

GEO-SPATIAL MODELING OF RUNOFF OF LARGE LAND MASS: ANALYSIS, APPROACH AND RESULTS FOR MAJOR RIVER BASINS OF INDIA

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ABSTRACT:

Soil Conservation Service (SCS) and overland flow models have been used for runoff modeling over major land mass of India. Remote sensing derived daily rainfall data (Climate Prediction Centre), high temporal NDVI data (SPOT VGT), DEM (GTOPO30) and soil texture maps were used as input for the runoff modeling. SCS model setup was done in GIS (Arc GIS) environment. In general the reported and model estimated runoff matched well for most of the basins. It was observed that there was a shift in the runoff pattern towards western region as compared to reported normal runoff. Total monsoon season (aggregating 1st June to 30th September) runoff was 126 Mha-m over mainland of India during 2004. About 44 percent of total rainfall was converted into surface runoff. Month-wise runoff contribution was of 17%, 35%, 36% and 12% during June, July, August and September months, respectively in 2004. SCS model doesn't take into account flow of runoff. Therefore, another overland model was setup by taking SCS model as input along with DEM data. The overland flow model results indicate large difference in the spatial behaviour of runoff compare to SCS model estimated runoff pattern because of flow of runoff water to the down gradient. Remote sensing derived parameters facilitate spatial modeling due to its spatial format. High temporal resolution remote sensing data has been found useful in deriving the landuse/cover required for such study as it captures the variation both in spatial and temporal domain, thus, improving the model performance.

1. INTRODUCTION

Information about the extent, spatial distribution and temporal variation of runoff at regional scales is essential to understand its influence on regional hydrology, as well as conservation and development of land resources. Conventional techniques of runoff measurement are useful, however in most cases such measurements are very expensive, time consuming and difficult. Therefore, rainfall-runoff models are commonly used for computing runoff. The Soil Conservation Service (SCS, 1985) curve number method, which is a versatile and widely used approach for quick runoff estimation and also relatively easy to use with minimum data and give adequate results (USDA, 1986; Schulze et al., 1992; SCS, 1972; Chatterjee et al., 2001; Bhuyan et al., 2003) was used. It is used extensively in various hydrologic, erosion and water quality models, including CREAMS (kinsel, 1980), EPIC (Sharpley and Williams, 1990), AGNPS (Young et al., 1989) and SWAT (Arnold et al., 1998). Generally, this model is well suited for small watershed of less than 250 km², as it requires details of soil physical properties, land use and vegetation condition (Ponce and Hawkins, 1996; Sharma et al., 2001). Therefore, so far it has been used mostly as lumped (taking the average value of the study area) model at watershed scale (Miloradov and Marjanovic, 1991; Rao et al., 1996; Kumar et al., 1997; Pandey et al., 2002; Nayak and Jaiswal, 2003). But, advances in computational power and the growing availability of spatial data from remote sensing techniques have made it possible to use hydrological models like SCS curve number in spatial domain with satellite remote sensing data and Geographic Information System (GIS) (Moglen, 2000). In the present study temporal 10-day composite Normalized Difference Vegetation Index (NDVI) images of SPOT-VGT sensor, and daily remote sensing derived rainfall data at 10 km resolution from NOAA-Climate

Prediction Centre has been used. SCS model has been used to estimate runoff for major river basins of India at 10 km spatial and daily temporal scales during 2004. The SCS model doesn't take into account flow of runoff water due to topographic variations. Therefore to overcome this limitation a distributed hydrological model MIKE SHE (Abbott et al., 1986a) overland module was used.

2. STUDY AREA

The water resources of India drain from 17 major drainage basins. These basins are namely, Indus, Ganga, Brahmaputra including Barak & others (BH-BRK), Luni and rivers of Saurashtra (LRS), Sabarmati, Mahi, Narmada, Brahmani-Baitrani (BR-BT), Mahanadi, Godavari, Rivers between Mahanadi and Godavari (BMG), Tapi, Krishna, Rivers between Krishna & Cauvery (BKC), Cauvery, West and South coast rivers (WSCR) and Subarnarekha. Three of these are snow fed in summer viz. Indus, Ganga and Brahmaputra and remaining fourteen are purely monsoon dependent (CWC, 2002). Dependable rainfall (75 % of total rainfall) is high (1657 mm) for WSCR, while it is low (296 mm) for Indus.

3. DATA AND ANALYSIS

3.1 Land use/cover

Satellite remote sensing has enabled the mapping of land use/cover at different spatial and temporal scales. The SPOT sensor (operates in four spectral bands red, blue, NIR and SWIR regions) 10 day composite NDVI images were downloaded from internet (www.free.vgt.vito.be). Various

studies suggest that NDVI is least affected by topographic features. Therefore, in this study multivariate data was used to prepare NDVI profiles of various land cover classes. The training sites were used from Agrawal et al., 2003 and crop region map of Survey of India (SOI, 1978). The NDVI profiles are studied to arrive at a logical framework to discriminate different land cover classes. A hierarchical logical model (Zade, et al., 2005) for land cover classification is prepared. An attempt has been made to stratify the different vegetation classes keeping in mind hydrological requirements (canopy, flow to retardance etc.) of land cover classes. Hydrological land use/cover is presented in Fig. 1. Classification was used to discriminate the crops into good, poor and fair crop categories. The rating of good, poor and fair was based on a combination of factors that affect infiltration and runoff, including canopy of vegetative areas, amount of year-round ground cover and percent of residue cover on the land surface.

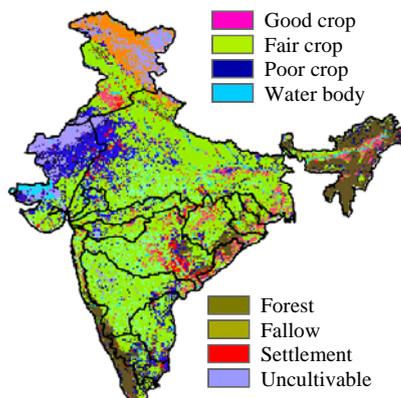


Figure 1. hydrological land use/cover class map

3.2 Hydrological Soil Group (HSG)

Soil texture map at 1: 6 M scale was used from Survey of India (SOI, 1978). There are fourteen soil textures over India. Soil textures obtained from Survey of India were used to prepare HSG map considering the soil infiltration and drainage characteristics (SCS, 1972). Area under different hydrological soil groups (A to D; high to low infiltration) were calculated and validated with the reported area. In the present study, area under different soil groups were found 9%, 51%, 17% and 23% (percentage calculated considering total 319 Mha area) for the A, B, C and D groups of soils, respectively. While, the reported areas are 11%, 54%, 16% and 19% (percentage calculated considering total 328 Mha area) for the A, B, C and D type of soils, respectively (Dhruv narayan, 1993).

3.3 Antecedent Moisture Condition (AMC)

Daily rainfall data has been downloaded from NOAA Climate Prediction Centre (CPC) site ftp.cpc.ncep.noaa.gov/fews/S.Asia for the year 2004 and 2007. The AMC is determined by cumulative last five days daily rainfall. The AMC is used as index of wetness in a particular area. Three levels are used: AMC- I: Lowest runoff potential. The soils are dry enough for satisfactory cultivation (rainfall < 35 mm)

AMC- II: Average condition (rainfall between 35 to 52.5 mm)
 AMC- III: Highest runoff potential. The area is practically saturated from antecedent rains (rainfall > 52.5 mm)

3.4 Hydrological Soil Cover Complex (HSCC)

Land use/cover and HSG maps were combined in the GIS environment to prepare combinations of land cover type and hydrological soil groups. Combined map has 32 combinations (for 4 HSG classes and 8 land use/cover classes). These combinations are termed as Hydrological Soil Cover Complex (HSCC) along with antecedent moisture condition were used to assign the curve number.

3.5 DEM and roughness factor

The topography defines the drainage surface for runoff flow. GTOPO30 (global topography) DEM data over Indian land region has been downloaded from Internet site (<http://www.edcftp.cr.usgs.gov>). Mean highest and lowest elevation are of 3169 m and 135 m for Indus and Sabarmati river basins, respectively. Coefficient of variation (CV) among river basins ranges from 1.78 to 0.43 for Ganga and Krishna basins, respectively.

The roughness factor, Manning number 'M' is used for the resistance to the flow. This number is reciprocal to the Manning's 'n'. Manning number is prepared using the roughness values (Dutta, et al., 2000) for different land cover classes (derived using SPOT S-10 data). Manning 'M' ranges from 12 to 40. The exact route was determined by the topography and flow resistance (Manning's 'M').

4. METHODOLOGY

4.1 SCS Model

The SCS model developed by United States Department of Agriculture (USDA) computes direct runoff through an empirical equation that requires rainfall (antecedent soil moisture condition), soil, land cover and the curve number (CN), which represents the runoff potential of the land cover soil complex (SCS, 1972). This model involves relationship between land cover, hydrologic soil class and antecedent soil moisture to assign curve number. Following layers were prepared for CN based runoff calculation: Since, standard table for CN values (ranges from 1 to 100), considering land use/cover and HSG are given for AMC-II (Vandersypen et al. 1972). Following conversion formulas were used to convert CN from AMC-II (average condition) to the AMC-I (dry condition) and AMC-III (wet condition) (SCS, 1972):

For dry condition (AMC-I):

$$CN(AMC-I) = \frac{4.2 * CN(AMC-II)}{10 - 0.058 * CN(AMC-II)} \quad (1)$$

For wet conditions (AMC-III):

$$CN(AMC-III) = \frac{23 * CN(AMC-II)}{10 + 0.13 * CN(AMC-II)} \quad (2)$$

Potential maximum retention for a given soil is related to the curve number. Losses due to infiltration, detention storage and interception were considered as initial abstractions. Vandersypen et al. (1972) developed the following relationship between initial abstractions and potential maximum retention

for Indian conditions; for black soil region (AMC-I) and for all other regions:

$$I_a = 0.3 * S \quad (3)$$

Where I_a = initial abstractions and S = potential maximum retention. For black soil region (AMC-II and AMC-III):

$$I_a = 0.1 * S \quad (4)$$

SCS, 1972 has shown the derivation of equation of runoff from the water balance equation under the critical assumption that the ratio of the actual runoff to the potential runoff (rainfall less initial abstraction) is equal to the ratio of the actual retention to the potential retention.

$$Q = \frac{(P - I_a)^2}{(P + I_a - S)^2} \quad (5)$$

Where P = rainfall and Q = runoff

Net rainfall fraction (NRF) or runoff coefficient, which is input to the MIKE SHE overland flow module, was also calculated using the following equation;

$$NRF = \frac{(P - Q)}{P} \quad (6)$$

The methodology for runoff estimation using SCS model is shown in Fig. 2. Soil texture and temporal SPOT NDVI maps were used to prepare hydrological soil group and land cover class maps, respectively. These two maps, HSG and land cover class were combined to generate Hydrological Soil Cover Complex. Considering the established curve numbers for different combinations of HSCC, a base CN map was prepared for AMC-II. Antecedent moisture condition maps were prepared considering the summation of last five days rainfall. Daily changes in the AMC condition and its distribution due to variation in the rainfall estimate were used to modify base CN map for AMC-I and AMC-III using the formulas presented in equation 1 and 2, respectively. These modified CN maps were used to estimate initial abstractions, which covers losses due to interception, infiltration and detention storage. Further, losses were modified taking into account black cotton soil for different AMC conditions. Finally, daily runoff and net rainfall fraction maps had been prepared. Above-mentioned procedure to develop daily spatial runoff and net rainfall fraction was translated in the GIS environment using an Arc Macro Language (AML).

4.2 Overland Flow Model

SCS model does not take into account flow process due to topographic variations. Therefore, SCS model limitations were modified by coupling SCS model with an overland flow model. Methodology for hybrid modeling technique for runoff flow modeling is shown in Fig. 3. In this coupling SCS model estimated net rainfall fractions along with Manning's roughness, 'M' (inverse of the Manning roughness, n) factor and DEM were used

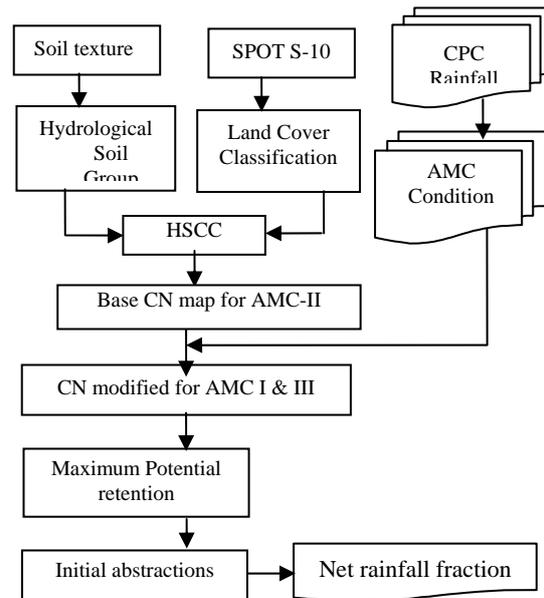


Figure 2. Methodology for spatio-temporal runoff/net-rainfall fraction estimation

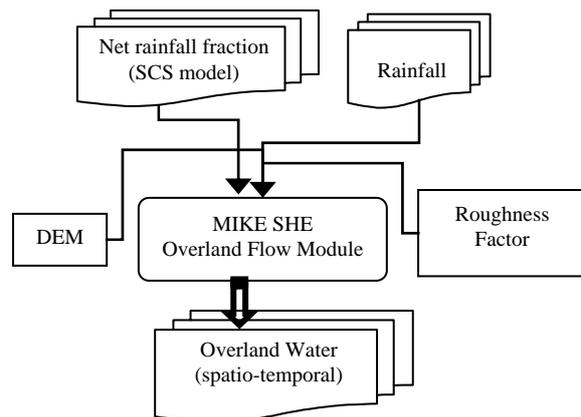


Figure 3. Hybrid technique for overland flow modeling

as input to the overland flow module of the MIKE SHE model for runoff/overland flow modeling. The overland flow process was simulated in each grid square by solving the two dimensional diffusive wave approximations of Saint-Venant equations for conservation of mass and momentum. SCS and overland model estimated runoff water characteristics and effect due to flow modeling were analyzed in the spatio-temporal domain.

5. RESULTS AND DISCUSSION

In this section results for SCS model estimated runoff for major river basins of India are presented. Effect of the flow modeling in the runoff pattern using an overland flow model was also analyzed for different basins.

5.1 Runoff analysis

Runoff estimation was done at daily scale but in this paper results are presented for monthly scales (aggregated using daily

data). Runoff spatial extents for different months during 2004 have been presented in Fig. 4. Quarterly total mean runoff values considering all the basins range from 39 mm (Indus and BH-BRK; because of early occurrence of rainfall in these regions) to 0.01 mm (Sabarmati), 277 mm (Indus) to 20 mm (LRS), 616 mm (Subarnrekha) to 155 mm (Krishna) and 178 mm (Cauvery) to 5 mm (LRS) for Jan-Mar, April-June, July-September and October-December periods, respectively. The runoff pattern from June-September typically matched well

with the advancement of monsoon system. Surprisingly runoff was too high for Sabarmati basin in comparison to the previously reported runoff (Table 1). This shows shift in the rainfall induced runoff towards western region in the recent past. The runoff in the northern and central region became low for October-December period, whereas it was significant in the southern basins like Cauvery. This could be re-treating southwest monsoon and the north-east monsoon. Thus the spatial variability of runoff was high during monsoon period.

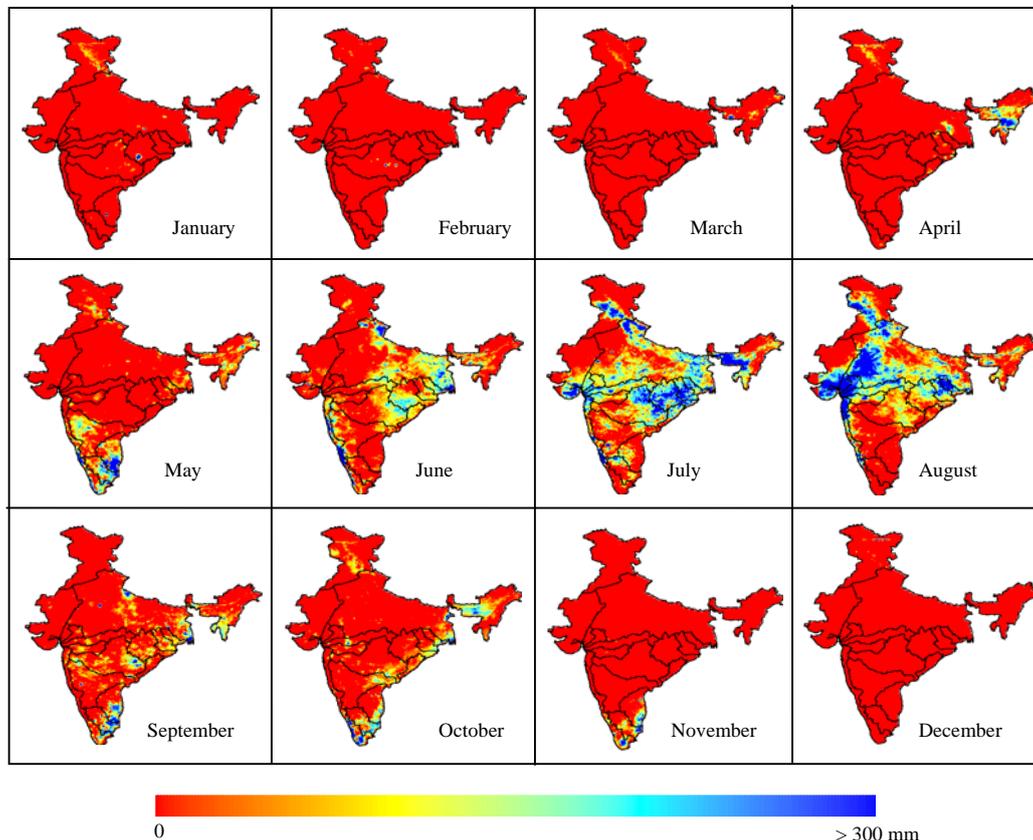


Figure 4. Monthly runoff map over main land of India (2004) using SCS model

During other period, there was low spatial variability of runoff due to low rainfall. Coefficients of variation were also calculated and found to be high for Indus (0.53), BMG (2.11), Mahi (3.52) and BMG (1.82), for different quarterly periods starting from January month. Rainfall variability was high for Subarnarekha and BR-BT basins during first three quarterly period, while in fourth quarter (October-December), it was high for BMG (6.47) and Cauvery (3.58) basins. Rainfall to runoff conversion was highest of 61 % for Sabarmati basin during July-September. Runoff contribution was of 1.2 %, 23.2 %, 64.4 % and 11.2 % for Jan-March, April-June, July-September and October to December periods, respectively. High runoff concentration has been observed in BR-BT, Subarnarekha, Mahanadi, and parts of Godavari, Ganga and, BH-BRK basins. While, low runoff concentration was seen in LRS, Krishna, Cauvery, BKC and Indus basins. This low and high runoff in different basins was because of low/high rainfall occurrence and curve number pattern in these basins.

Daily runoff maps were aggregated to prepare annual runoff. Overall annual rainfall to runoff conversion was high (54 %) for Sabarmati and low (28 %) for Krishna among the major river basins of India. Over India, rainfall to runoff conversion was of 36 %.

5.2 Comparison with the reported data

Comparison is done for both input and output data. The accuracy of the input data required to estimate CN is vital for accurate runoff calculations. Hence, area under different HSG types has been calculated in the present study were

confirmed with the reported HSG area. In the present study, area under different soil types have been found 8.3%, 51.5%, 17% and 23.2% (percentage calculated considering total 313 Mha area) for the A, B, C and D type of soils, respectively. While, the reported areas were 11.1%, 53.7%, 16.8% and 18.4% (percentage calculated considering total 328 Mha area) for the A, B, C and D type of soils, respectively (Dhruv narayan 1993). Basin-wise reported total annual runoff (Rao, 1975; Chaturvedi, 1976) were compared with the model-estimated runoff during 2004 and presented in Table 1.

Basin	Reported (1975) Mha-m	Reported (1976) Mha-m	Estimated (2004) Mha-m
Ganga	55.0	49.3	37.6
LRS	1.2	-	5.4
Sabarmati	0.4	0.3	1.4
Mahi	1.2	0.9	2.0
Narmada	4.0	4.1	5.0
BR-BT	4.4	-	3.8
Subarnarekha	-	0.8	2.7
Mahanadi	7.1	6.7	8.8
Godavari	11.5	10.5	13.2
Tapi	2.0	1.8	2.7
WSCR	22.7	-	11.2
BMG	1.7	-	2.6
Krishna	5.8	6.7	8.5
BKC	2.5	0.3	7.9
Cauvery	1.9	2.1	4.7
Indus	7.7	4.2	10.0
BH-BRK	59.7	51.0	23.3

Table 1. Basin-wise reported and estimated annual runoff

There was a close agreement between the reported and estimated runoff in most of the basins except BH-BRK, WSCR and Sabarmati basins. For Sabarmati basin high runoff was due to high rainfall in the western regions in the recent past, while for other basins low runoff was because of underestimated rainfall obtained from remote sensing technique in the hilly regions (elevation > 700 m from msl; Choudhary et al., 2006) and also very good vegetation (forest) cover, which lowers the curve number and consequently runoff.

5.3 Effect of runoff flow modeling

The SCS model gives information about the runoff generation in a particular location but overland flow modeling provide actual distribution of runoff water on the ground surface. Runoff maps generated using SCS model were used for net rainfall fraction calculation (runoff coefficient), which were utilized for flow modeling using an overland flow model. Effects in runoff pattern due to flow modeling were analyzed in spatio-temporal domain and also compared with the SCS model estimated runoff results. Monthly runoff maps obtained from overland model simulations (Fig. 5) were subtracted with the SCS model estimated runoff to see the difference in the spatial variability of the runoff.

Results show that runoff produced using SCS model flows down to the gradient and accumulated in the low lying areas in all the river basins. However, runoff production area was quite high as compared to runoff stored area. Since SCS model doesn't take DEM and flow process into account, a great deal of difference has been observed in the spatial extent of runoff obtained using overland flow model in comparison to runoff estimated using SCS model. This is because of two dimensional flow modeling with DEM and roughness factor. Coefficient of variation was very high for overland model simulated runoff as compared to SCS model estimated runoff in all the river basins and also for different months. Very low CV range of 0.19 (Mahi) to 1.85 (Indus) was observed for SCS model estimated runoff as compared to the range of 3.3 (BMG) to 6.4 (LRS) for overland model simulated runoff water during the monsoon season (June to September). Seasonal runoff difference map between SCS estimated and overland model simulated runoff overlaid on the three-dimensional DEM is presented in Fig. 6.

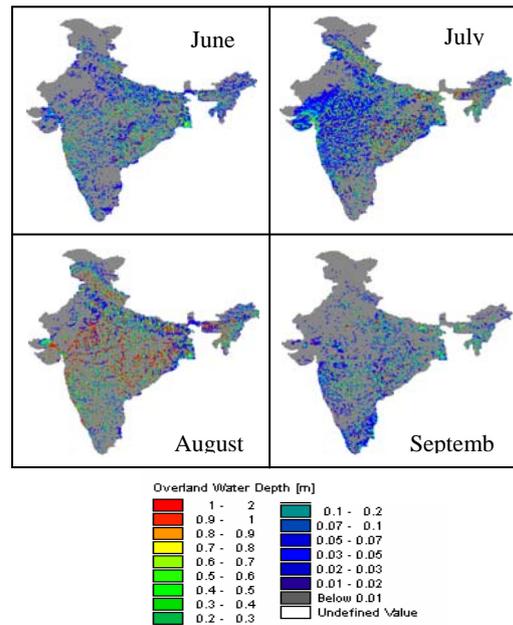


Figure 5. Monthly runoff pattern using overland flow

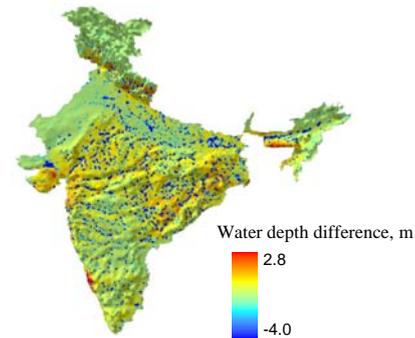


Figure 6. Seasonal (June to September, 2004) difference map of overland and SCS model estimated runoff

It can be observed that dark colour regions are overland model simulated high runoff water concentrated areas, which are low lying areas, while light colour regions indicates high runoff areas estimated using SCS model. Seasonal coefficient of variation was high of 4.2 for overland model simulated runoff as compared to 0.62 from SCS runoff over mainland of India. This indicates that there was a large effect of flow modeling in the spatial variability of runoff pattern compared to SCS model estimated runoff pattern.

6. CONCLUSIONS

SCS model has been used to estimate runoff over mainland of India. This model gives quick estimate of generated runoff in a particular location with reasonably good accuracy but doesn't take into account flow processes due to topographical variations. Therefore, another overland flow model was applied using the SCS model result, net rainfall fraction which is the ratio of the runoff to the rainfall as input to the model. It was observed that there was a great difference between the runoff generation (SCS model) and its actual accumulation (overland flow model) in the field. After water flow modeling, most of water flows down to the gradient and accumulated in low-lying areas (rivers and flat regions). Coefficient of variation was observed very high and ranges between 3.3 (BMG) to 6.4 (LRS) considering all the basins during monsoon season. It was observed that after water

flow modeling, topographical variations were taken care very well for runoff accumulation. Hybrid technique was found well suitable for runoff modeling at regional scales.

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