Journal of Geomatics Vol 10 No. 1 April 2016

Runoff estimation from a tributary of lower Tapi basin using SCS-CN method integrated with remote sensing and GIS data

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(Received: Sep 28, 2015; in final form: Jan 27, 2016)

Abstract: The purpose of this research paper is to identify watersheds with high flood potential based on their characteristics for formation of surface runoff. The SCS-CN method relies on remote sensing and GIS data for obtaining watershed characteristics. A 30m raster grid size digital elevation model (DEM) has been generated from field survey using Global Positioning System (GPS) of 3m accuracy integrating with Survey of India topographical maps of 1:50,000 scale having 10m contour interval. The undisturbed soil samples from field have been collected and laboratory analysis was carried out using modified proctor compaction test as per ASTM D1557 and sieve analysis as per ASTM C136. This has helped in establishing hydrological soil map while land use map has been prepared using Landsat 7 ETM+ image band 2, 3, 4 (30m) merged with PAN band 8 (15m) for classification. The supervised maximum likelihood classification approach has been employed for preparation of land use map for Varekhadi catchment having 442 km^2 of geographical coverage. The major land use categories classified on 10 Nov 2001 Landsat 7 ETM+ image were agriculture (32%), forest (29%), wasteland (20%), fallow land (14%), built-up (4%) and water bodies (2%). The hydrological soil groups generated in GIS environment have identified two soil groups viz. group B and group C that exist under study area. The Varekhadi catchment has been delineated into five watersheds viz. Amli, Zankhwaw, Visdaliya, Godsambha and Wareli delineated using DEM and stream network. The SCS-CN model was applied for estimating of daily run-off for each sub-watershed. The results obtained on the flood potential analysis shows that Wareli watershed has highest flood potential while the Amli watershed lowest. It should be noted that highest value of flood potential belongs to lowest part of watershed, where high population density is found. This analysis reflects an increased vulnerability and risks to floods and inundations for Wareli watershed. Stream gauge data has been used for result validation with a common event of 2010 and it shows good agreement with the model. The flood potential analysis within the lower Tapi basin tributary suggests that the SCS-CN method with hydrological parameters derived using remote sensing and GIS data can be applied to predict run-off in poorly gauged watersheds.

Keywords: SCS-CN method, Remote sensing, GIS, Landsat 7 ETM+, Runoff, Ungauged catchment

1. Introduction

Surface runoff generation is dependent on climatic, geo-morphological, topographical and landuse characteristics of a catchment or watershed. Of above, the topographical characteristics and soil types with land use as hydrological soil group have been of immense importance. A combination of characteristics favourable for runoff generation and runoff concentration increases the flood potential in a watershed. Most of the watersheds in India have been poorly gauged or un-gauged, as they do not have adequate records of runoff generation for a rainfall event to understand the hydrological response. In the flood prone catchments, it is required to calculate peak flood discharge or flood potential from each watershed. A number of discharge estimation methods available in the literature namely Rational method, Soil Conservation Service- Curve Number (SCS-CN) method, Cook's method and Unit hydrograph method. However, the SCS-CN method for predicting direct run-off or discharge from rainfall excess of ungauged watershed is extremely important. Balvanshi and Tiwari (2014) have reviewed SCS CN method for runoff estimation and recommended that. It is being used in a wide range of design situations by the practicing engineers and hydrologists. Sindhu et al. (2013) have carried out estimation of surface runoff in Nallur Amanikere Watershed using SCS-CN method. They found the variation in runoff potential with different land use/land cover and with different soil conditions.

This method allows the identification and zoning of watersheds with a high risk of generating floods and of those exposed to runoff generation processes. Soil and landuse parameters, which control surface runoff, can be evaluated and mapped through remote sensing satellite images. Sharma and Singh (1992) in their research work for Luni river catchment have successfully used Landsat TM and SCS-CN model to estimate runoff potential. Katimon et al. (2003) estimated flood potential of two small watersheds of Salengor and Pontian in Malaysia using SCS-CN method and GIS based empirical approach to predict daily event storm runoff. They have pointed out that SCS-CN and GIS have limitations in flood estimation in absence of accurate hydrologic soil group data. They have noted large variations in the surface runoff if hydrological soil group changes. Later, Behzad et al. (2012) used SCS-CN method for estimating flood potential for different return periods. They emphasised on geomorphologic characteristics of Tarik flood basin in Iran. Several other methods on peak flood discharge and associated parameters estimation have been suggested in the literature for ungauged basins. Zhang and Haung (2004) have developed Arc-CN tool integrated with ArcGIS and applied SCS-CN method for estimating run-off and preparing CN and run-off maps. However, the parameter reliability between various methods varies to a large extent and none is found to be suitable universally. In spite of few limitations, SCS-CN along with hydrological soil group and land use remain to be a popular method for estimation of flood potential under poorly gauged or ungauged catchments due to its performance and reliability.

SCS-CN has been applied in the present study for the estimation of run-off from five watersheds of Varekhadi catchment- a tributary of lower Tapi basin. This SCS-CN requires information on catchment characteristics related to DEM, land use and hydrologic soil group for estimation of catchment runoff. The purpose of this method is to determine the curve number (CN) of the catchment accurately that assesses the estimated runoff potential. Hydrologic soil group, land use type, vegetation cover are important physical characteristics of a watershed used for the calculation of CN. Thus, the most important step in estimation of surface runoff or flood discharge is to calculate watershed characteristics accurately. Remote sensing and GIS data together with field surveys and field measurements are input for classification of watershed characteristics. Landsat 7 ETM+ image band 2, 3, 4 (30m resolution) have been merged with PAN (15m resolution) data for supervised classification of land use classes using Gaussian maximum likelihood classifier. Hence, the runoff CN for different watersheds were determined using land use and hydrological soil group map within the study area.

2. Study area

Tapi river basin covers three states viz. Madhya Pradesh (9804 km^2), Maharashtra (51504 km^2) and Gujarat (3837 km^2) having a geographical area of 65145 km^2 and is the India's second largest inter-state westward draining river in Arabian sea. The Tapi river basin can be classified in three zones, viz. upper Tapi basin, middle Tapi basin, and lower Tapi basin (LTB). The area between Ukaidam to Arabian sea has been considered as LTB, mainly occupying Surat and Hazira twin city along with tens of small towns and villages along the river course. LTB has a geographical area of 2920km^2 which has been experiencing periodic floods in urban settlements of Surat and Hazira. The Surat and Hazira are about 106km and 122km downstream of Ukai dam, respectively. Both these cities have been affected by recurrent floods during last 5-decades and flood frequency in the basin has been estimated to be occurring once in 6-years. One among the major causes of flood in LTB is attributed to formation of peak discharge early from various tributaries such as Varekhadi, Anjanakhadi, Serulkhadi, Mau khadi and Gal khadi. The flood during August 2006 in LTB caused huge damage to personal and property resulting into 300 people being killed and US$ 4.5 billion value property damage (Singh et al., 2009).

Varekhadi catchment is a tributary of LTB having a river length 50 km covering a geographical area is 442km^2 (figure 1) which confluences near Mandvi town. The Varekhadi catchment has been divided into 5-watersheds consisting of lone urban centre Zankhwaw along with almost 150 rural settlements. It has 2 major surface water reservoirs viz. Issar and Amli dams which are located in the study area. The dam storage is mainly used for flood control during monsoon season and for irrigation during the post-monsoon through gravity canal system. The right bank canal from Kakrapar weir located 30km upstream of Varekhadi confluence passes through watershed and is being predominantly used for irrigation purpose.

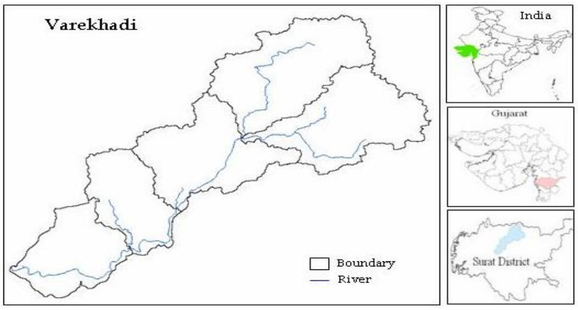


Figure 1: Study area

The geographic coordinates of the study area are $21^0$14'N $73^0$07'E to $21^0$30'N $73^0$30'E as lower left and upper right corners. The study area receives an average yearly rainfall of 1376mm. The temperature in the catchment is variable which has a range of 22°C and 40°C as minimum and maximum temperature. Major land use categories are built-up area as settlements, agriculture, forest, fallow land, water bodies and other uses. Considering the definition of land use CN and soil types, the hydrological soil groups available in Varekhadi catchment are B and C. Major problem in study area is flood in low laying areas near Wareli village at the confluence of Varekhadi catchment with main Tapi river.

3. Methodology

The proposed research methodology can be considered to have two parts. The part one is the modelling of the spatial variability of topographical parameters using remote sensing and GIS while the part two involves analysis of the digital data base to derive hydrological model parameters. The research methodology used for estimation of surface run-off vis.a.vis flood potential using SCS-CN method consist of five steps viz. Sub-watershed delineation, land use map and hydrological soil group map generation, CN calculation and run-off estimation. The flow chart of methodology is given in figure 2.

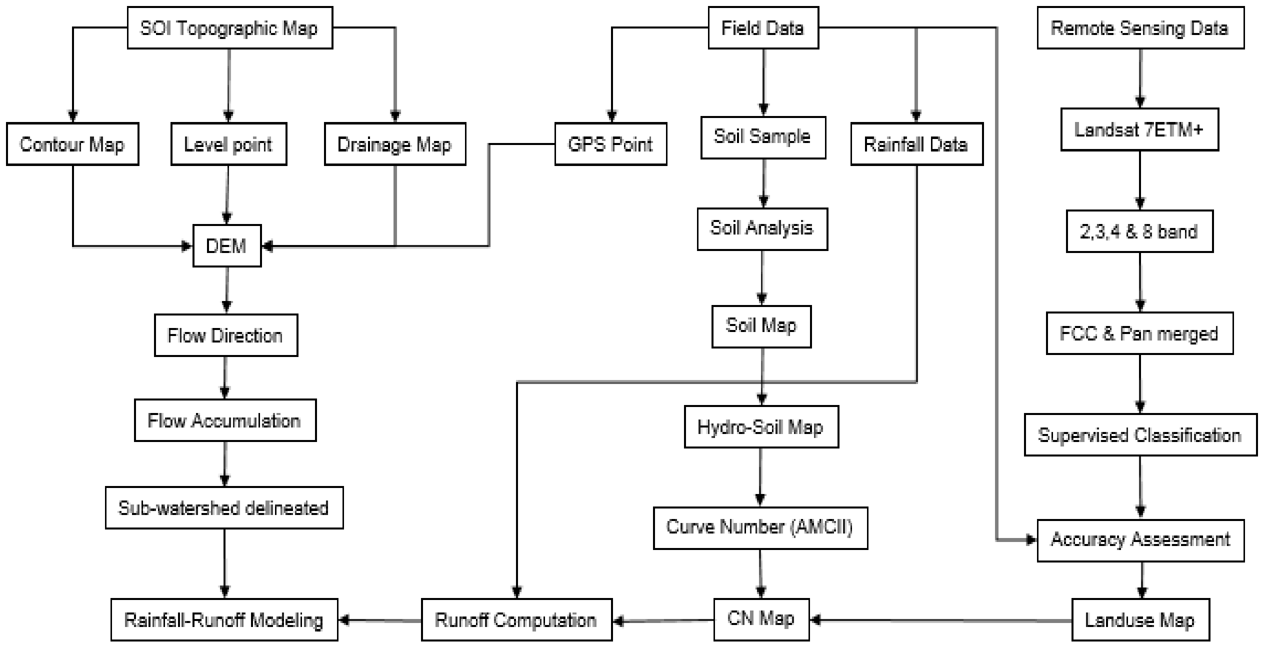


Figure 2: Flow chart of methodology

In this paper, hydrological data related to runoff estimation such as DEM, Landsat 7 ETM+ satellite imagery, global positioning system (GPS) for level points, soil map for grain size and soil moisture, land use for CN, hydrological soil group as AMC (antecedent moisture condition) and rainfall have been used. A DEM of 30m raster grid size has been generated from field survey using GPS of 3m accuracy integrating with Survey of India topographical maps of 1:50,000 scale having 10m contour interval.

3.1 Watershed delineation

A DEM of 30m raster cell size and 0.5m vertical accuracy has been used to delineate 5-watersheds for Varekhadi river basin using BASIN hydrological model. The steps followed in a given sequence are (i) creating a depressionless DEM; (ii) calculating flow direction based on 3x3 cell neighbourhood algorithm; (iii) calculating flow accumulation and identify cell having given area; (iv) delineation of watershed outlet points leading to delineation of watersheds for a given threshold area. Five such watersheds have been delineated named as Amli, Zankhwaw, Visdaliya, Godsambha and Wareli. Watershed parameters such as flow length, river length, watershed outlet point, watershed area, river length and river slope were obtained from DEM (Figure 3). The validation of DEM has been done using 24 ground control level points using GPS.

3.2 Generating landuse map

The land use map of Varekhadi watershed has been generated by image analysis of satellite data. The image of Landsat 7 ETM+ (10 Nov 2001) bands 2, 3, 4 with (30m) spatial resolution and PAN with (15m) ground resolution were analysed.

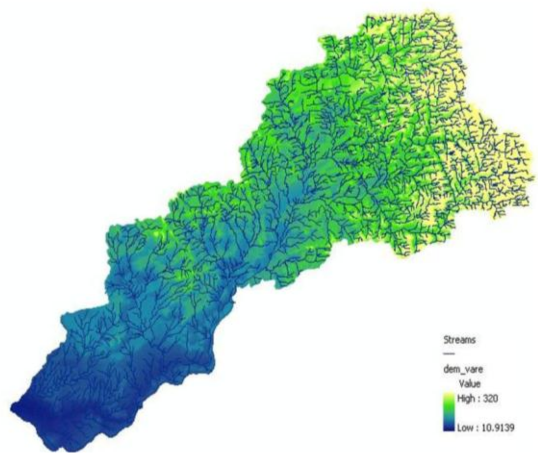


Figure 3: Digital Elevation Model (DEM)

Image geometric correction has been done and land use map were derived using Gaussian maximum likelihood algorithm of supervised classification with field sample. Land use categories considered in the study area are built-up land, agriculture, forest, fallow land, water bodies and other as shown in figure 4 and their statistics are given in table 1. SCS-CN method related land use description as an input for runoff generation process. The CN can be empirically determined based on SCS (1985) land use description, hydrological soil group and AMC conditions

3.3 Generating hydrological soil group map

To create hydrological soil group map, soil survey of study area was conducted. Thirty points were selected for soil sample in study area and soil samples have been analysed in the laboratory. Soil properties have been identified and a GIS map of hydrological soil group was prepared. There are two type of soil in study area group B and C as shown in figure 5.

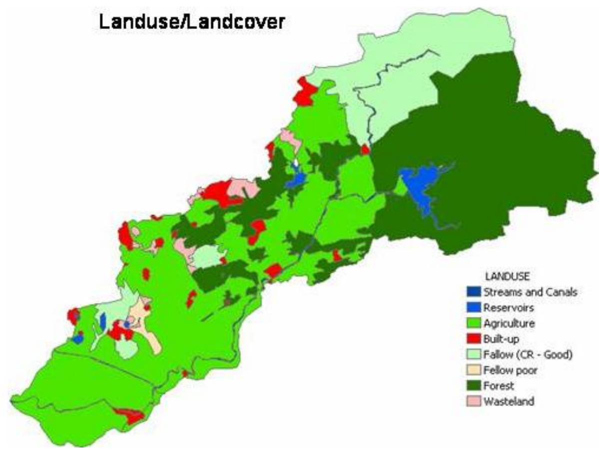


Figure 3: Land use / land cover map

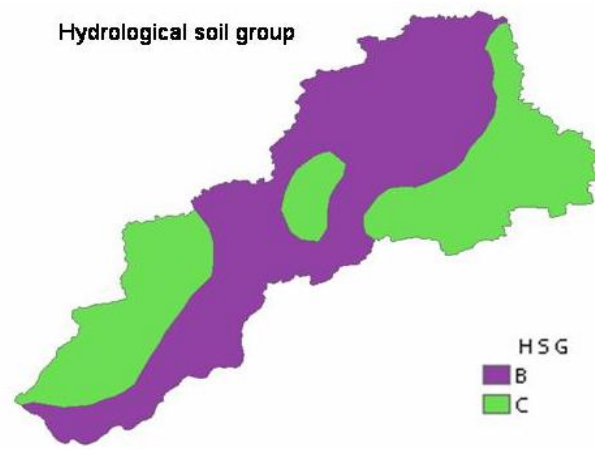


Figure 4: Hydrological soil map

3.4 Generating CN map

The CN value has been used to estimate potential maximum soil retention. The value of CN is 100 for impervious surfaces and between 0<CN≤100 for other surfaces. The maximum potential storage which relates to CN depends on land use, hydrological soil group, hydrological condition and AMC (Ponce and Hawkins, 1996). Arc CN extension of ArcGIS software has been used to generate the CN map of Varekhadi watershed. The hydrologic soil group field from the soil map and the land use field from the land use map were selected for intersection under vector environment in GIS. After intersection, a map with new polygons representing the merged soil hydrologic group and land use (land-soil map) was generated.

CN map directly effect on surface runoff, all the surface water bodies gives the CN value zero and resulted run off is also zero. Average CN also have been calculated and the details are given in table 2. In shows that Wareli watershed has highest CN value 86.07 and Zankhwaw has lowest CN value 68.95.

3.5 Run-off estimation

The SCS-CN method assumes that surface runoff will be generated once initial losses are satisfied. The SCS-CN method explaining the water balance can be given by equation 1. The main hypothesis in this method is that the ratio of direct runoff to the rainfall depth minus initial losses (P- Ia) is equal to the cumulative infiltration as given in equation 2 (Mishra and Singh, 2003).

$$P = Q + F + I_a \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$Q \;/ (P\text{-}Ia) = F / S \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where the terms P is total precipitation (mm); Ia is the initial abstraction (mm); F is cumulative infiltration (mm); Q is direct runoff (mm); S is the potential maximum retention or storage capacity of soil (mm). As per USDA-SCS (1985) guidelines the initial abstraction (mm) is assumed to be abstraction fraction (usually λ= 0.2) of the potential maximum retention as shown in equation 3.

$$Ia = \lambda.S \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

The direct storm runoff Q (mm)can be related to the effective rainfall and actual retention through the water balance equation 4 (Yu, 1998). Equation 4 is valid only

When $P \geq \lambda S$ and generally $I_a = 0.2S$, hence equation 4 can be written as;

$$Q_p = (P\text{-}I_a)^2/(P\text{-}I_a+S)$$

$$= (P\text{-}0.2S)^2/(P+0.8S) \ldots\ldots\ldots \quad (4)$$

If effective rainfall $P \leq \lambda S$, then direct storm runoff Q (mm) is taken as zero

In practice, the potential maximum retention S (mm) of the soil is determined using the CN given in equation 5.

$$S = (254400/CN) - 254 \ldots\ldots\ldots\ldots\ldots \quad (5)$$

The term CN is determined from a table based on land use, hydrological soil group and AMC. The hydrological soil group has four classes A, B, C and D based on landuse, hydrological soil group and AMC. The hydrological soil group has four classes A, B, C and D based on infiltration rate of soil. AMC has three classes I, II and III according to rainfall limits for sowing and growing season.

3.6 Stream gauge installation

Varekhadi has no discharge measurement gauging station and is classified as un-gauged watershed. This being a remote location, it has been proposed to install automatic sensors with data logger capabilities. WL-16U stream gauge sensors of 25m cable from Global Water USA were procured and installed in field during June 2010. The sensor has 0.1mm measurement accuracy and can record 10 reading per second. Three discharge sites viz. Amli, Visdalia and Godsamba have been selected for installation of stream gauge. The output data has been used for result validation for deferent sub watershed.

4. Results and discussion

The direct storm runoff depends on land use, soil type and hydrological soil group and CN. Landsat 7 ETM+ data of 10 Nov 2001 has been used for supervised classification of 5-land use classes. A merge product of Landsat 7 ETM+ band 2, 3, 4 of 30m cell size with PAN band of 15m spatial resolution was used for classification. The land use distribution within Varekhadi catchment shows that it is primarily an agriculture catchment as 32% of study area is under agriculture, 46% of area under agriculture and current fallow; 66% of area under wasteland, fallow land and agriculture (Table 1).

Table 1: Landuse Classification

Land use	Area km^2	% of total area
Agriculture	142	32
Fallow Land	60	14
Wasteland	87	20
Built-up land	17	4
Water bodies	7	2
Total	442	100

The value of volume and surface runoff were calculated for extracting percentage flood contribution for each sub-watershed which is shown in table 2.

Table 2: Estimation of runoff for each watershed (1999-2008)

Location	Zankhwaw	Amli	Godsamba	Vishdalia	Wareli
Area (km^2)	100.52	91.85	78.85	71.05	99.73
Retention S (mm)	83.40	114.12	100.6	75.95	41.11
Weighted CN (-)	75.28	68.95	71.63	76.98	86.07
Rainfall (mm)	277.0	267.5	251.0	251	252
Runoff (mm)	197.15	166.68	160.81	178.77	201.73

It can be seen that sub-watershed Wareli has high flooding potential and Amli has low flooding potential. Flooding potential depends on CN and CN depends on land use and soil properties of watershed which is clearly reflected in results.

It is required to estimate a coefficient that reduces the total rainfall to runoff potential after losses in terms of evaporation, absorption, transpiration and surface storage. It can be stated that the higher the CN value leads the higher runoff generation. Wareli watershed has 86.07 weighted CN so that Wareli is a high flooding potential watershed and Amli has 68.95 weighted CN sothat it gives low run-off. Geospatial distribution of CN value in figure 6

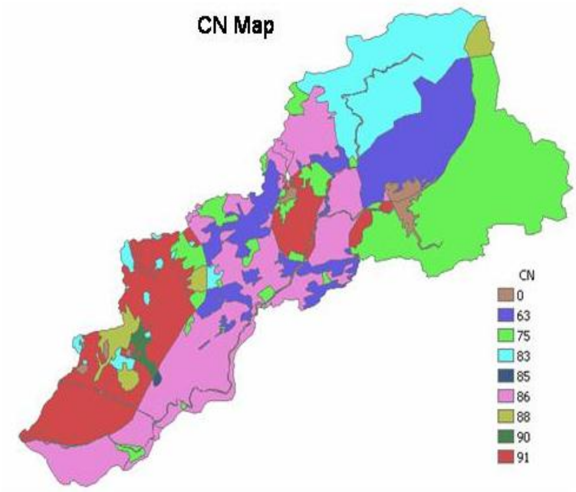


Figure 5: Curve number (CN) map

Runoff depth value calculated for each grids from the equation. Figure 7 depicts the distribution of runoff depth upon 262mm rainfall. Figure 8 (a), (b), (c), (d), (e) depict the graphs of runoff vs. rainfall data will conform to a simple linear relationship with a good fit polynomial trend line. The 10 years rainfall data from 1998-2008 run-off has been used to calculate runoff for each sub-watersheds and graphs was drawn. The correlation coefficient R^2values are similar for all 5 sub-watershed 86.07 weighted CN so that Wareli is a high flooding potential watershed and Amli has 68.95 weighted CN so that it gives low run-off. The details run-off depth map is given in figure 7.

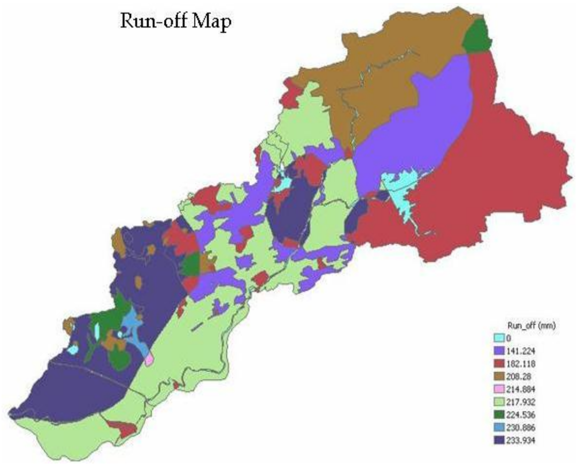
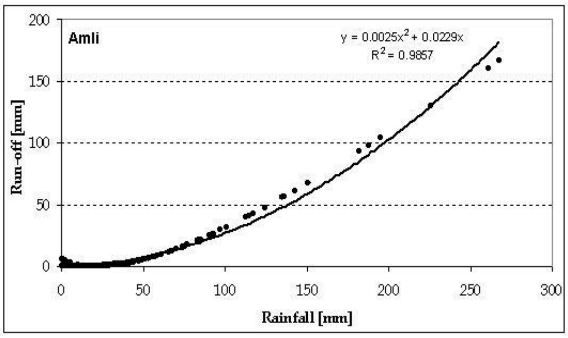


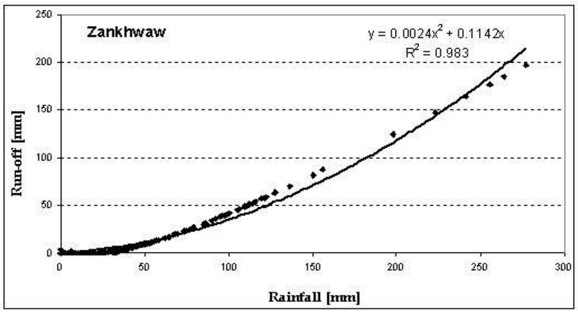
Figure 6: Runoff distribution

Regression analysis has been carried out for each sub-watershed. This can be used for calibration purpose as given in table 3.

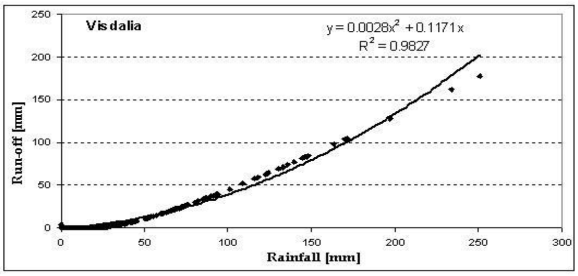
Stream gauge data were used for result validation (figure 9) for a common event of 2010. It is found that model can give a good and accurate result for ungauged catchment.



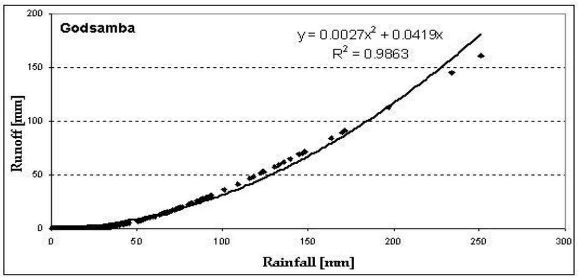
(a)



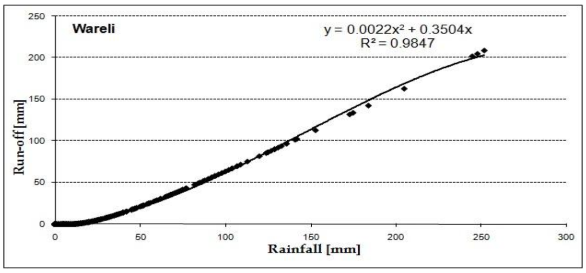
(b)



(c)



(d)



(e)

Figure 8: Results of rainfall runoff relationship for sub-watersheds (a) Amli; (b) Zamkhwaw; (c) Visdalia; (d) Godsamba; and € Wareli

Table 3: Regression relationship between rainfall and runoff for the sub watershed

Sub-watershed	Second order polynomial relationship between rainfall [X] and runoff [Y]; $Y=AX^2+Bx$		
	A	B	R^2
Zankhwaw	0.0024	0.1142	0.9830
Amli	0.0025	0.0229	0.9857
Visdalia	0.0028	0.1171	0.9827
Godsamba	0.0027	0.01419	0.9863
Wareli	0.0022	0.3504	0.9847

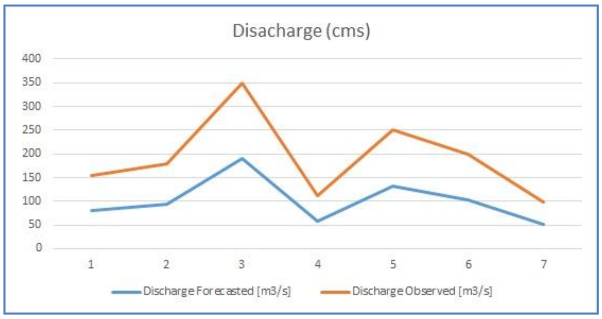


Figure 9: Results of validation of predicted or calculated with stream gauge data

5. Conclusion

Remote sensing and GIS data are of great use for surface runoff estimation when conventional methods of runoff estimation are inadequate. Both the techniques have been used for generating model input for determination of physical characteristics of watershed such as land use, hydrology soil group and CN number. Gaussian maximum likelihood classifier has been used for classification of land use and shows good field acceptability. It has been integrated with SCS-CN method for identification of watershed, estimation of flood potential for a part of lower Tapi basin.

This analysis provides satisfactory results for rainfall-runoff modelling. It will be useful for flood forecasting, flood contribution of each watershed and flood discharge measurements. The method may be good tool for runoff estimation for lower Tapi basin and un-gauged catchment like Varekhadi catchment. It can also state that higher the CN value of catchment leads to more runoff and gives highest contribution for flood.

Acknowledgement

The authors express their sincere thanks to State Water Data Centre officers Mr MG Golawala, Superintending Engineer and Mr SG Shah, Deputy Executive Engineer for supplying daily rainfall data of 8-stations in and around study area. We acknowledge assistance rendered by graduate students of Department of Civil Engineering, Nirma University for carrying out field surveys and soil analysis in laboratory.

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