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Rainfall Run Off Modeling Using Fuzzy Numbers

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***Abstract* - This paper proposes a new approach to predict the flow characteristic of the ungauged watershed. The selected study area has only one rain gauge station located near the Kundha bridge giving birth to considerable uncertainties in predicting the catchment flow. Application of fuzzy logic in prediction can minimize these uncertainties of the ungauged watershed. Fuzzy logic model helps to simulate the unknown relationship between the hydrological data and the catchment attributes. The research paper weighs soil type, land use, slope with fuzzy numbers. Finally, to obtain the runoff the comprehensive weight is multiplied with the rainfall data. The runoff thus obtained is used to create runoff map of the watershed. Natural break classification system is utilized to classify the runoff of the entire watershed. The model is validated with the water level records of the Kundha reservoir. This runoff map is valuable in landslide susceptibility analysis. This model not only serves for prediction but also prove to be an effective tool for further research.**
***Keywords:* Rainfall, runoff, modeling**

I.INTRODUCTION

Rainfall runoff is part of the widely discussed environmental issue by environmentalists and policy makers (Evans, 1996, Cirmo and McDonnell, 1997, Band, 1993, Moore *et al.*, 1993). Runoff model forms the basis for the hydrological part of the environmental modeling. Rainfall runoff model determines the runoff signal which leaves the watershed from the rainfall signal received by the basin (Dilip Kumar et. al., 2011). The existing rainfall runoff models either apply empirical formula or statistical techniques (Sherman 1932, Box and Jenkins, 1970, Abrahart and See, 2000, Tokar AS et al., 2000, Kouraev et al., 2004, G Otzinger et al., 2005, Price, 2006, Bjerklie, 2007, Solomatine et al., 2008). Black et al., defined the best model as a series of quality assurance principles and actions to ensure that model development, implementation and application are the best achievable, commensurate with the intended purpose. In practice, this is subject to data availability, time, and budget.

Rainfall runoff models have diverse applications in the field of water resource and disaster managements. Therefore, researchers have to choose the appropriate model to suit the purpose and availability of data for analysis and calibration. Fuzzy numbers can be used to in the watersheds where there is varying spatial distribution of land use, soil type and slope. The present model uses fuzzy numbers to analyse the relationship between the rainfall and runoff. This method provides an integrated approach that enables effective interaction between all domains pertinent to water management. The proposed model holds good for the disaster management and especially landslide susceptibility prediction.

II.STUDY AREA DESCRIPTIONS

Nilgiris hills rising a loft from the uplands of Coimbatore is a plateau sloping in to Mysore plateau towards North and merging with Western Ghats in the North West, West and South West. Kundha watershed lies in the Nilgiris district. The elevation ranges from 300 m in the Moyor Gorge to 2634 m above MSL at Doddabetta peak. The watershed bounded by 76° 29' to 76° 47' N and 11° 11' to 11°25' E (Fig.1) consists of thirteen sub watersheds with an aerial extension of 314 km^2.

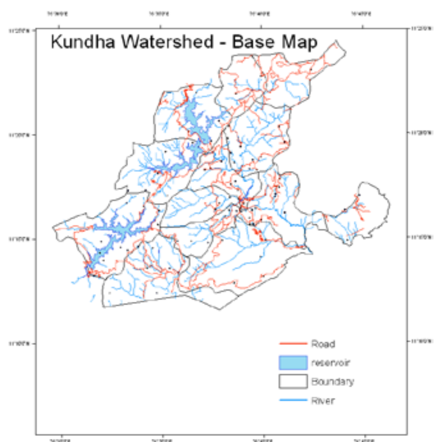

Fig.1 Base Map

The watershed area is characterized by dense forest, tea plantation, forest plantation, agro horticultural plantation, scrub land, open forest and water bodies. Thirty five per cent of the watershed is covered with forest, and 29% of the area is covered with forest plantation. The watershed is drained by multitudinous streams. The foliation of the rocks and the joining patterns influence the drainage pattern. It is observed that the major rivers in the watershed flow along the prominent fractures. The river Kundha and its tributaries drain the watershed.

The existence of six hydro power plants makes the Kundha watershed which is constructed across the river

Kundha and its tributes significant to the power generation and environment. Landslides play havoc on the functioning of the power houses. The past records suggest that the rainfall is the primary triggering factor for landslides. Therefore, it is essential to study the rainfall runoff behavior to predict the landslides in this watershed.

III.METHODOLOGY

Fuzzification

Fuzzification is the process which converts each piece of input data to degree of membership by the lookup in the one or several membership functions. The fuzzification block thus matches the input data with the conditions of the rules to determine how well the conditions of each rule matches that particular input instance. There is a degree of membership for each linguistic term that applies to that input variable. The result of Fuzzification is called Fuzzy degree of membership, which varies in between 0 to 1. All inputs and output variables were separately divided into subsets, as extremely low (EL), very low(VL), low(L), medium(M), high(H), very high(VL), extremely high(EH). More subsets are considered to increase the accuracy of prediction.

The main concern of this model is to simplify the complexity involved in the rainfall runoff modeling. In this work, data mining approach is adopted. This method overcomes many limitations of the earlier models *viz.*, i) there is no need to have a large set of historical landslide data of the study area; ii) the heterogeneity and uncertainty in the data can be overcome; iii) the nature of the input data (*viz.*, Continuous, discrete or, categorical) shall not have an impact on the model and its results (Binaghi *et al* 1998).

Weighting is an indispensable technique by which the contribution of each factor towards the development of landslide is assessed. Although several researchers have worked different methods to weigh the factors, difficulties arise in making a precise decision due to the complex nature of the problem. Fuzzy data can be expressed in linguistic terms or fuzzy numbers. After the preparation of the thematic maps (slope map, soil map and land use map), weights are assigned to the individual factors and their sub classes using the expert knowledge. The weights are subsequently converted in to fuzzy number. The conversion of the linguistic variables into fuzzy numbers is done by using the trapezoidal membership function following Wei-dong *et al* (2009) method. Equation 1 shows the trapezoidal membership function, where a, b, c and d are the real numbers. Table 1 gives the linguistic variables and their fuzzy numbers.

$$\mu_{\tilde{A}}(x) = \begin{cases} \dfrac{x-a}{b-a} & a < x < b \\ 1 & b \le x \le c \\ \dfrac{x-d}{c-d} & c < x < d \\ 0 & x \le a \text{ or } x \ge d \end{cases}$$

TABLE I LINGUISTIC VARIABLES AND FUZZY NUMBERS

Linguistic Variables	Fuzzy Numbers
Very Low	(0,0,0,3)
Low	(0,3,3,5)
Medium	(3,5,5,7)
High	(5,7,7,10)
Very High	(7,10,10,10)

Then the aggregated fuzzy weights were computed for individual factors or subclasses and defuzzified. The defuzzified weights for both the prime factors and the subclasses where normalized.

Aggregated Fuzzy Weight $= (a_j, b_j, c_j, d_j)$

$= (\sum a_{1to3} / 3, \sum b_{1to3} /3, \sum c_{1to3}/3, \sum d_{1to3}/ 3)$ (2)

Defuzzified Weight $= (a_j + b_j + c_j + d_j) / 4$ (3)

The comprehensive weight is calculated by multiplying the weight of the main factor and the weight of the subclasses. The following table gives the normalized weight of each subclass and the comprehensive weight. The factor maps were created as raster maps and comprehensive weights are attached to the maps. The raster maps are overlaid in an ArcGIS environment. Runoff is calculated as the product of the sum of the weight and the annual rainfall in mm. Grid x, has a particular combination of soil, land use and slope. The formula given below is used to calculate the runoff of the grid x.

$$\text{Runoff}_x = \left(\sum_{i=1}^{3} w_i^x \, w_{ik}^x\right) \times \text{annual rainfall}$$

Where w_i^x is the weight of the major factor in the grid x, w_{ik}^x is the weight of the sub class of the major factor in the grid x.

IV.RESULT AND DISCUSSIONS

Kundha watershed receives rainfall throughout the year and majority of the rainfall is received from the south - west monsoon. The rainfall data is obtained from the metrological department and the rain gauge station is located near Kundha Bridge. The annual rainfall ranges from 1300 to 2000 mm. Analysis of rainfall data indicates that the annual rainfall increases year by year. July, august, September, October and November are the rainy months. The month of October receives maximum rainfall followed by November. Minimum rainfall is recorded during the month of January. Landslides occur in this area during the rainy season and make the study of runoff important.

TABLE II RAINFALL RUNOFF MODELLING
EVALUATION FACTOR SYSTEM AND WEIGHTS

S.No.	Major Factors (Normalized Weight)	Sub- Classification	Normalized Weight	Comprehensive Weight
1	Slope (0.430)	Nearly level	0.117	0.05
		Moderate Slope	0.213	0.091
		Steep Slope	0.277	0.119
		Very Steep Slope	0.394	0.169
2	Soil Type (0.267)	Moderately Eroded Gravelly Clayey Soils	0.238	0.064
		Calcareous Loamy Soils	0.238	0.064
		Gravelly Loamy Soil with Escarpments	0.309	0.083
		Highly Eroded Gravelly Clayey Clay	0.214	0.057
3	Land use (0.302)	Dense Forest	0.021	0.006
		Forest Plantation	0.084	0.025
		Forest Blank	0.115	0.035
		Open Forest	0.084	0.025
		Mixed Forest	0.073	0.022
		Land With Scrub	0.073	0.022
		Agro-Horticulture Plantation	0.062	0.019
		Tea Plantation	0.073	0.022
		Waterbody / Lake / Reservior	0.135	0.041
		Land Without Scrub	0.106	0.032
		Settlement	0.135	0.041
		Industrial / Mining Area	0.040	0.012

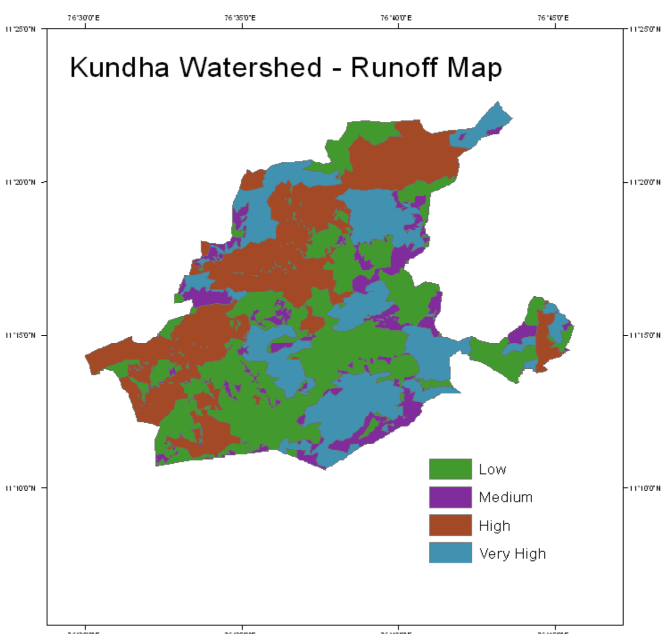

Fig. 2 Runoff Map

The runoff generated using the fuzzy numbers was classified using natural break. The classification of the runoff is given in the table 3. The entire watershed is classified in to four zones very high, high, medium and low. Runoff is one of the important factors used in landslide analysis. The runoff map of the watershed shows that 25% of the area has very high runoff and 10% of the area has high runoff. It was observed that the area having slope greater than 35^0 have very high runoff. It proves that land slope is an important factor controlling the amount of rainfall infiltrating inside the ground. The increase in rainfall runoff in the steep slopes cause scouring and cutting of soil and induces landslides in this watershed.

TABLE III RUNOFF CLASSIFICATION

S.No.	Classification	Runoff (mm)
1	Low	155-228
2	Medium	228-272
3	High	272-313
4	Very high	313-378

The water level records of the Kundha reservoir are used to validate the model. During the measuring period, the rainfall event recorded in the rain gauge station located in the Kundha bridge is used to calibrate the rainfall runoff model. The model was in good agreement with the observed reading. Using fuzzy numbers to produce the rainfall runoff model helps us to learn and reflect on reality.

Comparison of landslides with the runoff of the area

Earlier literature reveals that most of the researches did not study the influence of run off on landslides. The main reason behind this is due to the complexity involved in generating the runoff. Although it is clear that there are many other factors to assess the landslide susceptibility, it is considered that run off has a vital role to play, and it is worth to put more effort in terms of its interpretation. The run off of the entire watershed is classified as low, medium, high and very high. Low and medium categories of the run off shares almost equal percentage of frequency of landslides. Twenty five percent of the watershed has very high run off, and only ten percent of the area has high run off. Figure 3 shows the area distribution within classes of runoff.

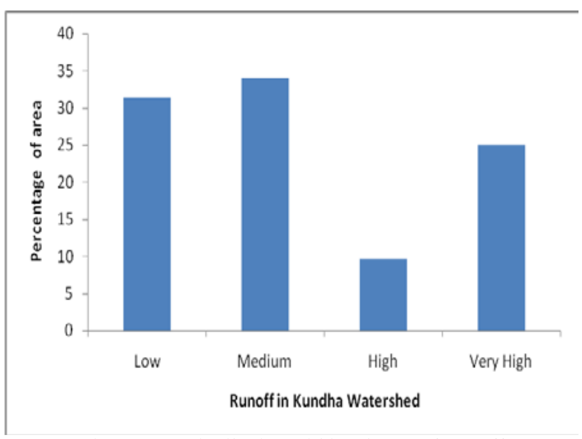

Fig. 3 Area Distribution within Classes of Runoff

The frequency of landslides is plotted against the subclasses of runoff classes to understand the relationship between run off and landslide (Figure 4).The classes show peculiar variability with the number of landslides occurring in the very high and low run off categories. This makes it clear that this factor if taken alone, does not seem to have a good explanatory power of landslide distribution.

Thirty six percent of frequency of landslides falls under the low category of runoff. The low runoff area was found to have highly eroded clay soil. For a given intensity of rainfall, in a low runoff region only less quantity of the water flows as runoff, and the majority of the rainwater infiltrated into the soil. When highly eroded clay soil absorbs more amount of water it gets swollen and a tremendous amount of pressure built. At a threshold pressure, the land becomes unstable and starts sliding.

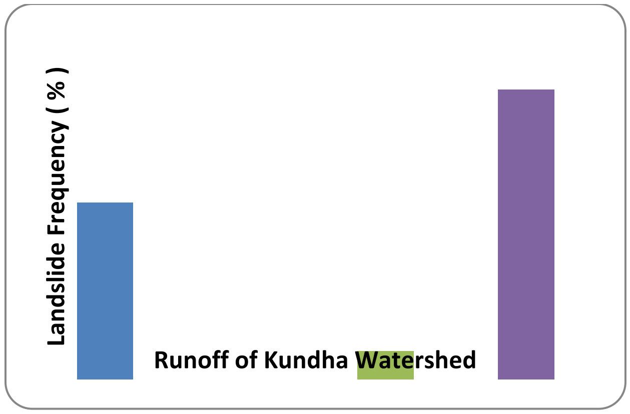

Fig. 4 Frequency of Landslides within Classes of Runoff

The moderate runoff has zero occurrence of landslide. This is because of the balance which exists between the water flowing as runoff and the water infiltrating inside the soil. The water getting infiltrated inside the soil is not enough to create the threshold pressure which triggers the landslide. The very high runoff area has the highest frequency of landslide (59%). The area under high runoff category has gravelly loamy soil with escarpment and very steep slope. This combination means large quantity of water flowing on the surface with greater velocity on the gravel on top of a steep slope, which would cause slope instability.

V.CONCLUSION

The rainfall–runoff relationship is the most intricate hydrological process. The complex spatial and temporal variability of the catchment characteristics and rainfall patterns make the modeling process complicated. Fuzzy logic approach has presented promising results. This study suggests that use of fuzzy numbers to generate the rainfall runoff model can outperform their complex counterparts. It can be concluded that this model effectively uses the commonly available data set to predict the hydrologic response.

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