SYNOPSIS

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Modelling Runoff using Modified SCS-CN Method for
Middle South Saurashtra Region (Gujarat-India)

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MODELLING RUNOFF USING MODIFIED SCS-CN METHOD FOR MIDDLE SOUTH SAURASHTRA REGION (GUJARAT-INDIA)

ABSTRACT
Modelling the runoff becomes more challenging as runoff generation process is highly complex, nonlinear, dynamic in nature, and affected by many interrelated physical factors. Furthermore, the temporal and spatial scale of estimating runoff exhibits another complex issue. However, with present technological capabilities, computing techniques and software tools, it is possible to identify, assess and understand the response of the dominant processes rather accurately. Many methods are being used to estimate runoff in literature, however, the Natural Resources Conservation Service Curve Number (NRCS-CN) (formerly called as SCS-CN) method developed by the U. S. Department of Agriculture (USDA) still remain the most popular, fruitful and frequently used method. The major reasons for this popularity may be attributed to ease of use, less number of input parameters, robustness of model results, and acceptability among both researcher and practitioner community.

The runoff curve number (CN) which is a function of land use/land cover (LULC), soil type, and soil moisture is a key factor of the SCS-CN method. The attractive feature of SCS-CN method is that it integrates the complexity of runoff generation into single parameter, i. e. CN. However, lumped conceptual approach and simplicity of a single parameter introduces great uncertainty to estimate runoff in practical applications. The CN is usually calculated from available tables in the National Engineering Handbook, Section 4 (NEH-4) as well available curves; however, this procedure is very tedious, laborious, and time consuming. It was further observed that large errors can be expected in surface runoff estimation where the validity of the hand book tables for CN was not verified. The SCS-CN method does not adequately model all of the important physical processes of runoff generation–namely impact of land use changes, morphometric parameters, and long term evapotranspiration loss. Thus, it would benefit to larger research and practitioner community to modify the SCS-CN method to encompass these processes.

This research work describes how to improve the performance of SCS-CN method by modifying CN for selected watersheds in India. Composite CN for watershed is determined from LULC map and soil map using soil taxonomy, Remote Sensing (RS) and Geographic Information System (GIS) techniques for watersheds of the Middle South Saurashtra region.
The author has developed three independent models by modifying CN to enhance the performance of SCS-CN method. In the first model, cumulative rainfall-runoff ordered data were applied to modify asymptotic CN using frequency matching technique. In the second model, morphometric parameters were incorporated in computation of weighted CN. While in the third model, the evapotranspiration was introduced to modify CN. All the three proposed models are tested and validated for Ozat, Uben, and Shetrunji watersheds of the Middle South Saurashtra region of Gujarat at daily time scale.

The research analysis reveals that the RS and GIS can be effectively used to detect the changes occurred in LULC in each watershed, and for that the composite CN can be appropriately estimated. The statistical criterions show that the proposed models improved the runoff prediction accuracy of the SCS-CN method for the study region. It can be stated that this research work provides better models to the users for runoff prediction.

BRIEF DESCRIPTION ON THE STATE OF THE ART OF THE RESEARCH TOPIC

Estimation of runoff from a watershed is an important aspect and its accurate estimation plays vital role in flood prediction and warning navigation, water quality management, hydropower production and many other water resources applications. The rainfall-runoff relationship at the watershed scale is one of the important problems faced by hydrologists, agriculturists and engineers since long. Worldwide numerous attempts have been made to determine watershed runoff but many of them are costly, time consuming and difficult to apply because of lack of inadequate data. Simple methods for predicting runoff from watersheds are mainly imperative and mostly feasible in hydrologic engineering, hydrological modelling and in many hydrologic applications, such as flood design and water balance calculation models (Abon et al., 2011; Steenhuis et al., 1995; Van Dijk, 2010).

Mainly three methods are used to compute runoff (i) SCS-CN method (ii) Horton’s equation, and (iii) Continuous soil moisture balance. Out of these methods, the SCS-CN method is widely used to estimate runoff due to its flexibility, simplicity, convenience, and world-wide acceptability. It accounts for major runoff-generating watershed characteristics, viz. soil type, land use/treatment, surface condition and antecedent moisture conditions. Further, it requires readily available inputs and gives versatility and consistent runoff estimation. On the other hand, it does not address the impact of rainfall intensity, spatial and temporal distribution of rainfall, effects of adjacent moisture condition (Hawkins, 1993; Michel et al., 2005). In last four decades, extensive research work has been conducted to
overcome existing demerits of the SCS-CN model. In spite of many modifications done in SCS-CN model, a need of its further improvement has always been expected to satisfy unresolved challenges.

Recent modifications in determination of CN are reported by slope adjustment procedure (Sharpley and Williams, 1990; Huang et al., 2006), asymptotic determination of CNs from measured rainfall-runoff data (Hawkins et al. 1993; Bonta, 1997; Hjelmfeld et al., 2001; Hawkings et al., 2009; Kowalik et al., 2015), two-CN system approach (Soulis and Valiantzas, 2012), determination of CN by incorporating evapotranspiration (ET) for continuous hydrological simulation (Kannan et al., 2008; Jajarmizadeh et al., 2012), composite CN-generation using RS variables sensing variables like vegetation, impervious surface, and soil (Fan et al., 2013). For complex watersheds with high temporal and spatial variability in soil and land use, the SCS-CN model integrated into the RS/GIS system (Zhan and Huang, 2004; Geetha et al., 2007, Viji et al., 2015). SCS-CN model rely on its single sensitive parameter CN, which plays significant role in runoff estimation. In conventional CN determination procedure, the impact of land use change, long memory characteristics and variance heterogeneity of watershed due to accumulation of soil moisture does not address. It also does not take into account the effect of slope, stream length and other morphometric parameters which are highly influenced on runoff generation. Further, it does not incorporate long-term losses such as evaporation and evapotranspiration. Therefore, it is necessary to modify the CN to improve the performance of the SCS-CN model.

Gaps and Shortcomings of Previous Approaches

The principal shortcomings of the previous models include the following points:

1. The Asymptotic Fit Method (AFM) is based on ordered data and frequency matching approach, thus the effect of the cumulative data has been ignored in AFM method (Asymptotic CN approach).

2. Limited attempts were made in previous research work to account for the morphometric parameters of watershed considered in CN determination. It has been noted that morphometric parameters have strong influence on runoff generation.

3. A need was felt to develop CN accounting procedure based on continuous losses like evapotranspiration (ET) for long-term hydrological simulation.
DEFINITION OF THE PROBLEM

Watershed development projects for agriculture and allied sectors production necessitate high investment costs. Feasibility of these projects is often determined based on results of hydrologic modelling, analysis and assessment. Poor hydrologic analysis for estimating runoff may result into over designed or under designed hydrologic infrastructure. This may result into loss of billions of dollars annually in water harvesting and sometime leads to failures of hydraulic structures such as dams or weirs. Hydrologic models are used for accurate hydrological assessment (Mazi et al., 2004); however, most hydrologic models have been primary developed for humid agro-climatic regions (Wheater, 2005). Greater care to be taken when hydrologic models developed for humid agro-climatic regions are applied and adopted to semi-arid regions of India.

For effective planning, development and management of water resources in a watershed, the study of rainfall and runoff relationship is one of the important aspects. Literatures reviews indicate that SCS-CN method is widely used and accepted method for runoff estimation at watershed scale. In SCS-CN method effects of several important hydrological processes integrated in to single parameter CN (Garen and Daniel, 2005). The primary weakness of SCS-CN method is that it ignores the impact of rainfall intensity and its temporal distribution, impact of morphometric parameters of the watershed, effect of accumulation of soil moisture, and other dynamic processes like evapotranspiration. CN has not been thoroughly determined accurately (Ponce and Hawkins 1996, McCutcheon et al. 2006) and empirical evidence suggests that with the current conventional SCS-CN method, hydrologic infrastructure is being over designed by billions of dollars annually (Schneider and McCuen 2005).

The semi-arid Middle South Saurashtra region of Gujarat (India) has faced several water resources problems in the past. The some of the important problems can be summaries as;

1. Erratic rainfall pattern and inadequate rainfall amount resulting into periodic drought years.
2. Soils are of volcanic origin, generally derived from basaltic rock known as “Deccan trap”. These soils have limited groundwater recharge (8 to 12 % of precipitation) thus high dependency on surface water and runoff. Therefore, ground water resources are very limited or nil.
3. Soils have limited infiltration resulting into threats of flash floods, limited capacity of aquifer recharge and natural aquifer water retention.
4. Large parts of the region have already become water stressed.
5. Access to water for drinking, sanitation and hygiene is an even more serious problem.
6. Wide temporal and spatial variation in availability of water in the region as well in upper and lower parts of watershed.
7. Inadequate sanitation and sewage treatment facilities in the watershed resulting into polluting the scarce surface water sources.
8. If current population and water consumption trends be continuing in future, it further increases water scarcity in the region.

Poor hydrologic analysis due to inappropriate modelling of the distinctive features of the watershed and insufficient data is the main constraint for efficient watershed development in such region. Therefore, there is a need of research which satisfactorily addressed the above problems. To modify the existing SCS-CN method towards better runoff prediction is reliable and feasible solution to cope these problems.

Three models are developed to improve runoff predictability of the SCS-CN method in the present research study are:

1. Modified asymptotic CN approach (CNasy).
2. Weighted CN by incorporating morphometric parameters (CNmor).
3. Modified CN by incorporating reference evapotranspiration (CNtemp).

OBJECTIVE AND SCOPE OF WORK

The specific issues aforementioned pragmatically led to the research objectives of the present study. It is possible to reduce structural inconsistencies of the SCS-CN method by incorporating impact of cumulative data, morphometric parameters and evapotranspiration. The main aim of this study is to develop models by modifying CN for better runoff prediction in Middle South Saurashtra region. The modification involved three different methods to determine CNs for the study region.

The following research objectives are explored in this study:

1) To develop HSG map for the study region based on soil order, infiltration rate, soil depth, and soil characteristics of the watershed.
2) To detect the extent of LULC change occurred in the study region and examines its impact on CN.
3) To develop Model:
   - Based on cumulative rainfall-runoff ordered data for determination of the modified asymptotic CN.
Incorporating morphometric parameters of the watershed in weighted CN.

Integrating ET loss in to CN determination for long-term hydrological simulation.

4) Test, evaluate and compare the performance of the proposed models with existing models for Ozat, Shetrunji and Uben watersheds of the study region.

5) To provide recommendations for continued academic research which addresses areas requiring refinement for further modeling efforts.

Scope of Research work

1. This research was aimed to modify existing SCS-CN method to make it more suitable and efficient for Middle South Saurashtra region. The need for better runoff prediction in such semi-arid region has persisted for decades now. The developed models are comparatively more physically based model that emphasizes the impact of antecedent moisture, watershed morphometric parameters and long term loss.

2. The scope of research is significant to identify the problems of modelling the runoff in semi-arid region and find out solutions to improve the performance of widely used SCS-CN method.

3. Developed models are run at daily time scale, hydrologic analysis at smaller time scale is out of scope of this study.

4. This research study depended upon the secondary rainfall-runoff data and hence limitations of secondary data are indirectly incorporated in modelling process.

5. HSG maps for different watersheds of the study region are developed by considering soil map, LULC map, and formative elements of soil taxonomy.

6. LULC may not be remained constant for a long period. Further, CN calculation is difficult for unclassified LULC. Therefore, effect of dynamic change in major categories of LULC on CN is studied.

ORIGINAL CONTRIBUTION BY THE THESIS

In the present work, three models are developed by modifying CN which provide better options to the user for runoff estimation. The research study will make following original contributions as listed below:

1. HSG maps are developed for the selected watersheds of the study region based on the NBSS & LUP soil classification, formative elements of soil taxonomy, soil depth, infiltration rate, and soil characteristics.
2. RS and GIS techniques effectively integrated in CN determination procedure to explore the impact of dynamic LULC change over a temporal scale.

3. (CN\textsubscript{asy}) model is proposed by modifying existing Asymptotic Fit Method. Cumulative $P_{n}-Q_{n}$ ordered data were replaced with ordinary $P-Q$ ordered data in modified model to incorporate long-term accumulative effects of soil moisture.

4. Watershed morphometric parameters based model (CN\textsubscript{mor}) is attempted which makes more accurate physical representation than conventional SCS-CN model.

5. An empirical sub model for the study region is developed to estimate reference ET. The maximum temperature was found to be the most dominant meteorological variable affecting reference ET through dependency analysis.

6. (CN\textsubscript{temp}) model is developed for long-term hydrologic simulation by incorporating reference evapotranspiration (ET) in CN determination.

7. The developed models were validated at macro-scale using secondary field data obtained from the secondary sources. The data were collected from Bhaskaracharya Institute for Space Application and Geo-informatics (BISAG), Gandhinagar, State Water Data Centre, Gandhinagar, Junagadh Agro meteorological Cell and Amreli Agricultural Research Station of Junagadh Agricultural University, Junagadh (Gujarat-India).

METHODOLOGY OF RESEARCH, RESULTS/ COMPARISONS

Methodology

Three gauged watersheds viz. Ozat watershed (351.06 sq. km), Shetrunji watershed (234.12 sq. km), and Uben watershed (496.54 sq. km) of the Middle South Saurashtra region of Gujarat state (India) were selected to evaluate the performance of developed models. The methodology is developed by considering the availability of input data. Daily rainfall and temperature are the required input parameters which are available at most of the meteorological stations of the study region. 50\% of the recorded dataset is utilised for calibration and the rest 50\% is used for validation of the models. The proposed models (CN\textsubscript{asy} and CN\textsubscript{mor}) run at daily time-step without any calibration parameter while CN\textsubscript{temp} model has single calibrated parameter. All these models are prepared and run in Microsoft excel spread sheets.

Topographic data from Survey of India (SOI) toposheets of scale 1:50,000 viz. 41K (0-3-6-10-11-14-15-16) were used to identify the study area. Remote sensing Imageries of the
Indian Remote Sensing satellite with Linear Imaging Self Scanning Sensors (IRS – LISS III) satellite data of scale 1:50000 were used to prepare LULC map of the study area. Satellite data were preprocessed in ERDAS imagine for geo-referencing, mosaicking and sub setting of the image on the basis of area of interest. The watersheds were classified into six major land cover/use classes viz. Agriculture, Built-up, Forest, Others, Wastelands and Water Bodies as per standard classification system using ArcGIS tool. Soil information of the study area obtained is used for making appropriate HSG maps. The physical and morphometric characteristics like LULC, Soil, area of drainage basin, length of streams, slope, etc. were measured in GIS environment. To assess the runoff variability due to alternate land-use scenarios, composite CN II was estimated by using associated classified land uses area for calibration and validation period. The composite CN II values of selected watersheds are shown in Table 1. The methodology adopted in assessing the runoff potential is presented in Figure 1.

Figure 1: The Methodology Adopted for Runoff Generation

The performances of developed models were evaluated using three popular statistical criterion refined Willmott’s index (d_r) (Willmott et al., 2012) (Dimensionless statistic) and mean absolute error (MAE) (error index statistic), mean bias error (MBE). Performances of
proposed models were compared with existing models viz. AFM, Huang, and Kannan. To judge best model \( F_{test} \) and Akaike's Information Criterion (AIC) (Akaike, 1973; Hurvich and Tsai, 1989) were used. Sample months from validation period were selected based on maximum precipitation. Months having maximum rainfall (June 2005 (Ozat), July 2006 (Uben) and August 2004 (Shetrunji)) from validation period were selected for comparison of the performance of different models at daily time scale. The value of initial abstraction ratio \( (\lambda) \) was adopted 0.20 for all the watersheds.

Table 1: Land use /Land cover classes, Areas in \( \text{Km}^2 \) and Composite CN.

<table>
<thead>
<tr>
<th>Land Use Land Cover</th>
<th>(Ozat) 1994-95</th>
<th>(Ozat) 2005-06</th>
<th>(Shetrunji) 1994-95</th>
<th>(Shetrunji) 2005-06</th>
<th>(Uben) 2001-02</th>
<th>(Uben) 2005-06</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>277.0739</td>
<td>291.6939</td>
<td>86.9192</td>
<td>144.9282</td>
<td>408.7282</td>
<td>415.5799</td>
</tr>
<tr>
<td>Built-up</td>
<td>0.0000</td>
<td>4.2587</td>
<td>0.0000</td>
<td>2.1850</td>
<td>0.0000</td>
<td>5.7088</td>
</tr>
<tr>
<td>Forest</td>
<td>0.0000</td>
<td>0.0000</td>
<td>99.2376</td>
<td>45.2687</td>
<td>41.5711</td>
<td>39.0348</td>
</tr>
<tr>
<td>Others</td>
<td>0.0000</td>
<td>0.0540</td>
<td>0.0000</td>
<td>0.6298</td>
<td>0.0000</td>
<td>1.9325</td>
</tr>
<tr>
<td>Wastelands</td>
<td>73.9895</td>
<td>48.0306</td>
<td>47.9644</td>
<td>37.2948</td>
<td>46.2455</td>
<td>27.9515</td>
</tr>
<tr>
<td>Water Bodies</td>
<td>0.0000</td>
<td>7.0261</td>
<td>0.0000</td>
<td>3.8148</td>
<td>0.0000</td>
<td>6.3374</td>
</tr>
<tr>
<td>Total Area in ( \text{Km}^2 )</td>
<td>351.0633</td>
<td>351.0633</td>
<td>234.1213</td>
<td>234.1213</td>
<td>496.5448</td>
<td>496.5448</td>
</tr>
<tr>
<td>Composite CNII</td>
<td>81.64</td>
<td>81.58</td>
<td>65.43</td>
<td>72.39</td>
<td>79.17</td>
<td>79.26</td>
</tr>
</tbody>
</table>

Results and Comparisons

\( \text{CN}_{asy} \) Model

Ordinary \( P-Q \) ordered data use to determine asymptotic CN in standard AFM. These data sets not have much explanatory power to describe complex long term soil moisture condition of the watershed. Due to spatial and temporal variability of rainfall, and the variability of antecedent rainfall and the associated soil moisture amount, the \( CN \) has sufficient room for variability. However, there is no explicit guideline for soil moisture fluctuation with the antecedent rainfall of certain duration and the possible long-term cumulative effect of certain parameters. Furthermore, there is no known statistical method to model these effects. It is obvious that cumulative \( P_n-Q_n \) ordered data have more explanatory power than ordinary \( P-Q \) ordered data to describe accumulative soil moisture condition. Therefore, in the present study, a new model (\( \text{CN}_{asy} \)) based on the concept of AFM with cumulative \( P_n-Q_n \) ordered data is proposed to determine modified asymptotic \( CN \). Comparison of results obtained from \( \text{CN}_{asy} \) model, AFM and SCS-CN model are shown in Table 2.

It is evident from Table 2 that the \( \text{CN}_{asy} \) model produced comparatively better results for all watersheds, (Ozat \( (d_r=0.77, \text{MAE}=2.38, \text{MBE}=-1.94) \), Uben \( (d_r=0.67, \text{MAE}=1.13, \text{MBE}=-0.66) \), and Shetrunji \( (d_r=0.72, \text{MAE}=1.66, \text{MBE}=-1.51) \)) while AFM produced marginally good results (Ozat \( (d_r=0.60, \text{MAE}=4.25, \text{MBE}=3.31) \), Uben \( (d_r=-0.46, \text{MAE}=6.33, \text{MBE}=5.07) \), and Shetrunji \( (d_r=0.39, \text{MAE}=3.62, \text{MBE}=1.83) \)) for sample data from
validation period. However, no significant improvement has been found after attaining n days cumulative data (Ozat (n=5 Days), Uben (n=12 Days), and Shetrunji (n=4 Days)). This implies that the n days period more significant when taking AMC into account. The results indicate that based on the hydro-meteorological conditions, land use and soil characteristics, every watershed has different storage capacity; therefore cumulative data adequately incorporate the effect of storage in the proposed model.

Table 2: Comparison of the Performance of CN\textsubscript{asy} Model with different Models in Validation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Ozat (June)</th>
<th>Uben (July)</th>
<th>Shetrunji (August)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>CN\textsubscript{asy}</td>
<td>AFM</td>
<td>SCS</td>
</tr>
<tr>
<td>Cum Day</td>
<td>5</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>F</td>
<td>13.2624</td>
<td>87.0523</td>
<td>8.5303</td>
</tr>
<tr>
<td>F\textsubscript{cr}</td>
<td>12.6775</td>
<td>78.1324</td>
<td>8.1907</td>
</tr>
<tr>
<td>At P Value</td>
<td>5.78E-10</td>
<td>2.16E-21</td>
<td>6.24E-08</td>
</tr>
<tr>
<td>Significant</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>d\textsubscript{r}</td>
<td>0.77</td>
<td>0.67</td>
<td>0.72</td>
</tr>
<tr>
<td>MAE</td>
<td>2.38</td>
<td>-1.13</td>
<td>1.66</td>
</tr>
<tr>
<td>MBE</td>
<td>-1.94</td>
<td>-0.66</td>
<td>-1.51</td>
</tr>
<tr>
<td>AIC\textsubscript{c}</td>
<td>158.8258</td>
<td>200.3115</td>
<td>153.2340</td>
</tr>
<tr>
<td>LER</td>
<td>8.9843</td>
<td>30.0666</td>
<td>14.4300</td>
</tr>
<tr>
<td>ICS- AFM</td>
<td>Decisive</td>
<td>Decisive</td>
<td>Decisive</td>
</tr>
<tr>
<td>Overall d\textsubscript{r}</td>
<td>0.76</td>
<td>0.73</td>
<td>0.74</td>
</tr>
<tr>
<td>Overall MAE</td>
<td>0.80</td>
<td>0.42</td>
<td>0.39</td>
</tr>
<tr>
<td>AIC\textsubscript{c}</td>
<td>122.6521</td>
<td>75.4340</td>
<td>115.9708</td>
</tr>
<tr>
<td>LER</td>
<td>16.8393</td>
<td>30.0666</td>
<td>14.4300</td>
</tr>
<tr>
<td>ICS-CN\textsubscript{asy}</td>
<td>Decisive</td>
<td>Decisive</td>
<td>Decisive</td>
</tr>
</tbody>
</table>

F-Test, p-value (<0.05) and AIC criteria indicate that the CN\textsubscript{asy} model outstandingly performed better and fits the data significantly better than the existing AFM and SCS-CN model.

**CN\textsubscript{mor} Model**

Drainage maps of all three watersheds were prepared based on 1:50,000 scale topographical sheets and satellite images in GIS environment. The watershed were analyzed as per the laws of (Horton, 1945) and done by following (Strahler, 1964) stream ordering system on respective topographic drainage map. The major sub-watersheds were identified and delineated based on the 3rd order stream. Four major morphometric parameters slope (S), total length of main stream (L), length to the centroid of area (L\textsubscript{ca}) and drainage density (DD) were calculated for each sub-watershed using standard formulae. All the four morphometric parameters have direct relationship with runoff depth. In this study, a model (CN\textsubscript{mor}) is attempted by introducing these morphometric parameters of the watershed in CN determination for enhancement of conventional SCS-CN model. A weighted CN is determined for entire watershed by using morphometric parameters and individual CN for
each sub-watershed. The values of morphometric parameters of the watersheds were calculated with the help of ARC-GIS tools in GIS environment and are presented in Table 3.

**Table 3:** Physical Characteristics and Morphometric Parameters of Watersheds

<table>
<thead>
<tr>
<th></th>
<th>Ozat Watershed</th>
<th>Uben Watershed</th>
<th>Shetrunji Watershed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Area of catchment (A)</td>
<td>351.06 Sq. Km.</td>
<td>496.54 Sq. Km.</td>
<td>234.12 Sq. Km.</td>
</tr>
<tr>
<td>Total Length of Main Stream (L)</td>
<td>36.63 Km</td>
<td>44.14 Km</td>
<td>26.50 Km</td>
</tr>
<tr>
<td>Length from centroid (Lc)</td>
<td>15.96 Km</td>
<td>22.35 Km</td>
<td>13.55 Km</td>
</tr>
<tr>
<td>Slope %</td>
<td>0.58</td>
<td>0.27</td>
<td>0.64</td>
</tr>
<tr>
<td>Drainage Density (DD)</td>
<td>0.91 Km/Km²</td>
<td>0.83 Km/Km²</td>
<td>1.07 Km/Km²</td>
</tr>
</tbody>
</table>

The watersheds included in the current study have slopes varying from 0.27 % to 0.64 %, drainage density varying from 0.83 Km/Km² to 1.07 Km/Km² (Table 3). (Huang et al., 2006) studied the effect of slope on runoff and developed a slope-adjusted equation for CN determination. The proposed model (CN\textsubscript{mor}) developed by integrating three more morphometric parameters beside slope (S) in determination of modified CN. The results of the CN\textsubscript{mor} model, Huang model and SCS-CN model are presented in Table 4.

**Table 4:** Comparison of the Performance of CN\textsubscript{mor} Model with different Models in Validation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>F-Test</th>
<th>Ozat (June)</th>
<th>Uben (July)</th>
<th>Shetrunji (August)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>CN\textsubscript{mor}</td>
<td>HUANG</td>
<td>SCS</td>
<td>CN\textsubscript{mor}</td>
</tr>
<tr>
<td>F</td>
<td>13.9627</td>
<td>2.3623</td>
<td>102.6822</td>
<td>3.1398</td>
</tr>
<tr>
<td>F\textsubscript{cr}</td>
<td>12.6775</td>
<td>12.6775</td>
<td>91.9043</td>
<td>6.6796</td>
</tr>
<tr>
<td>At P Value</td>
<td>3.08E-10</td>
<td>0.0132</td>
<td>2.07E-22</td>
<td>0.0015</td>
</tr>
<tr>
<td>Significant</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Dr</td>
<td>0.76</td>
<td>0.53</td>
<td>0.02</td>
<td>0.73</td>
</tr>
<tr>
<td>MAE</td>
<td>2.53</td>
<td>4.90</td>
<td>10.32</td>
<td>0.93</td>
</tr>
<tr>
<td>MBE</td>
<td>-1.50</td>
<td>4.86</td>
<td>10.32</td>
<td>-0.86</td>
</tr>
<tr>
<td>AIC\textsubscript{c}</td>
<td>121.1084</td>
<td>17.1745</td>
<td>31.315</td>
<td>31.1782</td>
</tr>
<tr>
<td>LER</td>
<td>174.4117</td>
<td>5.5999</td>
<td>178.4266</td>
<td>7.7020</td>
</tr>
<tr>
<td>SCS-CN\textsubscript{mor}</td>
<td>121.1084</td>
<td>17.1745</td>
<td>31.315</td>
<td>31.1782</td>
</tr>
<tr>
<td>SCS-HUANG</td>
<td>174.4117</td>
<td>5.5999</td>
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<td>7.7020</td>
</tr>
<tr>
<td>Overall Dr</td>
<td>0.76</td>
<td>0.44</td>
<td>0.57</td>
<td>0.67</td>
</tr>
<tr>
<td>Overall MAE</td>
<td>0.80</td>
<td>0.97</td>
<td>1.45</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Based on the dr, MAE, and MBE values, it is revealed from Table 4, that the CN\textsubscript{mor} model and Huang model performed better than the SCS-CN model for all three watersheds. The CN\textsubscript{mor} model (Ozat (dr=0.76, MAE=2.53, MBE=-1.50), Uben (dr=0.73, MAE=0.93, MBE=-0.86), and Shetrunji (dr=0.64, MAE=2.11, MBE=-1.03)) performed better than Huang model (Ozat (dr=0.53, MAE=4.90, MBE=4.86), Uben (dr=-0.22, MAE=4.38, MBE=-2.73), and Shetrunji (dr=0.38, MAE=3.70, MBE=1.47)).
Further, it is observed from F-Test, p-value (<0.05) and AIC criteria that CN\textsubscript{mor} model fits the data significantly better than the Huang model and SCS-CN models for the study area. The results support the adopted methodology.

**CN\textsubscript{temp} Model**

Long-term loss like evaporation and evapotranspiration (ET) are essential to incorporate in continuous hydrological modeling for seasonal yield evaluation. ET is second largest term after precipitation in the terrestrial water budget and also significantly influenced on the water balance of a watershed. (Williams and LaSeur, 1976; Hawkins, 1978; Kannan et al., 2008) were incorporated ET in to the SCS-CN method for continuous hydrologic simulation. Unfortunately, most of the ET estimation methods are parameter rich methods and not feasible for application in data scarce regions. For the study region, maximum temperature is found to be the most dominant meteorological variable influence the reference evapotranspiration (ET\textsubscript{o}) based on the dependence analysis. (Gundalia and Dholakia, 2015) modeled the daily ET\textsubscript{o} based on max temperature for the study region. Among the all meteorological variables, temperature is mostly available at most of the weather stations because practically it is easy to measure and maintain. Hence, in the present study a new model CN\textsubscript{temp} is formulated to enhance the SCS-CN method. In this proposed methodology, the I\textsubscript{e}-S relationship is modified by introducing precipitation (P), and the CN is modified by incorporating ET\textsubscript{o}.

| Table 5: Comparison of the Performance of CN\textsubscript{temp} Model with different Models in Validation |
|---|---|---|---|---|---|---|---|---|
| F-Test | Ozat (June) | Uben (July) | Shetrunji (August) |
| Parameters | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 |
| Model | CN\textsubscript{temp} | KANNAN | SCS | CN\textsubscript{temp} | KANNAN | SCS | CN\textsubscript{temp} | KANNAN | SCS |
| F | 393.2514 | 11.4204 | 2796.2840 | 154.4740 | 155.5059 | 98.3888 |
| F\textsubscript{cr} | 386.1092 | 456.8088 | 2789.5095 | 3525.8709 | 142.7373 | 161.9375 |
| At P Value | 7.82E-29 | 9.996E-09 | 9.67E-42 | 1.88E-23 | 3.06E-24 | 7.58E-21 |
| Significant | Yes | No | Yes | No | Yes | No | Yes | No |
|  \(d_r\) | 0.78 | 0.41 | 0.02 | 0.70 | 0.31 | -0.59 | 0.57 | 0.70 | 0.07 |
| MAE | 2.34 | 6.25 | 10.32 | 1.03 | 2.35 | 8.22 | 2.54 | 1.80 | 5.50 |
| MBE | -1.98 | 5.45 | 10.32 | -0.73 | 0.57 | 6.97 | -0.03 | -1.37 | 4.24 |
| AIC\textsubscript{c} | LER | AIC\textsubscript{c} | LER | AIC\textsubscript{c} | LER |
| SCS-CN\textsubscript{temp} | 120.1513 | 17.3824 | Decision | 73.1584 | 30.5607 | Decision | 126.4325 | 12.1582 | Decision |
| SCS-KANNAN | 186.0663 | 3.0691 | Decision | 140.4920 | 15.9394 | Decision | 121.6149 | 13.2044 | Decision |
| Overall  \(d_r\) | 0.75 | 0.75 | 0.57 | 0.73 | 0.61 | -0.30 | 0.73 | 0.49 | 0.65 |
| Overall MAE | 0.83 | 0.85 | 1.45 | 0.41 | 0.61 | 2.22 | 0.42 | 0.39 | 0.54 |
The \( \text{CN}_{\text{temp}} \) model, Kannan model and conventional SCS-CN model were applied to selected watersheds and results are presented in Table 5. The results show that proposed model performed consistently well for Ozat (\( d_r=0.78, \text{MAE}=2.34, \text{MBE}=-1.98 \)) and Uben (\( d_r=0.70, \text{MAE}=1.03, \text{MBE}=-0.73 \)) watersheds. For Shetrunji watershed, Kannan (\( d_r=0.70, \text{MAE}=1.80, \text{MBE}=-1.37 \)) model performed better than proposed model (\( d_r=0.57, \text{MAE}=2.54, \text{MBE}=-0.03 \)). However, in F-test, at p-value (<1E-24) \( \text{CN}_{\text{temp}} \) model is found statically better than Kannan model. This is due to Kannan model has one more calibration parameter than \( \text{CN}_{\text{temp}} \) model and hence it has less degree of freedom. Overall performance of the \( \text{CN}_{\text{temp}} \) model (\( d_r=0.73, \text{MAE}=0.42 \)) in validation period is better than that of Kannan model (\( d_r=0.49, \text{MAE}=0.39 \)) and SCS-CN model (\( d_r=0.65, \text{MAE}=0.54 \)) for Shetrunji watershed. Shetrunji watershed has 19.34% dense forest, Uben watershed has 7.86% dense forest and Ozat watershed has no dense forest area. Forest soils have a large infiltration capacity due to the presence of vegetation and a thick organic horizon supported by decomposing vegetation on the surface. These features reduce the effect of ET and reduce the surface runoff. As a result, Shetrunji watershed has low runoff coefficient (0.10) than Ozat (0.33) and Uben (0.19) watersheds. Further, Shetrunji watershed (559 mm) is falling on leeward side and has low annual average rainfall than Uben (861 mm) and Ozat (786 mm) watersheds. This low annual precipitation could also be viewed as less frequent rainfall events, which prevents a better estimation of the depletion coefficient and, therefore, gives poor predictions of runoff.

F-Test, p-value (<0.05) and AIC criteria indicate that the proposed \( \text{CN}_{\text{temp}} \) model fits the data significantly better than the Kannan model and conventional SCS-CN model for all three watersheds.

From Table 2, Table 4 and Table 5, it is seen that \( \text{CN}_{\text{asy}} \) model performed consistently better when overall comparison is made.

**ACHIEVEMENTS WITH RESPECT TO OBJECTIVES**

In the present work, to accomplish the objectives, three developed models (\( \text{CN}_{\text{asy}}, \text{CN}_{\text{mor}}, \) and \( \text{CN}_{\text{temp}} \)) have been applied to enhance the performance of the conventional SCS-CN method.

**Objective 1:**

This objective is achieved by identifying soil order, soil depth, infiltration rate, and soil characteristics of the study region from soil map and interpreting formative elements of soil taxonomy. The research reveals that HSG B, C, and D explicitly assigned to the soil orders Entisols, Inceptisols and Vertisols respectively by considering its characteristics. HSG map
for each watershed is developed based on soil order, soil depth, infiltration rate, and soil characteristics of the watershed.

**Objective 2:**
This objective is accomplished by comparing LULC changes of the years 1994-95 and 2005-06. Resultant LULC and overlay maps generated in ArcGIS indicated a significant shift from Forest and Wastelands to Agriculture. These LULC transformations slightly increase CN value of watersheds.

**Objective 3:**
To achieve this objective, the ‘frequency matching’ based $\text{CN}_{\text{asy}}$ model has been developed by applying different degree of cumulative days ordered data to three selected watersheds of the study area. The results show that, the proposed $\text{CN}_{\text{asy}}$ model is judged to be more consistent at 4, 5 and 12 days cumulative daily data set for Shetrunji, Ozat and Uben watersheds respectively.

Four major morphometric parameters $S$, $L$, $L_{ca}$ and $DD$ were computed for each sub-watershed. Weighted CN was determined from the CN and morphometric parameters ($S$, $L$, $L_{ca}$ and $DD$) of each sub-watershed. The proposed $\text{CN}_{\text{mor}}$ model is appeared to be the more appropriate than Huang model (accounted only slope) and conventional SCS-CN method for runoff prediction when tested on the selected watersheds.

Based on the dependence analysis, the maximum temperature was found to be the most significant factors influencing $ET_o$ in the Middle South Saurashtra region. A sub model based on the most dominant meteorological variable is developed to estimate $ET_o$ for the study region. $\text{CN}_{\text{temp}}$ model is formulated by incorporating the $ET_o$ and tested on selected watersheds. The results indicate that the attempted $\text{CN}_{\text{temp}}$ model is found statically better than the existing Kannan model and conventional SCS-CN method.

**Objective 4:**
The performances of the proposed models are tested, evaluated and compared with the existing models to the selected watersheds. The $\text{CN}_{\text{asy}}$ model is found to be the best-performing model among all the developed models for the Middle South Saurashtra region in overall performance comparison.

**Objective 5:**
The present research work opens the scope for wide varieties of problems created in the field of modeling runoff using SCS-CN method. Some of the future scopes and recommendations are also suggested for further study in the region.
CONCLUSIONS

Improper modelling and paucity of sufficient data are main reasons for the poor hydrologic analysis in such semi-arid and data scarce region. In such situation, the reliable solution is modifying existing SCS-CN method which is not too simple to ignore the major processes and yet not requiring very much detail of data that are not available in real life application. In the present work, three hydrologic models have been proposed to modify existing SCS-CN method for better runoff estimation in the Middle South Saurashtra region. The strength of the developed models is that the effect of cumulative rainfall-runoff ordered data, morphometric parameters of the watershed and evapotranspiration loss, which are greatly influencing the runoff generation process are integrated in CN determination procedure. The following conclusions are drawn.

1. HSG Maps for the selected watersheds are developed for the study region by interpreting soil map with the help of Soil Taxonomy.

2. Soil orders are differentiated by the presence or absence of diagnostic horizons that reflect soil forming processes. HSG B, C and D are explicitly assigned to soil order Entisols, Inceptisols and Vertisols respectively.

3. Composite CN II value is determined for each sub watershed by integrating LULC and HSG Map.

4. Study found that watersheds having more vertisols generate more Runoff while watersheds having more Entisols generate less runoff.

5. Cumulative $P_n - Q_n$ ordered data eliminate long memory characteristics due to accumulation of soil moisture and variance heterogeneity of the watershed. Application of cumulative $P_n - Q_n$ ordered data in CN determination significantly improve the performance of the SCS-CN method.

6. In CN$_{asy}$ model, comparatively lower asymptotic CN value is attained than AFM model which is due to effect of cumulative $P_n - Q_n$ ordered data. Hence, this modified asymptotic CN value is reduced over estimation of the SCS-CN method.

7. CN$_{asy}$ model is consistently performed better for all the three watersheds.

8. AFM model poorly performed for Uben watershed. Only 5 years data were available and are used to determine asymptotic CN. AFM model is data driven model, therefore, short length data set not adequately described P-CN relationship.

9. The prediction accuracy of the SCS-CN method improved greatly when the CN is modified by taking in to account the effect of morphometric parameters of the watershed.
10. The study depicts that watershed having slope less than 5%, slope-adjusted CN alone (Huang model) not adequately improved the performance of the SCS-CN method.
11. HUANG model performed better for watersheds having larger slope (performed better in Shetrunji (0.64%) watershed as compare to Ozat (0.58%) and Uben (0.26%) watersheds).
12. Maximum temperature was found to be the most dominant meteorological parameter influenced on ET in the study area.
13. Proposed CN_temp model is performed better than the equivalent existing Kannan model for the study area.
14. It is observed that Kannan model performed better in Shetrunji watershed which has larger forest area, low annual average rainfall and low runoff coefficient. Kannan model is specifically developed for shallow soils and soils with low storage. Shetrunji watershed has more Shallow soils and Entisols. However, due to one more parameter it is not statically significant better than the CN_temp model.
15. CN_temp models comparatively performed poor in Shetrunji watershed as it has larger forest area. In forest area, temperature not adequately influenced the rate of ET loss and CN value.
16. F-test, p-value and AICc criteria clearly indicate that the developed models fit the data statically and significantly better than the existing models.
17. Among the three proposed models, CN_asy model gives the best-performing results for the Middle South Saurashtra region. Therefore, CN_asy model is recommended when rainfall-runoff data are available. This result is in good agreement to the report of NRCS (Woodward et al., 2010). NRCS recommends AFM procedure as the preferred technique for CN determination.
18. Owing to a significant degree of agreement between the observed and calculated runoff, the proposed models are recommended for field applications in this study region.

LIMITATIONS
1. Similar to the existing method, the proposed model also does not consider the spatial effect on runoff, the effect of rainfall intensity or duration on runoff.
2. Beside rain fall and runoff data, temperature data is needed in CN_temp model.
3. The method is not effective in simulating runoff due to snowmelt or rain on frozen ground.
4. The model only computes direct runoff and does not consider sub-surface and ground water flow.
5. The proposed $CN_{asy}$ model does not suitable for watershed showing complacent response. P-CN relationship cannot be adequately defined for such watershed.

6. The problem of simulating the peaks is still remains in these models.

**RECOMMENDATIONS**

The following areas need further research and development:

1. In-situ soil moisture, wetness index, climate variability (other than ET) and groundwater variables (infiltration rate, water table, hydraulic conductivity, field capacity etc.) need to be included as input parameters in SCS-CN based methods.

2. Impact of LULC change, hydrological, meteorological and morphometric parameters on CN can be more prominently identified by measuring rainfall-runoff at hourly time scale for each sub-watershed.

3. The present study covers Ozat, Uben and Shetrunji watersheds of the Middle South Saurashtra region lying in Gujarat, India, which can be extended to the entire Saurashtra region or other region having similar hydro-meteorological conditions.

4. The proposed models can be applied to different watersheds with different topography, land uses, soil type and drainage characteristics. The models should also be applied to watersheds in different climatic regions with different rainfall patterns.

5. The developed models are tested and applied at daily time scale. Model testing on microscopic level explores more information as compare to macroscopic level testing. Therefore, the developed Models should be tested at hourly time scale based on availability of data.

6. It is recommended that planning and management should be carried out at watershed scale rather than geographical area scale.

7. The potential uses of these models are to extend flow data from rainfall and temperature data and filling missing flow data.

8. They can also be used for flood forecasting if coupled with a rainfall forecasting scheme.
Reference


**LIST OF PUBLICATIONS**


