

Full Length Research Paper

Simulation of rainfall runoff process for Khartoum State (Sudan) using remote sensing and geographic information systems (GIS)

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Using geographic information systems (GIS) and remote sensing integration to determine runoff caused due to rainfall from watershed has performed increasingly attention in recent years. This study was conducted in the Khartoum State. Curve Number (CN) method was applied for estimating the runoff depth in the watershed. Hydrologic soil group and land use maps were generated in GIS Environment. Hydrologic soil groups and land use maps were used to generate the CN map. Soil Conservation Services-Curve number (SCS-CN) method was followed to estimate runoff for the watershed. It was found that the model can predict runoff reasonably well. It could be concluded that the SCS-CN method can be applied to predict runoff volumes for planning of various conservation measures and for other water resources applications.

Key words: Soil Conservation Services-Curve number (SCS-CN), geographic information systems (GIS), remote sensing, runoff estimation

INTRODUCTION

Surface runoff is the water flow that occurs when soil is saturated to full capacity and excess water from rain over the land. This is a major component of the water cycle. Rainfall generates runoff, and its occurrence and quantity are dependent on the characteristics of the rainfall event, that is, the intensity, duration and distribution. Apart from these rainfall characteristics, there are numbers of catchment specific factors, which have a direct effect on the occurrence and volume of runoff.

Measured rainfall is one of the most significant input data in applying the hydrological models for runoff estimations. Unfortunately, the distribution of rainfall usually varies significantly in both space and time. Therefore, the limited number of rainfall stations in the

catchment can have a major impact on the accuracy of runoff estimations. The accurate estimation of the spatial distribution of rainfall therefore requires a very dense rainfall network, which involves high installation and operational costs.

Remote sensing can provide measurements of many of the hydrologic variables used in hydrologic applications, either as direct measurements comparable to traditional forms, or as entirely new data set. The pixel format of digital remote sensing data makes it suitable to merge it with geographic information system (GIS).

Most of the previous work on adapting remote sensing to hydrologic modeling has involved the Natural Resources Conservation Service runoff Curve Number

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(CN) model. This involvement used remote sensing data as a substitute for land cover maps which had been obtained by conventional means.

The GIS technology provides suitable alternatives for efficient management of large and complex databases; it is used in hydrologic modeling to facilitate processing, management and interpretation of hydrologic data.

Several studies have been done to incorporate GIS in to hydrologic modeling of watersheds. The traditional method for establishing CN on small watersheds includes field surveys and interpretations of aerial photographs. For large drainage basins, field surveys are prohibitively expensive and an excessive number of aerial photographs may be required for complete coverage. A further disadvantage of conventional techniques may be the infrequency of the surveys and the consequent failure to account for changes in vegetative cover and land use.

Land use is an important characteristic of the runoff process that affects infiltration, erosion, and evapotranspiration. Hydrologic models, distributed models in particular, need specific data on land use and its location within the basin. Remote sensing can provide measurements of many of the hydrologic variables used in hydrologic and environmental model.

Rainfall-runoff modeling is a very important topic of research that can be utilized for management and control of water resources. Where there is lack of important elements such as digital land use map, digital curve number map, hydrological soil groups map and digital runoff map, these types of maps are very useful in hydrological investigations. In addition, future predictions with different scenarios can be undertaken by rainfall-runoff modeling.

The integration of remote sensing and GIS has been widely applied and has been recognized as a powerful and effective tool in estimating and evaluating rainfall; therefore the main aim of the present study is to apply a rainfall-runoff model using GIS and remote sensing techniques to simulate the rainfall-runoff process and create digital runoff map for the study area using SCS-CN method.

Nowadays, modeling has become a common practice in every field of endeavor, and runoff modeling is no exception (Donigian, 1995). The main reason behind the using of modeling in general is the limitations of the techniques used in measuring and observing the various components of hydrological systems (Beven, 2001). Also using hydrologic models will increase our understanding and explanation of the natural phenomena and its dynamic interactions with the surrounding systems (that is, climatic terrestrial, pedologic, lithologic and hydrologic systems) (Chiew, 1994). However, under some conditions, predictions can be made in deterministic or probabilistic sense.

Another use of modeling is to predict how the system will respond to the future alternative conditions and actions (Donigian et al., 1995; Linsley, 1982) summarized

the principal purposes for which hydrological model have or can be employed. In general they can be used for hydrologic research purposes, for forecasting and prediction of stream flow, and for engineering and statistical applications (record extension, operational simulation, data fill-in, and data revision).

Detailed analysis of flood hydrograph has special importance in flood mitigation, flood forecasting and/or establishing flows for many structures which must convey floodwaters (Linsley, 1982). Rainfall-Runoff modeling covers a wide range of applications and practices. This can be divided into two main groups, viz: flood studies (planning and designing new hydraulic structure, operating and/or evaluating existing hydraulic structures, preparing for and responding to flood, flood damage reduction, and regulating flood plain activities), and storage studies (catchment and reservoir yield analysis, and water resource potential) (Blandford and Meadows, 1990; Chiew, 1994; Connolly, 1995).

The Soil Conservation Service - curve number (SCS-CN) method has its origins in the unit hydrograph approach to rainfall-runoff modeling. The unit hydrograph approach always requires a method for predicting how much of the rainfall contributes to the storm runoff. The SCS-CN method arose out of the empirical analysis of runoff from small catchments and hill slope plots monitored by the USDA. The Curve Number method (SCS, 1972), also known as the Hydrologic Soil Cover Complex Method, is a versatile and widely used procedure for runoff estimation. In this method, runoff producing capability is expressed by a numerical value varying between 0 to 100.

METHODOLOGY

This study is conducted in Khartoum State, the study area located in the middle of Sudan, lies between latitudes 15.8° N to 16.45° N and longitudes 31.5° E to 34.45° E, surrounded by five states, divided to seven localities. It has an area of 22,122 km² (Figure 1).

The topography of the area is undulating. Khartoum featured as hot arid climate, with only months of July and August seeing significant precipitation. Khartoum averages a little over 155 mm (6.1 in) of precipitation per year. Temperatures may exceed 45°C in summer time.

Rainfall data is collected from National Meteorological Corporation. Data from five gauges were used here, namely: Al Sahafa, Jabalawlia, Shambat, Soba and Omdurman; the rainfall data were obtained for 20 years.

Soil data are obtained from the Ministry of Agriculture of Khartoum State. Land use map was obtained from remote sensing authority. Arc GIS version 9.3 produced by ESRI, 2008 was used for creating, managing and generating of different layers and maps.

Soils were classified into A, B, and D groups according to their minimum infiltration rate, which obtained for a bare soil after prolonged wetting as shown in Table 1.

To prepare the land use layers in the study area, eight major land use classes were identified. Classified land use map was integrated with the hydrological soil groups map to produce the CN. To estimate curve numbers for the entire basin, vector coverage of soil showing the HSG, and use map were overlaid. The soil layer and classified land use layer were used to calculate curve numbers

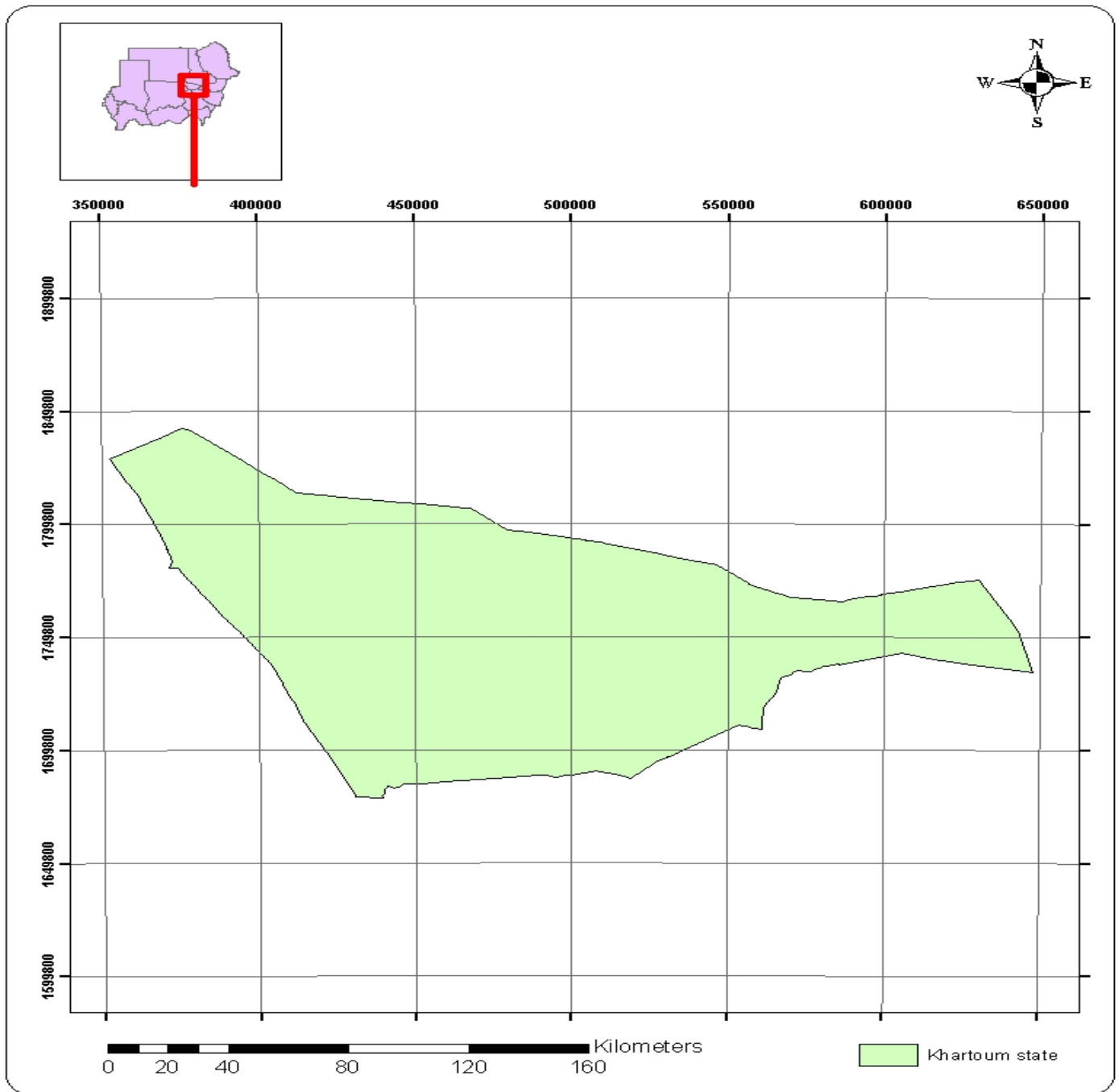


Figure 1. Study area.

value.

The rainfall-runoff equation used for estimating depth of direct runoff from storm rainfall (USDA, 1972):

$$Q=(P-0.2S)^2/(P+0.8S)$$

The CN is a dimensionless runoff index determined based on hydrologic soilgroup (HSG) and land use. The CN method is able to reflect the effect of land use on runoff. The NRCS runoff equation is widely used in estimating directRunoff because of its simplicity, flexibility and versatility.

RESULTS AND DISCUSSION

Remote sensing and GIS technologies are suitable tools for rainfall-runoff estimation which were used to determine CN distribution in the study area. It could be used to calculate runoff depth of the basin area. The results of this study may be very useful for flood forecasting and the development of hydrologic and hydraulic structure. These results are useful to understand

Table 1. Hydrological soil groups.

Soil Group	Characteristics
A	Low overland flow potential, high minimum infiltration capacity even when thoroughly wetted (>0.76 cm/h), deep, well to excessively drained sands and gravel.
B	Moderate minimum infiltration capacity when thoroughly wetted (0.13 to 0.76 cm/h), moderately deep to deep, moderately to well drained, moderately fine to moderately coarse grained (e.g. sandy loam).
D	High overland flow potential: Very low minimum infiltration capacity when thoroughly wetted (<0.13 cm/h) clay soils with high swelling potential, soils with permanent high water table. Soils with a clay layer near the surface, shallow soils over impervious bedrock.

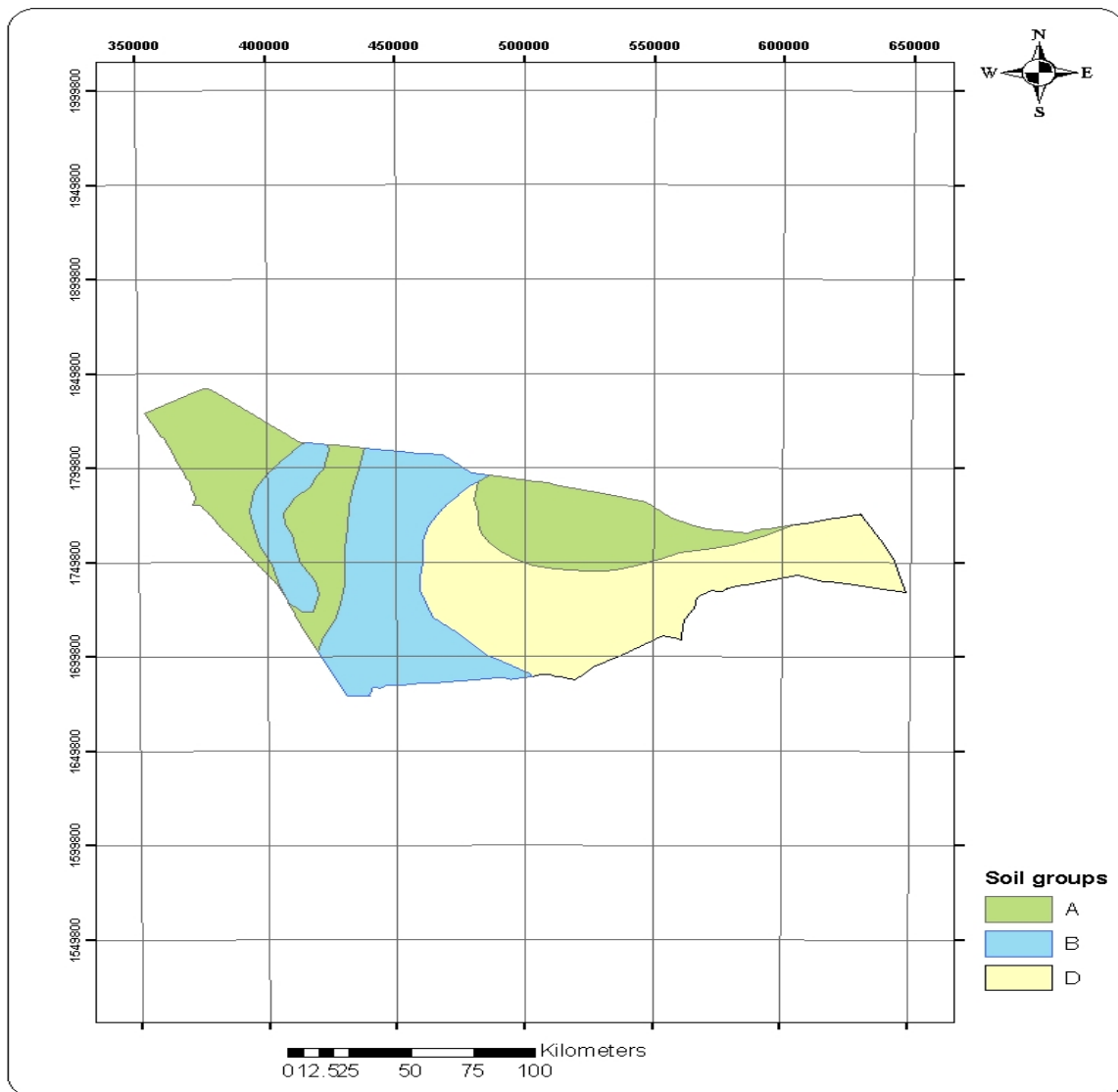


Figure 2. Hydrological soil groups (HSG).

hydrological characteristics of basin area.

From classified soil map three hydrological soil groups (HSG), it has been found that three HSG covered the

study area, namely A, B, and D. Figure 2 represents the distribution of these groups.

From Figure 2 it can be observed that 30% of the study

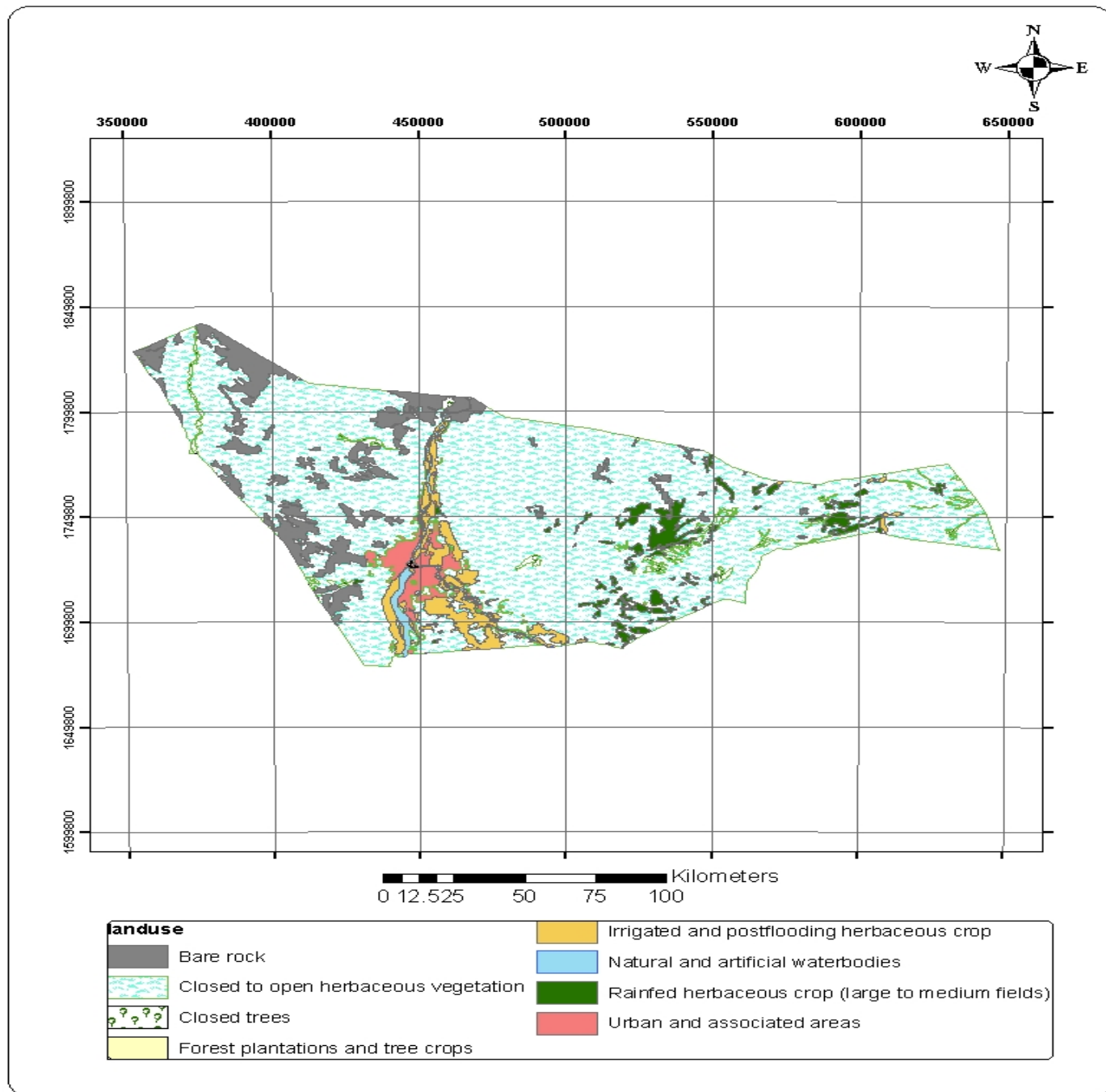


Figure 3. Land use classed distribution in the study area.

area is covered by group B and 34% is covered by group A while the rest of the area covered by group D (36%). The classified land use map is shown in Figure 3. The study area has been classified into eight major land use classes. Table 2 represents the percentage of each class.

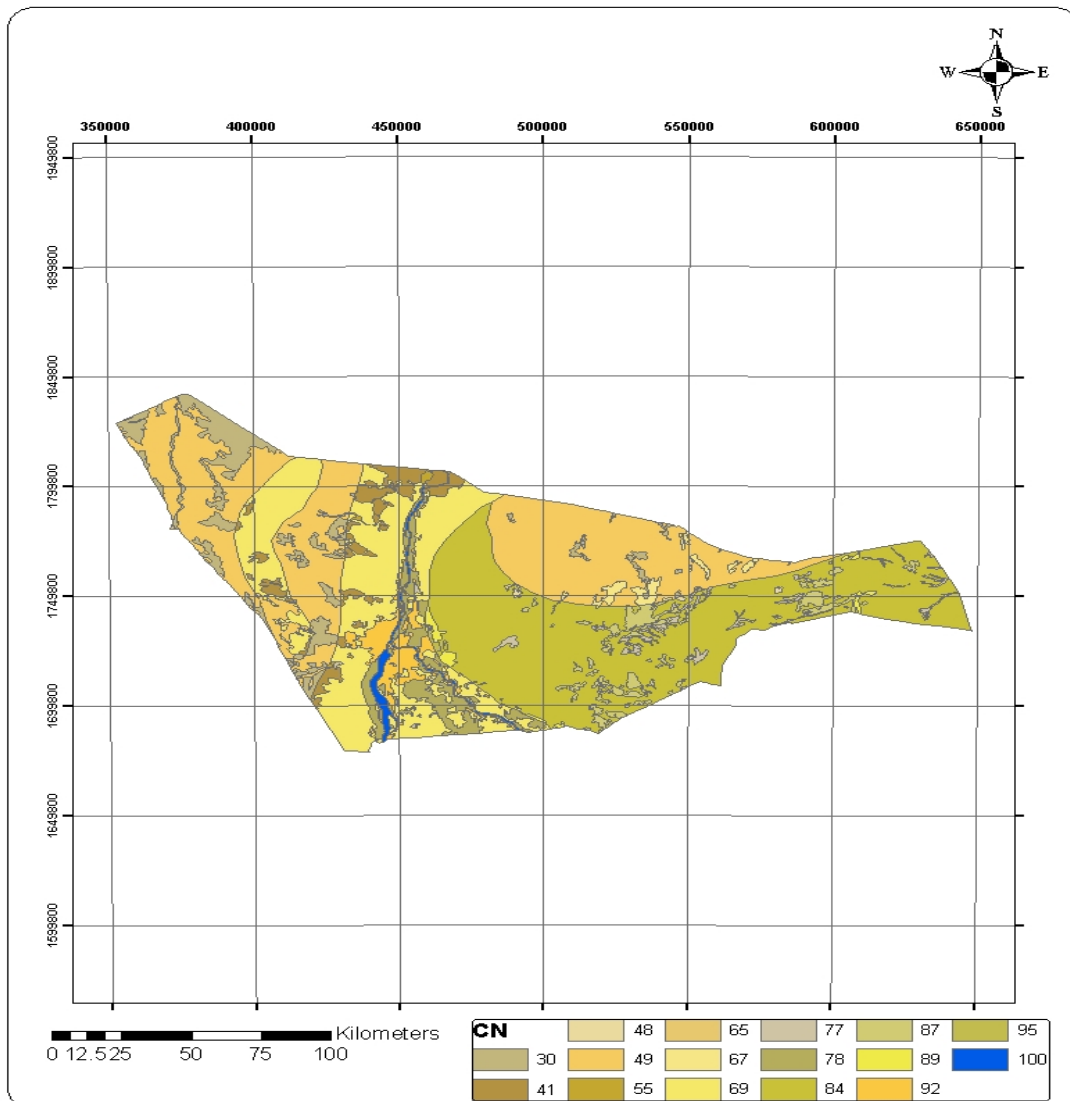
From Table 2 it can be observed that most of the study area was covered by closed to open herbaceous vegetation while the forest plantation and tree crops have

least coverage.

The CN value for each soil hydrologic group and corresponding land use class were calculated. Hydrologic soil groups A and B leads to low CN value while the hydrologic group D leads to high CN value in the study area. The lowest CN value was found to be 30 in closed trees while the highest CN value was found to be 100 in water bodies; watershed generates more runoff for a given rainfall in areas having greater CN values. The CN

Table 2. Percentage of land use classes.

Land use	% Area
Bare rock	9.09
Urban and associated area	2.67
Rainfed herbaceous crops	3.53
Irrigated and post flooding herbaceous crops	4.29
Natural and artificial water body	0.99
Forest plantation and tree crops	0.014
Closed trees	1.73
Closed to open herbaceous vegetation	77.66

**Figure 4.** Distribution of CN values in the study area.

values were mapped and displayed in Figure 4.

Runoff depths of the basin were estimated using CN values in the SCS-CN equation as shown in Figure 5.

Conclusion

Remote sensing and GIS technologies can be used to

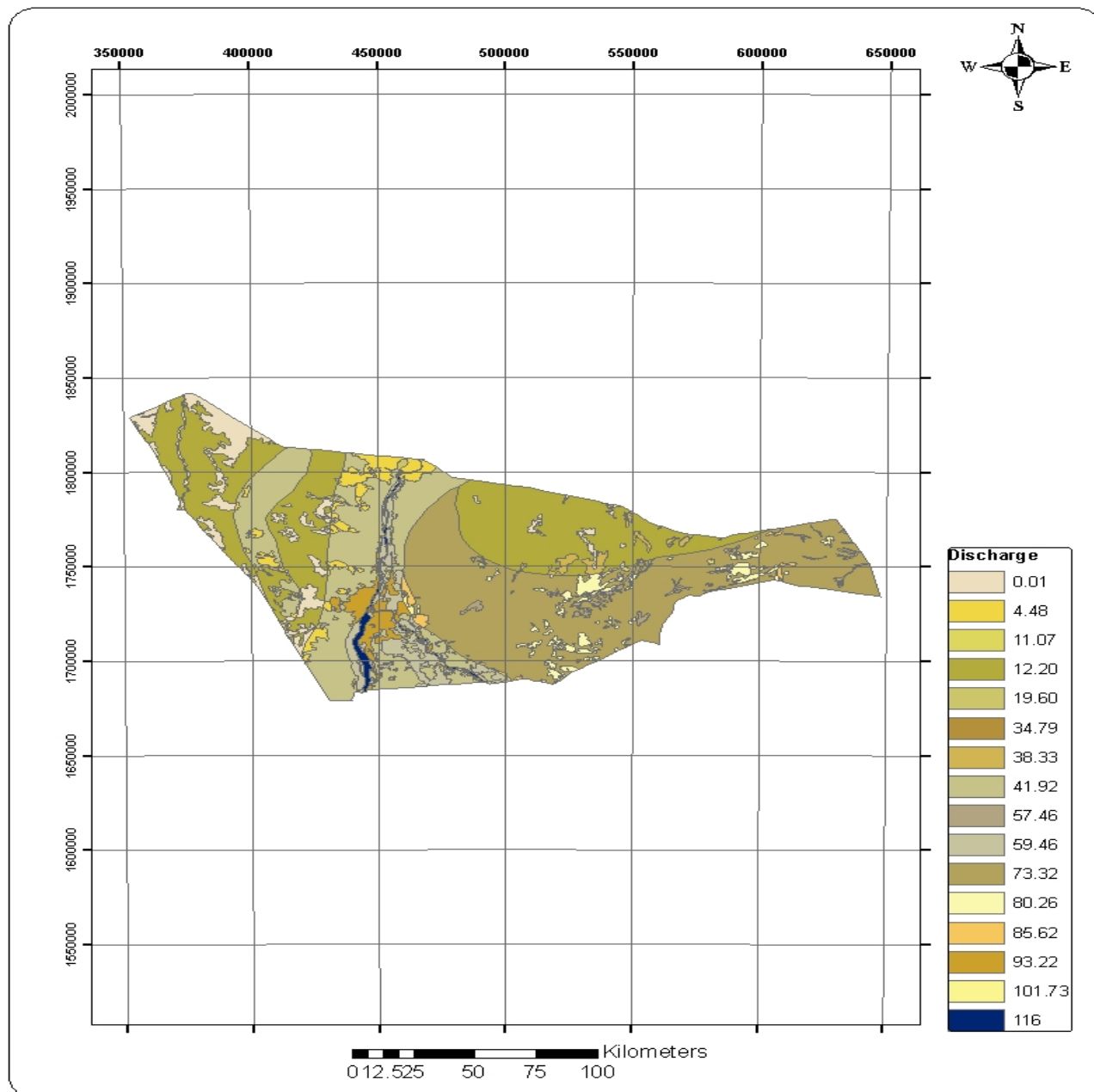


Figure 5. Runoff estimation based on CN values.

determine curve number values which could be used to calculate runoff depth. In this study, SCS-CN method was applied to simulate the rainfall-runoff process and create digital runoff map using GIS and remote sensing techniques. Three HSG covered the study area. The study area has been classified into eight major land use classes. Curve numbers values were estimated and thereafter the runoff amounts were determined for different areas. The results of the study would be very useful for flood forecasts and future land use changes scenarios.

Conflict of Interests

The author(s) have not declared any conflict of interests.

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