIII respectively. The values of these CN (CNI, CNII, and CNIII) emphasize that most part of Awash river basin is characterized by less vegetation coverage which trigged high level surface rainfall runoff rate.

Maximum soil water retention potential (S)

Maximum soil water retention potential (S) can be calculated from CN II using equation (2). The formula in equation (2) was executed on raster calculator tool in ArcGIS environment. As indicated in (Figure 3), the values of Maximum soil water retention potential (S) range from 16 at the north western part to 169 at the central and southern part of the Awash river basin. The highest values of S are located at areas covered with agriculture and vegetation, whereas the lowest S values are located at areas covered with bare land or little vegetation and built-up.

Rainfall map

Mean monthly rainfall data of CHIRPS was downloaded independently for Awash river basin. Monthly rainfall of the study region first needs to be computed for SCS-CN rainfall runoff simulation input. Therefore, rainfall data of each month was added together in raster calculator of ArcGIS environment to obtain the total annual rainfall for Awash river basin. Total annual rainfall of the year 2020 for study region was also developed in ArcMap (10.8 version). In (Figure 4), it known that the total annual rainfall of the Awash river basin varies from 146.73 mm to 1490.99 mm in 2020. The highest rainfall was observed at the south eastern highlands of Addis Ababa and the lowest rainfall was shown at northern part of Afar depression.

Runoff

Soil Conservation Service-Curve Number (SCS-CN) rainfall runoff was generated on the basis of maximum soil water retention potential (S) and mean annual rainfall (P). These values are used as an input for GIS based SCS-CN runoff simulation model. As shown in Figure (5), a variation that range from 83.95mm/year to a maximum of 1,416.75mm/year was observed due to rainfall variability across the study region and curve number resulted from land use land cover and hydrological soil group. As a result, areas with poor retention potential such as built-up are exposed to high runoff rate. Similarly, the highland areas of the river basin with fine soil particles are also exposed to high runoff volume. On the other hand, areas covered with agriculture and vegetation has shown high retention potential and resulted low runoff

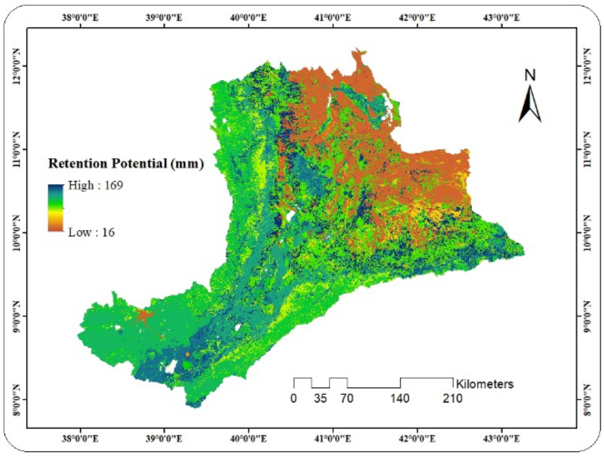

Figure 3: Soil water retention.

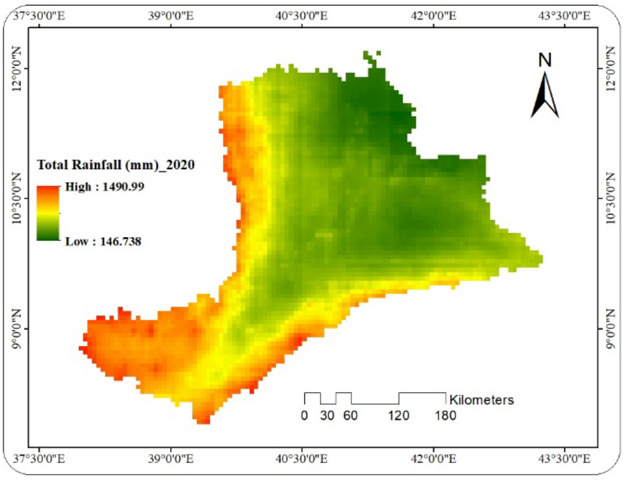

Figure 4: Rainfall.

volume. Therefore, high runoff rate in the study region was shown at the south western part, whereas the entire study region was covered with very low and medium runoff volume.

Rainfall-runoff correlation analysis

The scatter plot depicted in (Figure 6) shows a strong linear relationship between total annual rainfall and SCS-CN runoff with correlation coefficient of 0.9873. This correlation coefficient indicates that Awash river basin has high response to rainfall runoff. The results of this project findings agreed with [3], who states that SCS-CN runoff simulation model has been applicable at basin level; if the correlation coefficient of rainfall and runoff is greater than 0.5. In this case, SCS-CN runoff simulation model is suitable to generate rainfall runoff for Awash river basin with correlation coefficient of 0.9873 or 98.7% confidence interval.

Correlation between observed runoff and predicted runoff from GCN250

Estimated runoff using SCS-CN model on the basis of GCN250 data was validated with the observed runoff from Awash river basin. It is known from (Figure 7) that the observed runoff and predicted runoff in the study region was significantly corelated with correlation coefficient of 0.9253 for the year 2020. From coefficient of determination (R) value, it is observed that the new GCN250 data product can be considered as

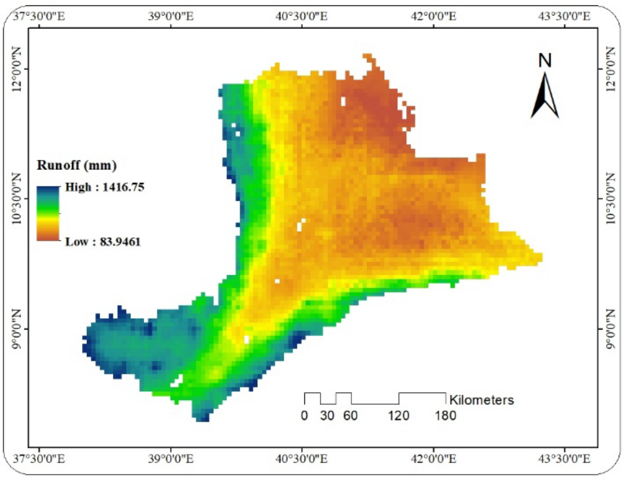

Figure 5: Runoff.

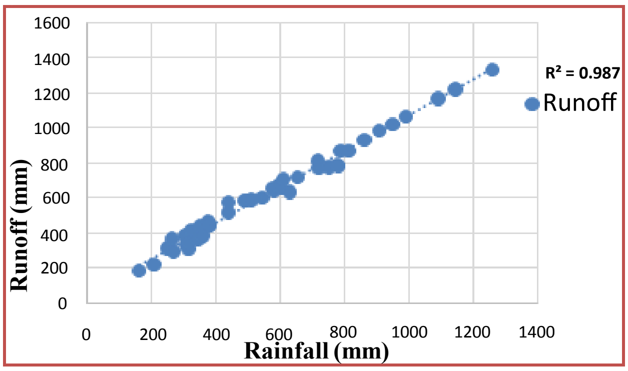

Figure 6: Rainfall-runoff correlation.

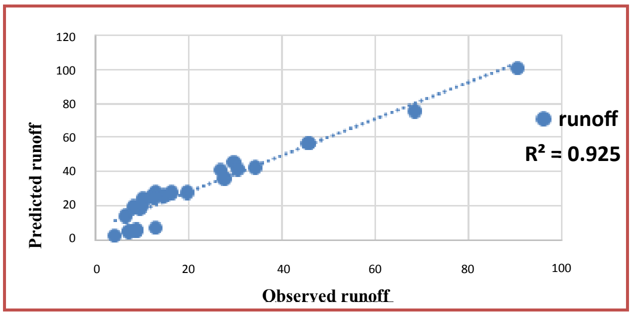

Figure 7: Predicted-Observed correlation.

effective SCS-CN runoff simulation model input to generate rainfall runoff at basin level.

Conclusion

GIS based SCS-CN runoff simulation model was applied to estimate surface runoff for Awash river basin. The total annual rainfall and Global Curve number (GCN250) were used as inputs in GIS based SCS-CN runoff simulation model. The total annual rainfall of the year 2020 in the study region was 146.73 mm/year to a maximum of 1,490.99 mm/year. The GCN250 of the Awash river basin was grouped into three classes, namely; CNI, CNII and CNIII based on five-day Antecedent Soil Moisture Condition (AMC). The average curve number (CNII) values range from 60 to a maximum of 90 and was used to calculate maximum soil water retention potential (S). The curve number values associated with CNI and CNIII range from the lowest 40 and 78 to the highest values of 85 and 98 respectively. On the other hand, maximum soil water retention potential (S) was calculated from average curve number (CNII) and the values are range from the minimum of 16 in built-up areas and to a maximum of 169 in areas covered with agriculture and vegetation. The final surface runoff values for the Awash river were generated on the basis of total annual rainfall and maximum soil water retention potential (S) of the year 2020. Accordingly, a runoff variation that range from 83.95 mm/year to a maximum of 1,416.75mm/year were observed in the study region. A correlation analysis was performed to explain the relationship between total annual rainfall and surface runoff. The relationship between these two variables indicates a strong linear relationship with correlation coefficient of 0.9873 or 98.73 % confidence interval. Furthermore, rainfall runoff predicted from GCN250 was validated with observed runoff obtained from station gauges in the study region. Predicted runoff was well correlated with observed runoff with correlation coefficient of 0.9253. From this stand point, it is observed that the new GCN250 data can be used as an input for SCS-CN model to estimate rainfall runoff at basin level.

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