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Estimaion of runoff using SCS-CN method and geographic information system under changing climatic scenarios in Halia catchment

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ABSTRACT

Climate change affects the hydrology mainly through changes in precipitation, temperature, evaporation, and it subsequently influences the temporal and spatial distributions of runoff and sediment. The study area, Halia river basin, located in Nalgonda district of Telangana state, covering an area of 3918.41 km^2 was delineated in Arc-GIS and 416 sub-catchments were generated. The spatial and temporal variations of rainfall and runoff were analyzed. Most of the study area has normal rainfall less than 790 mm. Different thematic layers were intercepted in Arc-GIS and Soil Conservation Services Curve Number (SCS-CN) method was applied to estimate the runoff spatially and most of the catchment has runoff ranged from 10.5% to 17.5% of average annual rainfall during 1951 to 2020. Runoff was estimated under changing climatic scenarios using the ENSEMBLE data of CMIP 5. Major portion of the basin has runoff in the range 7.5% to 15.0% of annual rainfall during baseline period (1976 to 2005) and the runoff varied spatially from 7.5% to 20.0% of rainfall. By 2030s, under RCP 4.5, the runoff was predicted to increase by 0.60% to 6.80% of annual rainfall and under RCP 6.0, it is expected to increase by 0.59% to 6.53% of annual rainfall with respect to baseline. Changes in the climatic conditions are resulting in the uncertainty in rainfall distribution.

1. INTRODUCTION

Runoff is one of the most important hydrologic components used in water resources applications. The quantity of runoff depends on soil, topography and rainfall characteristics like intensity, duration and distribution (Zhao *et al.,* 2022). Understanding surface runoff is important because when it occurs, it can move the location of recharge, affects the distribution of plant and wildlife communities, and impact the temporal and spatial distribution of water resources (Bera *et al.,* 2022). The direct runoff is the cause many problems like soil erosion and land degradation and without proper technique to estimate it; no preventive measures can be applied. In the developing country like India, the runoff and sediment yield data are scarcely available from few selected sites where gauging stations are available and therefore, mathematical models are widely used for its estimation (Patil *et al.,* 2008). A rainfall-runoff model is a mathematical model describing the rainfall-runoff relations of a catchment area / drainage basin. SCS-CN technique is one of the primogenital and simplest method for runoff modeling (Ramakrishnan *et al.,* 2009; Dhawale, 2013). Hydrologic soil group, land use and vegetation cover are the basic catchment characteristics used for curve number (CN) calculations (Behera *et al.,* 2022). Geographic Information System (GIS) techniques are widely used for planning, development and management of natural resources by integrating various data sets and perform spatial analysis for decision making. Earlier studies carried out by several researchers such as Mishra *et al*. (2004), Ramakrishnan *et al.* (2009), Nagarajan and Poongothai (2012), Chauhan *et al*. (2013), Mishra *et al.* (2013), Gajbhiye (2015) and Rejani *et al*. (2015) focused on the GIS approach which requires important properties of the watershed, specifically soil properties, land use / land cover (LU/LC) and antecedent soil moisture conditions.

Natural and human activities are responsible for climate change and global warming. Global warming is gradual increase of earth's surface temperature and indications like green house gases (GHGs) emission will determine the climate change (He *et al*., 2022). There is variability in precipitation patterns, intensities and some other climatic parameters due to climate change which affects the water resources. Rejani *et al.,* 2022 used ENSEMBLE data of CMIP 5 and predicted an increase in runoff potential in Northern dry zone of Karnataka by 2050s and 2080s. Lutz *et al*. (2016), Mehan *et al.* (2016) and Bajracharya *et al.* (2018) used the ENSEMBLE data of selected general circulation models (GCMs) and reported that for RCP 4.5 and RCP 8.5, the uncertainty of future climate in the selected regions were very large. There are several climate modeling groups such as National Center for Atmospheric Research (NCAR), Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS), National Center for Environmental Modeling (NCEP), Goddard Global modeling and Assimilation Office (GMAO) and Center for multi scale Modeling and Prediction (CMMAP) (Pathak *et al*., 2022; Zhao, 2022; Deliry *et al*., 2022; Sudesan *et al*., 2022; Salama *et al*., 2022; Bengtsson and Hodges, 2019) etc., which are focusing on climate data. The presented study was taken up with an objective to estimate the runoff spatially and temporally using SCS-CN method and GIS for Halia basin in Telangana and to analyze its variability over the years and under changing climatic scenarios.

2. MATERIALS AND METHODS

Study Area

The selected study area, Halia river basin, a tributary of Krishna river, situated in Nalgonda district of Telangana state. Geographically, it lies between 16º37'19" to 17º17' 21"N latitudes and 78º34' 23" to 79º29'20"E longitudes with an elevation ranging from 54 to 701 m above mean sea level (Fig. 1). The normal annual rainfall of the basin ranges from 700 mm to 800 mm. The catchment receives 90% of the rainfall during south-west monsoon, sets by middle of June and withdraws by middle of October. More than 70% of rainfall occurs during the months of July, August and September. The length of the river is 112 km and it drains from an area of 3918.41 km^2. The soil is clayey and loamy in texture. The LU/LC is mainly agriculture land followed by scrub land, current fallow and other waste land. The major crops in the basin includes cotton, rice, pulses, millets, groundnut etc.

Model Inputs

The model inputs includes digital elevation model (DEM), LU/LC, soil map and daily rainfall data (Table 1). Data used for the present study is obtained from ICAR-CRIDA, Hyderabad which includes daily rainfall grid data of IMD (0.25° × 0.25°) for 70 years (1951-2020) and ENSEMBLE data of CMIP 5 (0.5° × 0.5°) from ICAR HQ. The base line data for the period 1976-2005 and data for the future scenario (2030s) corresponding to different emission scenarios such as RCP 4.5 and 6.0 was used. In addition to this, the daily discharge data for the Halia station collected

Table: 1
Model inputs

Data	Source
DEM	ASTER (30 m Resolution)
LU/LC	NRSC Hyderabad
IMD rainfall grid data	IMD (0.25° × 0.25°)
ENSEMBLE rainfall data of CMIP5	ICAR HQ (0.5° × 0.5°)
Daily discharge	CWC
Soil data	NBSS&LUP

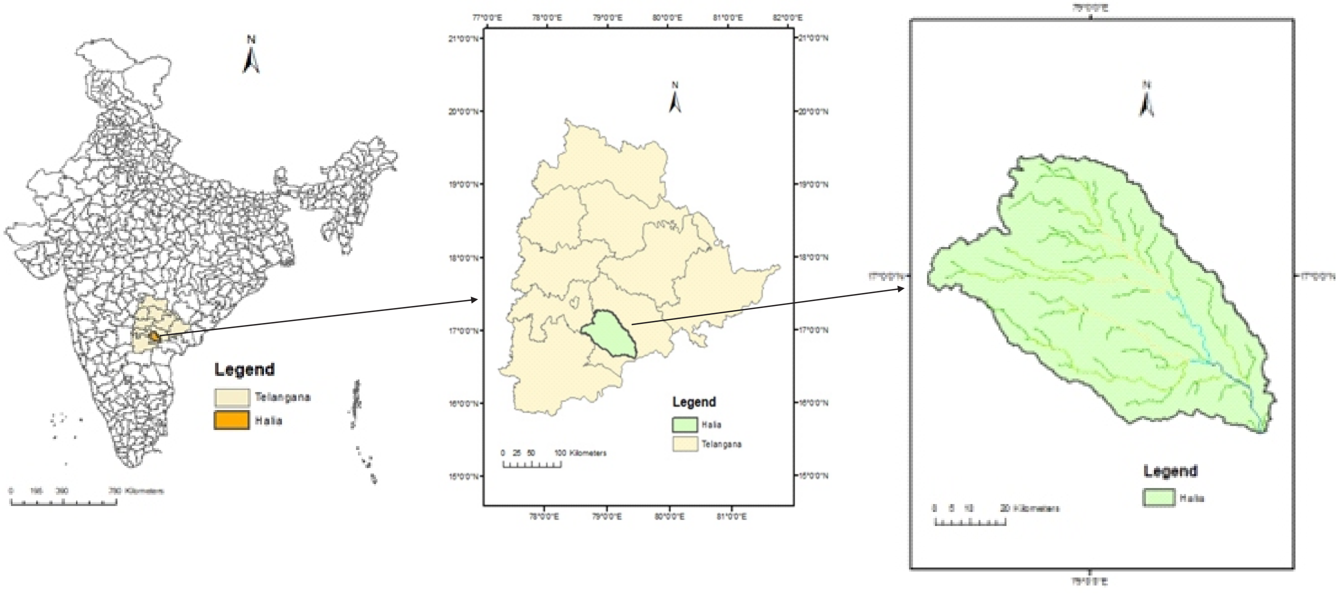

Fig. 1. Location map of the study area

by Central Water Commission (CWC) was also used for calibration and validation of the runoff. The daily discharge data (CWC) for the period June 1984 to May 2019 was downloaded from www.india-wris.nrsc.gov.in. The soil map from National Bureau of Soil Survey and Land Use planning (NBSS&LUP) (1:50,000) and LU/LC map (1:50,000) for 2013-14 from National Remote Sensing Centre (NRSC) was also used as thematic layers for estimation of runoff. ASTER DEM (30 m resolution) was used in this study for delineation of the basin and generation of stream orders. The elevation of the river basin ranges from 54 m to 701 m above mean sea level.

SCS-CN method

The soil conservation service (SCS) model developed by United States Department of Agriculture (USDA) computes direct runoff using an empirical equation that requires the rainfall and a watershed coefficient as inputs (Geetha and Pathan, 2019). This method needs daily rainfall, soil type and land use as input. The general equation for the SCS-CN method is as follows (eqs. 1 to 3):

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad \text{for } P > 0.2\,S \qquad ...(1)$$

$$Q = 0 \quad \text{for } P \leq 0.2\,S \qquad ...(2)$$

Where, P = total precipitation (mm); Q = surface runoff (mm); and S = potential maximum retention or infiltration (mm). The value of S is given as:

$$S = \frac{25400}{CN} - 254 \qquad ...(3)$$

The curve number (CN) varies between 0 and 100. In SCS-CN method, a CN is assigned to each watershed or portion of watershed based on land use, antecedent moisture conditions (AMC) and soil type. AMC refers to the water content present in the soil at a given time. CN values varies with the antecedent soil moisture conditions and categorized them as I, II, III, according to soil conditions and rainfall limits for dormant and growing seasons. Classification of AMC is shown in Table 2. Since, standard Table for CN values (ranges from 1 to 100), considering LU/LC and Hydrologic soil group are given for AMC-II, following conversion formulas are used to convert CN from AMC-II (average condition) to the AMC-I (dry condition) and AMC-III (wet condition) (Behera *et al.*, 2022).

Table: 2
Classification of antecedent moisture condition

AMC group	Total rainfall in previous 5 days (growing season)
I	Less than 35 mm
II	35 to 52.5 mm
III	More than 52.5 mm

$$CN_I \; for \quad AMC \quad I = \frac{CN_{II}}{2.281 - 0.01281 CN_{II}}$$

$$CN_{III} \, for \; AMC \; III = \frac{CN_{II}}{0.427 + (0.00573 \times CN_{II})}$$

Where, CN_{II} is the curve number for normal condition, CN_I is the curve number for dry condition and CN_{III} is the curve number for wet conditions. In the present study, different thematic layers of soil, slope and LU/LC were intercepted in Arc-GIS and the SCS-CN method was applied to estimate the runoff. The runoff estimated was dissolved after intercepting with the catchments to calculate surface runoff volumes catchment wise.

Calibration and Validation of the Spatial Runoff Estimation Model

The calibration of the spatial runoff estimation model was done for the period 2001-2005 and validation for the period 2007-2011. To assess the goodness-of-fit of the model, coefficient of determination (R^2) was used and the calibrated and validated model was used for estimating the runoff spatially and temporally for the period 1951 to 2020.

Runoff under Changing Climate Scenarios

Rainfall runoff models are tools used by hydrologists in climate change assessments to estimate how future stream flow that might change in response to a given (often hypothetical) climate scenario (Kumar *et al*., 2022). Ensemble-based approaches use data from a large array of future climate simulation instead of a selected small subset of simulations. Using various statistical methods, the results from the full array of GCM simulations are aggregated to develop a set of ensemble-based simulation. A climate scenario is a combination of an emission or radiation scenario, generated by a global climate model, a regional climate model and the modeled time period. The representative concentration pathways (RCP) scenarios (Moss *et al.,* 2010; Seibert and Bergstrom, 2022; Singh *et al.,* 2010) are RCP 2.6, 4.5, 6.0 and 8.5. ENSEMBLE data of CMIP 5 pertaining to RCP 4.5 and RCP 6.0 was used in this study. Data from 1976 to 2005 was considered as baseline period (Sunil *et al.,* 2021; Gupta and Mishra, 2019).

3. RESULTS AND DISCUSSION

Delineation of Halia Basin

The Halia basin having an estimated total area of 3918.41 km^2 was delineated using ARC Hydro tool and 416 sub-catchments were generated. The area of sub-catchments ranged from 1.7 - 6070 ha. The largest sub-catchment was 6070.10 ha and smallest sub-catchment was 1.7 ha.

Slope

As per Integrated Mission for Sustainable Development (IMSD,1995) guidelines, the slope map was classified into seven categories such as nearly level (0-1%), very gentle (1-3%), gentle (3-5%), moderate (5-10%), strong (10-15%), moderately steep (15-35%) and very steep (>35%). Under this study, most of the catchment has slope <5% and limited area has slope more than 10% (Fig. 2).

Land use and land cover (LU/LC)

One of the key criteria for selecting suitable sites for water harvesting structures is the LU/LC. The hydrological response of the river basins is affected by the LU/LC change and rainfall. The LU/LC in the study area consists of build up, agriculture, current fallow, forest, shrubs / degradation forest, scrub land, water bodies and other waste land. About 66.1% of the area is covered by agriculture land followed by 14.3% under scrub land, 9.6% current fallow and 7.9% under other waste land (Table 3).

Calibration and Validation of the Spatial Runoff Estimation Model

The spatial runoff estimation model was calibrated for monthly and yearly runoff for the years 2001-2005 and validated for 2007-2011. The runoff was estimated for the period 1951 to 2020 and the results were presented in the Fig. 3a&b. The statistical parameter, coefficient of determination (R^2) value for monthly calibration was 0.890 while the value for yearly calibration was 0.841. The R^2 values for monthly and yearly validation were 0.878 and 0.839, respectively and were found to be satisfactory.

Table: 3
Area covered under different land use land cover class

Land use classes	Area (km^2)	Area (%)
Built up	1268.95	0.3
Agriculture	258883.3	66.1
Current fallow	37802.5	9.6
Forest	1621.7	0.4
Shrubs / Deg. forest	2592.6	0.7
Scrub land	56114.5	14.3
Other waste land	30826	7.9
Waterbodies	2731.6	0.7
Total	391841.20	100.0

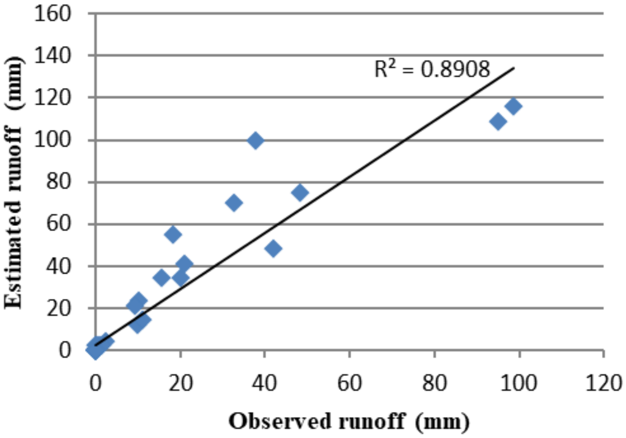

Fig. 3(a) Monthly calibration (2001-2005)

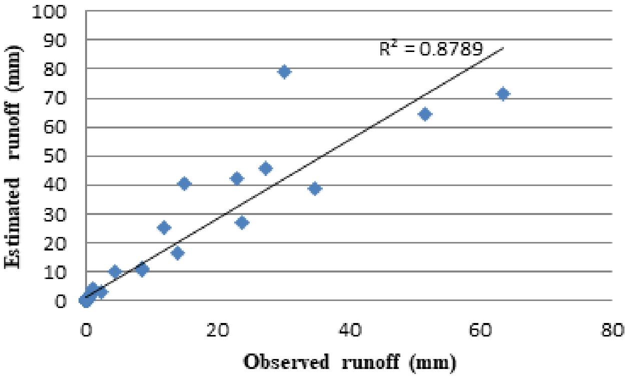

Fig. 3(b) Monthly validation (2007-2011)

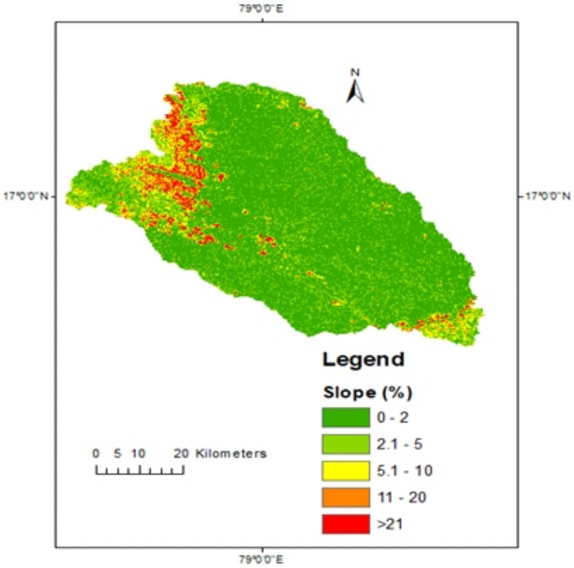

Fig. 2. Spatial variation of slope in Halia catchment

Spatial and Temporal Variation of Rainfall and Runoff

Rainfall is supposed to be the main factor on which runoff depends. It is the most important parameter which governs the surface runoff and hence it was given as a major input for runoff estimation. The runoff was estimated using the rainfall data for 1951 to 2020. It was found that the rainfall was differed from a minimum of 317.92 mm in 1999 to a maximum of 1541.33 mm in 1998 (Fig. 4b). The average annual rainfall was found to be 790.55 mm. The average rainfall varied spatially from 672 to 890 mm (Fig. 4a).

The percent runoff varied from 10.5% to 20.0% over the Halia catchment due to the low rainfall patterns prevalent in the watershed. The percent runoff was calculated from estimated runoff and rainfall values. Most of the catchment has runoff ranged from 10.5% to 17.5% of average annual rainfall (Fig. 4c). This agrees with the runoff values reported for the semi-arid watershed Goparajpalli in Warangal district of Telangana (Rejani *et al.*, 2015).

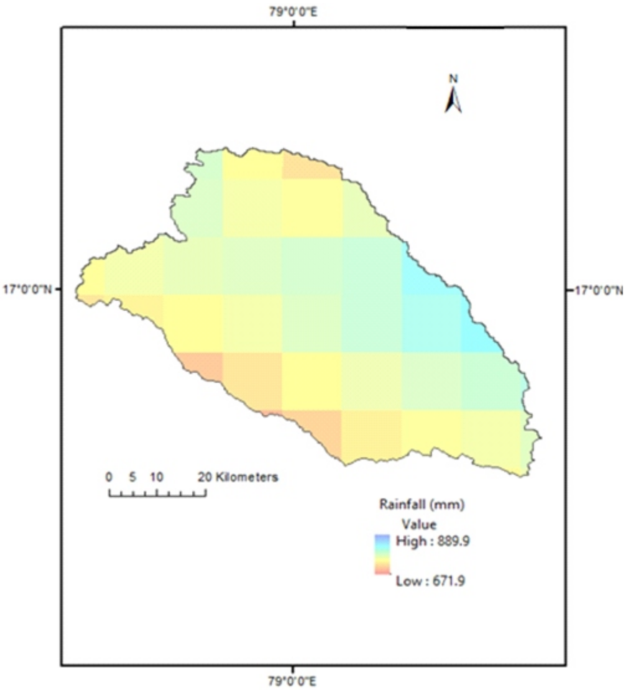

Fig. 4a. Spatial variation of rainfall at Halia catchment

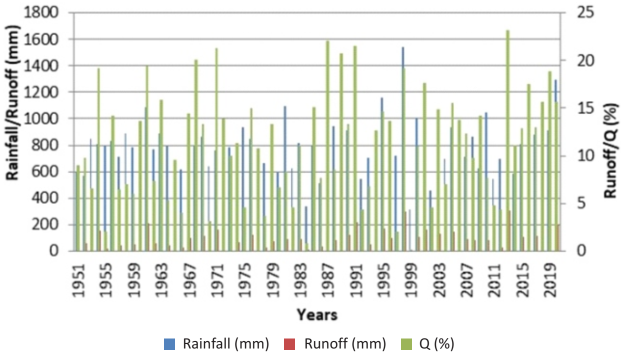

Fig. 4b. Temporal variation of rainfall and runoff at Halia

Effect of Climate Change on Runoff

The baseline period consists of 30 years (1976-2005) of rainfall data. The baseline data was used in SCS-CN model and the runoff values were estimated and it varied spatially from 7.5 to 17.5% of the rainfall (Fig. 5a). Most of the area has runoff ranged from 7.5% to 15.0 % of rainfall.

The 2030s data (2020-2049) under RCP 4.5 was used in SCS-CN model and the runoff values were estimated. The percent increase in runoff with respect to baseline period varied spatially from 0.60% to 6.80% of the rainfall (Fig. 5b). Under RCP 6.0, percent increase in runoff with respect to baseline period varied spatially from 0.59% to 6.53% of the rainfall with respect to baseline period (Fig. 5c).

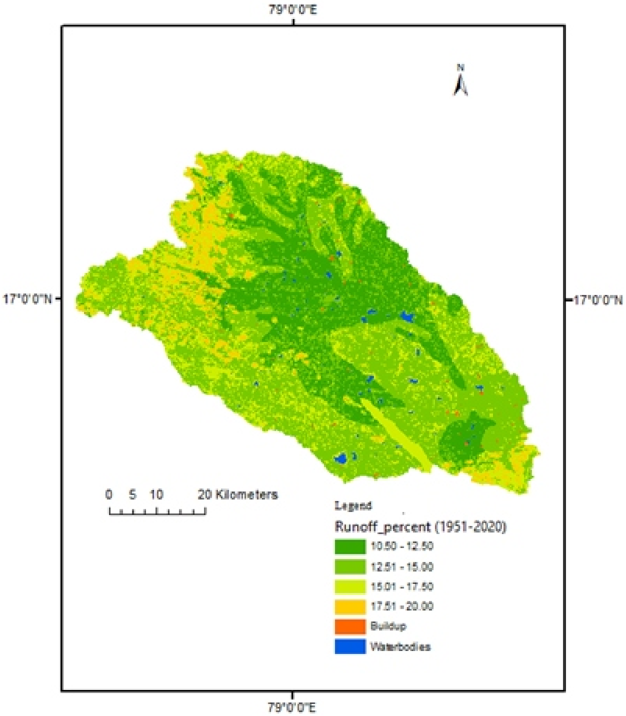

Fig. 4c. Variation of runoff at Halia catchment (1951-2020)

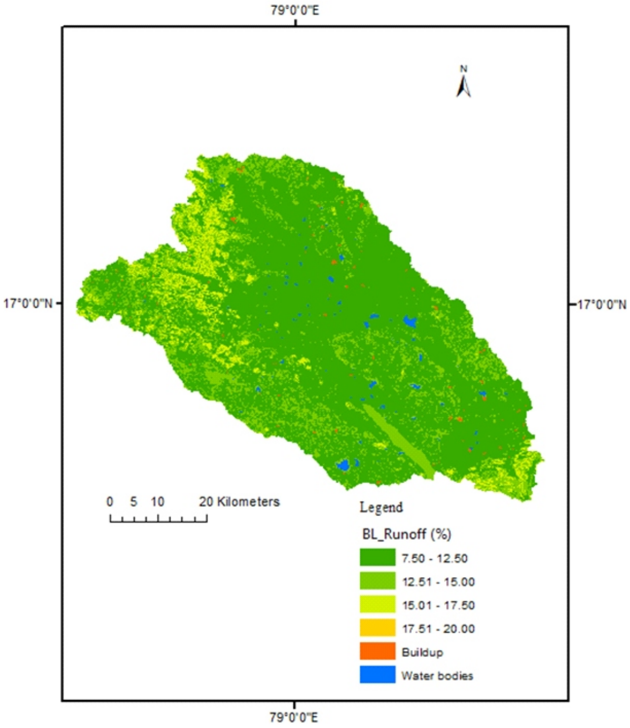

Fig. 5a. Runoff at Halia catchment during baseline period (1976-2005)

The present study uses a methodology for determining surface runoff by GIS and SCS-CN method. The spatial runoff estimation model was calibrated for the period 2001-2005 and validated for 2007-2011, respectively. The coefficient of determination (R^2) value for monthly calibration was 0.890 and for monthly validation was 0.878, respectively. Malekani *et al.,* 2014 compared the results of

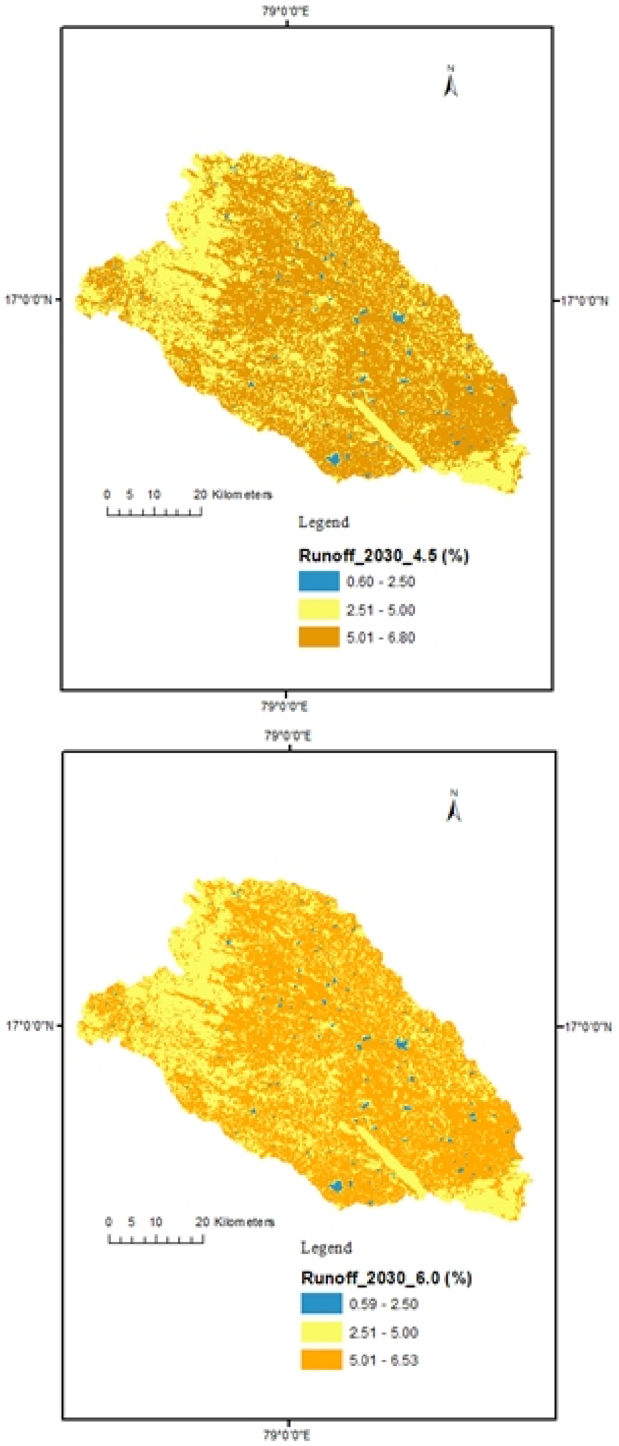

Fig. 5b&c. Increase in runoff from baseline during 2030s at Halia catchment under RCP 4.5 and 6.0 w.r.t. baseline

computed and observed runoff and reported that the use of GIS tools helps in the rapid calculation of the runoff and also increase the accuracy of the results. Joshi *et al*., 2019 estimated runoff using SCS-CN model and GIS and used linear regression model for verification of runoff and found satisfactory. For estimating runoff under changing climatic scenarios in Halia basin, ENSEMBLE data of CMIP 5.0 pertaining to RCP 4.5 and 6.0 was used in the study. The runoff during baseline period (1976-2005) spatially varied from 7.5% to 20.0% of rainfall and major portion of the basin has runoff in the range 7.5% to 15.0% of rainfall. Under RCP 4.5, the runoff was predicted to increase by 0.60% to 6.80% by 2030s and under RCP 6.0, the runoff is expected to increase by 0.59% to 6.53% by 2030s w.r.t. baseline period. Nikam *et al.,* 2018 predicted that the peak discharge in Krishna river basin may increase in the range of 57.7-76.8% and 68.5-77.5% under RCP 4.5 and RCP 8.5. Dash *et al.,* 2021 estimated the hydrologic behaviour of the Brahmani river basin and reported that the mean annual streamflow over the basin may increase by 20.86%, 11.29%, 4.45%, and 37.94% under representative concentration pathway (RCP) 2.6, 4.5, 6.0, and 8.5, respectively. The results of runoff estimated under climate change scenarios showed an increased potential for rainwater harvesting and its utilization for supplemental irrigations in future.

4. CONCLUSIONS

Gauging of runoff is always needed but is not possible for most of the locations at desired time. Without proper data on direct runoff; no preventive measures can be applied. Hydrological modeling is largely used to assess the runoff potential availability at watersheds / basin scale. For the prediction and assessment of spatial runoff, SCS-CN and GIS are very useful. In this study, Arc-GIS and SCS-CN method was applied to estimate the runoff spatially for Halia river basin in Telangana and most of the catchment has runoff ranged from 10.5% to 17.5% of average annual rainfall. Runoff estimated under changing climatic scenarios using ENSEMBLE data of CMIP 5.0 showed that by 2030s, under RCP 4.5, the runoff is predicted to increase by 0.60% to 6.80% of annual rainfall and under RCP 6.0, the runoff is expected to increase by 0.59% to 6.53% of annual rainfall w.r.t. baseline period. Increase in runoff potential shows for more scope for rainwater harvesting in future for Halia basin.

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