Application of Mamdani Fuzzy Inference System for Runoff Prediction

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Abstract: ***Watershed is the area covering all the land that contributes runoff water to a junction. There are various methods to find runoff, but runoff calculated by Soil Conservation Service Curve Number (SCS-CN) is used in the present study. After calculating runoff by SCS-CN method an effort is made to develop Runoff model by Mamdani Fuzzy Inference System (MFIS). In the present study daily rainfall data from 1992 to 2013 of monsoon season i.e. June to September; of four rain gauge station is used. The objectives of present study are to find runoff by using SCS-CN method and to develop MFIS to predict runoff. The output runoff by MFIS is compared with runoff by SCS-CN method. To develop model whole length of data is divided into two parts i.e. training and for validation. In 70:30 data sets, 70% data are used for training and 30% data are used for validation and similarly for 60:40 and 80:20 data sets. Three models have been developed using above data sets i.e. model 1 which is having 9 Linguistic variables, Model 2 which is having 5 Linguistic variable and model 3 which is having 7 Linguistic variables. The best MFIS model is Model 1 based on performance indices. The RMSE of model 1 is 3.61mm and coefficient of determination (R^2) is 0.9868 in training phase and 4.38mm and 0.9899 in validation phase respectively.***

Keywords: Runoff, SCS-CN, MFIS, Linguistic Variable

1. Introduction

Rainfall is known as the main contributor to the generation of surface runoff. Therefore, there is a significant and unique relationship between rainfall and surface runoff (Baharudin, 2007). By basic principle of hydrologic cycle, when rain falls, the first drops of water are intercepted by the leaves and stems of the vegetation. This is usually referred to as interception storage. Once they reach the ground surface, the water will infiltrate through the soil until it reaches a stage where the rate of rainfall intensity exceeds the infiltration capacity of the soil. The infiltration capacity of soil may vary depending on the soil texture and structure. For instant, soil composed of a high percentage of sand allows water to infiltrate through it quite rapidly because it has large, well connected pore spaces. Soils dominated by clay have low infiltration rates due to their smaller sized pore spaces. However, there is actually less total pore space in a unit volume of coarse, sandy soil than that of soil composed mostly of clay. As a result, sandy soils fill rapidly and commonly generate runoff sooner than clay soils (Ritter, 2006). Apart from rainfall characteristics such as intensity, duration and distribution, there are other specific factors which have a direct bearing on the occurrence and volume of runoff. The most common factor is the soil type. Due to the variation of runoff production, different studies have been conducted according to particular soil conditions. Another factor that can affect the runoff production is vegetation. An area which is densely covered with vegetation produces less runoff than bare ground while the amount of rain lost to interception storage on the foliage depends on the kind of vegetation and its growth stage. Vegetation has a significant effect on the infiltration capacity of the soil. Slope and catchment size also influence the generation of surface runoff. The essence of this paper is to establish a reliable relationship between rainfall and runoff and obtain runoff for the Kadana catchment area

Soulis, K and Valiantzas, J. (2011) considered the hypothesis that the observed correlation between the calculated CN value and the rainfall depth in a watershed reflects the effect of soils and land cover spatial variability on its hydrologic response is being tested. Based on this hypothesis, the simplified concept of a two-CN heterogeneous system is introduced to model the observed CN rainfall variation by reducing the CN spatial variability into two classes. The behavior of the CN-rainfall function produced by the simplified two-CN system is approached theoretically, it is analyzed systematically, and it is found to be similar to the variation observed in natural watersheds. Synthetic data tests, natural watersheds examples, and detailed study of two natural experimental watersheds with known spatial heterogeneity characteristics were used to evaluate the method. The results indicate that the determination of CN values from rainfall runoff data using the proposed two-CN system approach provides reasonable accuracy and it over performs the previous methods based on the determination of a single asymptotic CN value. Although the suggested method increases the number of unknown parameters to three (instead of one), a clear physical reasoning for them is presented.

Balvanshi, A and Tiwari, H.L (2014) stated that Rainfall-Runoff relationship is one of the most important phenomena in hydrologic design of hydrological structures and drainage systems. The estimation of runoff volume of a catchment is an important aspect in engineering planning, environmental impact assessment, and flood forecasting and water balance calculations. There are basically two types of methods for the estimation of runoff namely the direct method and the indirect method. The direct method is based on the direct measurements while the other one is based on the equations. One of the indirect methods for the computation of runoff is the National Resource Conservation Service curve number method. This paper gives a review of the origin of the curve number method and development of the curve number equations. The Natural Resource Conservation Service curve number technique is a well-accepted tool for estimation of direct runoff from storm rainfall. CN model is used where constraints like slope, land cover, type of soil, area of watershed etc. are considered for runoff estimation.

Ahmad, I et.al (2015) described study to compute the runoff depth using Soil Conservation Service-Curve Number (SCS-CN) method using Remote Sensing and Geographic Information System (GIS). The SCS-CN is a quantitative description of land use/land cover/soil complex characteristics of a watershed. This model is a widely used hydrological model for estimating runoff using runoff and curve number (CN). The CN is an index that represents the watershed runoff potential. In the present study SCS-CN method is used for estimating the runoff depth in the Sheonath river upper sub-basin of Chhattisgarh State of India. The present study reveals that the remote sensing and GIS based SCS-CN can be effectively used to estimate the runoff from the river basins of similar geo-hydrological characteristics.

2. Study Area and Data Collection

Mahi River is one of the major west flowing interstate River of India, draining into the Gulf of Khambhat. The basin is bounded on the North and the North - West by Aravalli hills, on the East by the ridge separating it from the Chambal Basin, on the South by the Vindhyas and on the West by the Gulf of Khambhat. The total drainage area of Mahi is 34,842 km^2. Mahi receives several tributaries on both the banks, out of which the main tributaries are Som, Anas and Panam. The Kadana dam is situated on the Mahi River in Panchmahal District of Gujarat. Kadana The catchment area up to this project is 25,520 km^2 and catchment area intercepted at Banswara in Rajasthan is 6149 km^2. The nearest meteorological station is in Diwada Colony, about 5 km away. The soil is typical sandy loam to clayey loam. For this study Rainfall data of past 21 years from 1992 to 2013 (June to September) is collected from Global weather of Kadana Catchment area. Land Use/Land Cover Data is collected from Bhuvan- ISRO's Geoportal.

3. Methodology

3.1 Soil Conservation Service Curve Number (SCS-CN) method

One of the popular methods for estimating the depth of surface runoff, water recharge, stream flow, infiltration, soil moisture content, and landfill leachate production from precipitation for a given rainfall event is the Soil Conservation Service Curve Number (SCS-CN) method. The SCS Runoff Curve Number method is developed by the United States Department of Agriculture (USDA) Soil Conservation Service (SCS). The runoff curve number method is a procedure for hydrologic abstraction developed by the USDA Soil Conservation Service. In this method, runoff depth (i.e. effective rainfall) is a function of total rainfall depth and an abstraction parameter referred to as runoff curve number or simply curve number.

The SCS-CN model calculates direct runoff depth (Q) using the following equation:

$$Q = \frac{(P-0.2*S)^2}{P+0.8*S} \qquad (1)$$

Where,
P= total precipitation (mm), I_a= initial abstraction (mm), and S= potential maximum retention (mm).

$$Q = 0, \text{ for } P \leq I_a$$

The initial abstraction is related to S by the equation:

$$I_a = \lambda * S$$

Where,
λ is an initial abstraction ratio. The value of λ varies in the range of 0.1 and 0.3.

The runoff Curve Number (CN) is used to compute S (mm) as,

$$S = \frac{25400}{CN} - 254 \qquad (2)$$

3.2 Hydrological Soil Group

There are four hydrologic soil groups ranging from A to D. HSG Group A: Soils with high infiltration rates, consisting mainly deep sands and gravels with high rate of water transmission (final infiltration rate greater than 0.3 in/hr).

HSG B: Soils moderately fine to coarse soils having a moderate rate of water transmission (final infiltration rate of 0.15 in/hr to 0.30 in/hr).

HSG C: Moderately fine textured soils that may have a layer that impedes downward movement of water, with slow infiltration and water transmission rates (final infiltration rate of 0.05 to 0.15 in/hr).

HSG D: clayey soil with permanent high water table or shallow soil over impervious material having very low infiltration and water transmission rates (final infiltration rate less than 0.05 in./hr).

3.3 Antecedent Moisture Condition (AMC)

AMC indicates the moisture content of soil at the beginning of the rainfall event. The AMC is an attempt to account for the variation in curve number in an area under consideration from time to time. Three levels of AMC were documented by SCS AMC I, AMC II & AMC III. The limits of these three AMC classes are based on rainfall magnitude of previous five days and season (dormant season and growing season). AMC for determination of curve number is given in Table 1.

Table 1: AMC classification

AMC Condition	*5 days Antecedent Rainfall*	
	Dormant season	*Growing season*
I	<13mm	<36 mm
II	13 to 28 mm	36 to 53 mm
III	>28 mm	>53 mm

3.4 Fuzzy Logic System

Since past few years have witnessed a rapid growth in the number and variety of application of fuzzy logic. The application rang from consumer products such as cameras, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision – support systems, and portfolio selection.

To understand the reasons for the growing use of fuzzy logic it is necessary, first, to clarify what is meant by fuzzy logic. Fuzzy logic has two different meaning. In a narrow sense, fuzzy logic is logical system, which is an extension of multivalued logic, but in a wider sense, which is in predominant use today, fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree. In this perspective, fuzzy logic in its narrow sense is a branch of FL. what is important to recognize is that, even in its narrow sense, the agenda of fuzzy logic is very different both in sprit and substance from the agendas of traditional multivalued logical systems.

3.5 Building System with The Fuzzy Logic Toolbox

In the present study, the GUI (Graphical User Interface) tools are used, which basically consists of five editors to build, edit and view the system, as shown in figure.

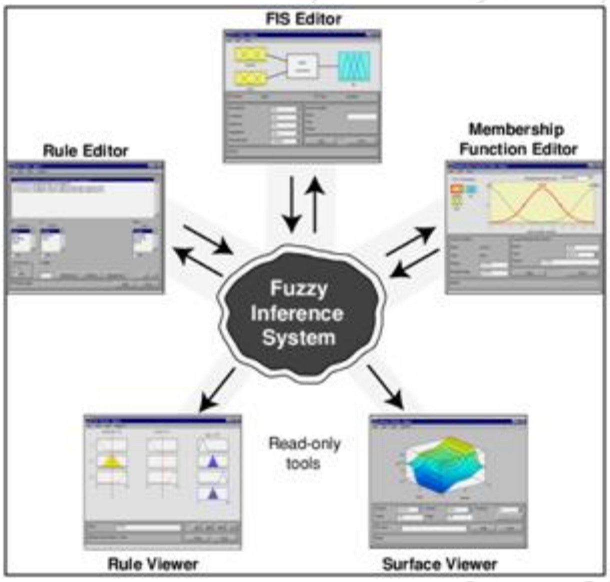

Figure 1: GUI editor in Mamdani Fuzzy method

1) Fuzzy Inference System (FIS) Editor -to handle the high-level issues for the system like number of input and output variables and their names.
2) Membership Function Editor- to define the shapes of all the membership functions associated with each variable.
3) Rule Editor- to edit the list of rules that defines the behavior of the system.
4) Rule Viewer- to view the fuzzy inference diagram. This viewer is used as a diagnostic to see, for example, which rules are active, or how individual membership function shapes influence the results.
5) Surface Viewer -to view the dependency of one of the outputs on any one or two of the inputs. It generates and plots an output surface map for the system.

3.6 Mamdani Fuzzy Inference System

Mamdani Fuzzy inference system involves five steps.

1. Fuzzification of the input variable

The first step in building a fuzzy inference system is to determine the degree to which the inputs belong to each of the appropriate fuzzy sets through the membership functions. The input is always a crisp numerical value limited to the universe of discourse of the input variable and the result of Fuzzification is a fuzzy degree of membership.

2. Apply fuzzy operator

Once the inputs are fuzzified, the degree to which each part of the premise has been satisfied for each rule is known. If the premise of a given rule has more than one part, then a fuzzy operator is applied to obtain one number that represents the result of the premises for that rule. The fuzzy logic operators such as the AND or OR operators obey the classical two valued logic. The AND operator can be conjunction (min) of the classical logic or it can be the product (prod) of the two parameters involved in it. Similarly, the OR method can be the disjunction operation (max) in the classical logic or it can be the probabilistic OR (probor) method.

3. Apply implication method

The fuzzy operator operates on the input fuzzy sets to provide a single value corresponding to the inputs in the premise. The next step is to apply this result on the output membership function to obtain a fuzzy set for the rule. This is done by the implication method. The input for the implication method is a single number resulting from the premise, and the result of implication is a fuzzy set.

4. Aggregation

Aggregation is the unification of the output of each rule by merely joining them. When an input value belongs to the intersection of the two membership functions, fuzzy rules corresponding to both the membership functions are invoked. Each of these rules, after implication, specifies one output fuzzy set. The input of the aggregation process is the list of truncated output function returned by the implication process of each rule. The output of the aggregation process is one fuzzy set for each output variable. The aggregation methods are given by: max (maximum), probor (probabilistic or), and sum (sum of each rules output).

5. Defuzzification

The result obtained from implication is in the form of a fuzzy set. For application, this is defuzzified. The most common defuzzification method is the centroid, largest of maximum, middle of maximum and smallest of maximum. In this study we used centroid method for defuzzification.

4. Result and Analysis

The runoff calculated using SCS-CN method depends on Soil type, land use/land cover, Infiltration rate, Hydrological Soil Group (HSG) etc.

In this present study, the soil type is deep black and sandy loam. The HSG of present study area is A. The variation of curve number under AMC II called CN_{II} for various land conditions commonly found in present study are shown in table 2 below.

Table 2: Classification of HSG

Land Use	*Hydrological Cover Condition*
Agricultural	Straight row
Forest	Scrub
Pasture	Good
Residential	-

To create and detect the curve number values for each classified area; the hydrological soil group and the land use and land cover results were used. The values of curve number for each area are presented in table 3.

Table 3: Values for Curve Number (CN)

Land use	*HSG*	*CN*	*Area (km²)*
Agriculture	A	76	321.02
Forest	A	33	31.59
Pasture	A	39	82.48
Residential	A	59	11.58

Based on the data given in Table 3, the composite curve number was found by using the following equation, (USDA, 1985):

$$CN = \frac{\sum A_i * CN_i}{\sum A_i} \quad (3)$$

Where, CN is the composite curve number, A_i is the area for each curve number.

The composite curve number for the study area is:
$CN_{II} = 66$

The conversion of CN_{II} to other two AMC conditions can be made through the following correlation equations.

For AMC I

$$\frac{CN_{II}}{2.281 - 0.01281\, CN_{II}} \quad (4)$$

For AMC III

$$\frac{CN_{II}}{0.427 + 0.00573\, CN_{II}} \quad (5)$$

From the above equation, we will get
$CN_I = 45$ and
$CN_{III} = 82$

These equations depend on the value of rainfall (P) and watershed storage (S) which calculated from adjusted curve number. Thus, before applying equation (1) the value of (S) should be determined for each antecedent moisture condition (AMC) as shown below.

There are three conditions: These results are summarized in the table 4.

Table 4: Values used in hydrological equation

AMC	*CN*	*S*	*P>0.2*S*
I	45	310.44	62.09
II	66	130.85	26.17
III	82	55.76	11.15

The data used for applying Fuzzy Rule to the develop MFIS model is Rainfall (mm) as input and Runoff (mm) as output.

Also various type of linguistic variable used to develop model as input and output i.e. very very very low, very very low, very low, low, medium, high, very high, very very high, very very very high.

Three Fuzzy Logic Models i.e., Model 1, Model 2 and Model 3 have been developed considering 9, 5 and 7 linguistic variables of 80:20%, data set of 60:40% and 80:20% datasets respectively. Based on the RMSE and co-efficient of determination (R^2), the best model has been analyzed.

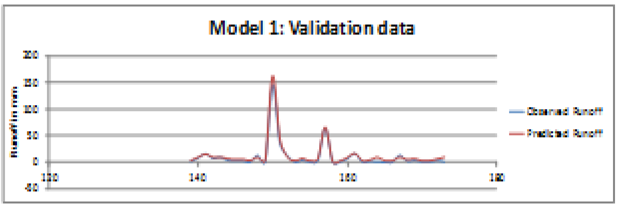

Figure 2: SCS-CN vs MFIS runoff training phase 80-20% data sets (9 linguistic variable)

Figure 3: SCS-CN vs MFIS runoff validation phase 80-20% data sets (9 linguistic variable)

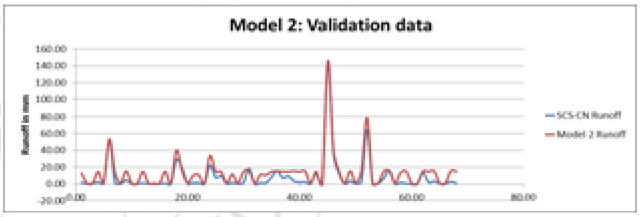

Figure 4: SCS-CN vs MFIS runoff training phase 60-40% data sets (5 linguistic variable)

Figure 5: SCS-CN vs MFIS runoff validation phase 60-40% data sets (5 linguistic variable

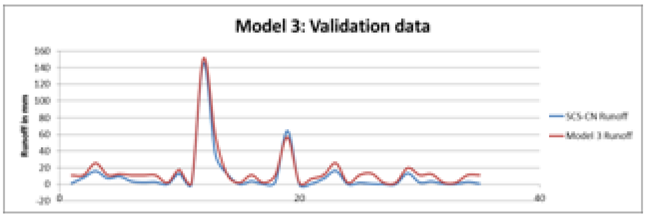

Figure 6: SCS-CN vs MFIS runoff training phase 80-20% data sets (7 linguistic variable)

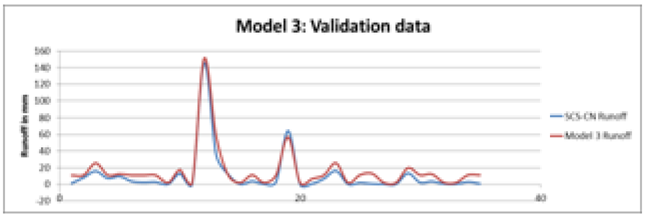

Figure 7: SCS-CN vs MFIS runoff training phase 80-20% data sets (7 linguistic variable)

The RMSE and R^2 of Developed model is shown in table 5.

Table 5: Values of RMSE and R^2

Model		*R^2*	*RMSE*
Model 1	By training	0.9868	3.61
	By validation	0.9899	4.38
Model 2	By training	0.9410	7.12
	By validation	0.9310	7.80
Model 3	By training	0.9589	6.65
	By validation	0.9648	7.45

From the table 5, it is clearly seen that RMSE and R2 of model 1 is less, so Model 1 is best Fuzzy rule base model for present study area.

4 Conclusions

- Since there were no runoff observations available from present study area, the results could not be compared with the measured values.
- Based on the results of soil classification, infiltration rates and land use, the study area was classified into hydrologic soil groups. The curve number for normal condition is 66, where for the dry and wet conditions are 45 and 82 respectively.
- Runoff predicted by model is developed using various rules, Linguistic variable and membership function. From the developed model is it clear that the RMSE value will be low and coefficient of determination (R^2) will be high, if the linguistic variable is more.
- In the present study model 1 made by using 9 Linguistic variables is best among the other model, which is chosen on the basis of RMSE and R^2 value. The model is developed using fuzzy logic with 70-30%, 80-20% and 60-40% data. The best model, i.e. model 1 have RMSE value of 3.6129 in training phase and 4.3815 in validation phase and value of R^2 is getting 0.9868 and 0.9899 in training and validation phase respectively.

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