Estimating Channel Cross Section Runoff Overflow Using Fuzzy Rule Based System: A Hydrologic Analysis of Mt. Isarog Watershed

R.V. Romero[1*], M.A. Iglesia[2], A.S. Pempena[2] 🆔, N.V. Romero[3], F.B. Romero[4]

1. Professor, College of Engineering, Partido State University, Goa, Camarines Sur, Philippines
2. Assistant Professor, College of Engineering, Partido State University, Goa, Camarines Sur, Philippines
3. Associate Professor, College of Engineering, Partido State University, Goa, Camarines Sur, Philippines
4. Associate Professor, College of Education, Partido State University, Goa, Camarines Sur, Philippines

Corresponding author: *munding25@yahoo.com.ph*

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ABSTRACT

This study estimated discharges of a watershed based from twenty four hour recorded precipitation of year 2018 using modified soil conservation system (SCS-CN) method. This established fuzzy rule based system which ultimately was used to estimate the sufficiency of river cross sectional area to accommodate water discharges on a river channel. The highest river flow of the month was described. Rain gauge was used in collecting daily rainfall data. Pattern recognition method was used in computing watershed area through satellite images. The method was also used in identifying areas affected by overflow. The process was centered on the cross sectional area of the river which eventually was used in computing the amount of river discharges. The highest precipitation event of the month of December has found that the river cross sectional area is insufficient to accommodate the accumulated rain water. Traces of overflow could be seen in satellite images.

1. Introduction

Watersheds and river basins are the physical systems where the input is the volume of precipitated water and the output is the volume of water drained at the river outlet [1]. As human activities affect the environmental impacts of change in climate, natural vegetation and availability of water resources it is essential to model the complex relationship between various hydrological processes and their behavior [2]. Precipitation is the most important input variable to numerically simulate the hydrological response [3] but in practice, has proven to be difficult because of errors in the model structure and input-output data leading to substantial uncertainty in the predictions. Adequate characterization of rainfall inputs is fundamental to succeed rainfall-runoff modelling while inaccuracies in rainfall inputs directly compromise model predictions and robust decision making on water and risk management options [4]. The amount of runoff depends on saturation and infiltration excess as it is influenced by soil properties, land cover, hill slope, vegetation and storm properties as well as rainfall duration, amount and intensity [5].

Unavailability of sufficient discharge data for many rivers enable hydrologist to use indirect method of estimating river discharges by applying channel geometry and hydrological models for estimation of peak discharge [6]. The SCS CN method was used for estimating discharges which covers slope vegetation cover and area of watershed [7]. However, this method does not consider the impact of rainfall intensity and its temporal distribution, the effect of spatial scale which is highly sensitive to changes in values of sole parameter and has no clear discourse on the effect of adjacent moisture condition [8]. Modern modelling technique has brought great attention to the prediction of runoff with rainfall input in the watershed using fuzzy logic model [9]. The method is widely used to calculate flood runoff in ungauged catchments but cannot calculate the spatiotemporal variability of rainfall [10]. The Fuzzy Rule Based System (FRBS) was developed to predict the actual discharge at the river outlet. Using the system was able to predict data of the runoff using rainfall and soil moisture [11]. In flood forecasting, the obtained data from fuzzy logic was found correlated with the corresponding values from linear regression [12]. Fuzzy models can take advantage of the capability to simulate the unknown relationships between a set of relevant hydrological data such as rainfall and river flow [13].

Artificial intelligence for soft computing are applied in various fields. The hybrid particle swarm optimization-artificial neural network (PSO-ANN) models to predict ripping production on different weathering zones using in-situ test [14] would become more interesting if fuzzy logic modeling was used instead of comparing the result to the parallel method of artificial neural network (ANN) modeling. On the other hand, a study on smart and optimal system which was used to design retaining wall structures and developed neural network systems and to establish an appropriate relationship between data and safety factor of retaining wall under different seismic condition [15] would become more remarkable if the result was compared with data gathered from fuzzy logic modelling.

The watershed on this study is part of Mt. Isarog Natural Park which is a protected area and potentially active volcano reaching up to 1,966 meters [16] in the province of Camarines Sur, Philippines. Residents around the mountain had a low level of awareness among watersheds but

had high level of awareness about the role of forests in maintaining a good water supply [17] however farmers around the mountain adopted various strategies in order to cope up with the impacts of extreme weather conditions [18].

This study was used to estimate the discharge in the watershed based from the gathered twenty four hour peak precipitation of year 2018 using SCS-CN method. The fuzzy rule based system was established and ultimately was used to estimate the output discharge in the channel cross section corresponding to peak precipitation events. This estimated overflow event of a river channel.

2. Methodology

2.1. Data and area of study

The precipitation data was taken from the installed rain gauge at coordinate 13.700285, 123.490531. The daily extreme precipitation of the month was the target of study for the discharge it delivers on river channel can cause flashfloods that could be deadliest, most destructive [19] and could bring great damages [20]. Pattern recognition was used to compute watershed area through satellite images [21] and similarly was used to identify and locate the runoff overflow on river channel. The recognized irregularities on the images were confirmed through site visit. The cross sectional area was measured on portion of river channel where runoff overflow occurs. Rounding off of the measured value was applied to facilitate computation using fuzzy logic.

2.2. The SCS-CN method

The discharge value was estimated by SCS-CN method using the following equations:

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

Where:

$$S = \frac{1000}{CN} - 100 \tag{2}$$

Q is the discharge in inches, P is the amount of precipitation in inches, S is the potential maximum retention and CN is the curve number on which the value for woodland at fair condition and with slope of more than 40% is 79. The units of the parameters in the equations are in English System that conversion to mm and cubic meter/day was manipulated based from the following equation:

$$Q = \frac{V}{t} \tag{3}$$

Where Q is in m^3/s, V in m^3 and t in day.

2.3. The fuzzy rule-based model

Fuzzy logic was applied to estimate the capacity of the river channel. It was used to investigate if the river cross section is adequate to transmit river discharge. Fuzzy modelling has many application such as in estimating the punching shear capacity of concrete column slab connection [22], evaluation of slope stability [23] and in estimating of sediment transport rate [24]. The discharge simulation system was evaluated through the rules consequent to an opinion that conforms to an itemized arrangement based from the data. The following steps were achieved [25]: 1) fuzzification on which the crisp value of the input variable was modeled with a singleton membership function. 2) evaluation on which the input fuzzy set was given directly the degree of membership, 3) conjunction on which the activation degree of the rule was obtained, 4) implication and composition that on this step the then operation was computed, 5) rule aggregation wherein the final output of the fuzzy set of the overall system was obtained, and 6) defuzzification which was applied by calculating the center of gravity of a mass with the difference that the points on the mass are replaced by the degrees of membership of the output set. This is expressed by the equation:

$$\overline{X} = \frac{\int \mu_\lambda(x).xdx}{\int \mu_\lambda(x).dx} \tag{4}$$

2.4. Percentage of overflow

Percentage of river overflow (O) was computed by dividing the difference of peak discharge (Qp) and channel discharge capacity (Qc) by the channel discharge capacity (Qc) then was multiplied by one hundred percent.

$$O = \frac{Q_p - Q_c}{Q_c} x100\% \tag{5}$$

2.5. The flowchart

The following flowchart illustrates the full process of implementation until this study was completed.

3. Result and discussion

3.1. Runoff water on the watershed

The watershed (See Figure 2) with an estimated area of 11 km^2 is the crater of Mt. Isarog capable of collecting precipitation water that eventually is drained in Rangas River down to Lagonoy Gulf. The watershed area is ungauged that in terms of discharge no scientific record could be found. Hence estimation was applied using the SCS-CN method by computing the discharge based from the gauged precipitation. The highest daily precipitation of the month was used to calculate the event that peak discharges occur (See Table 1).
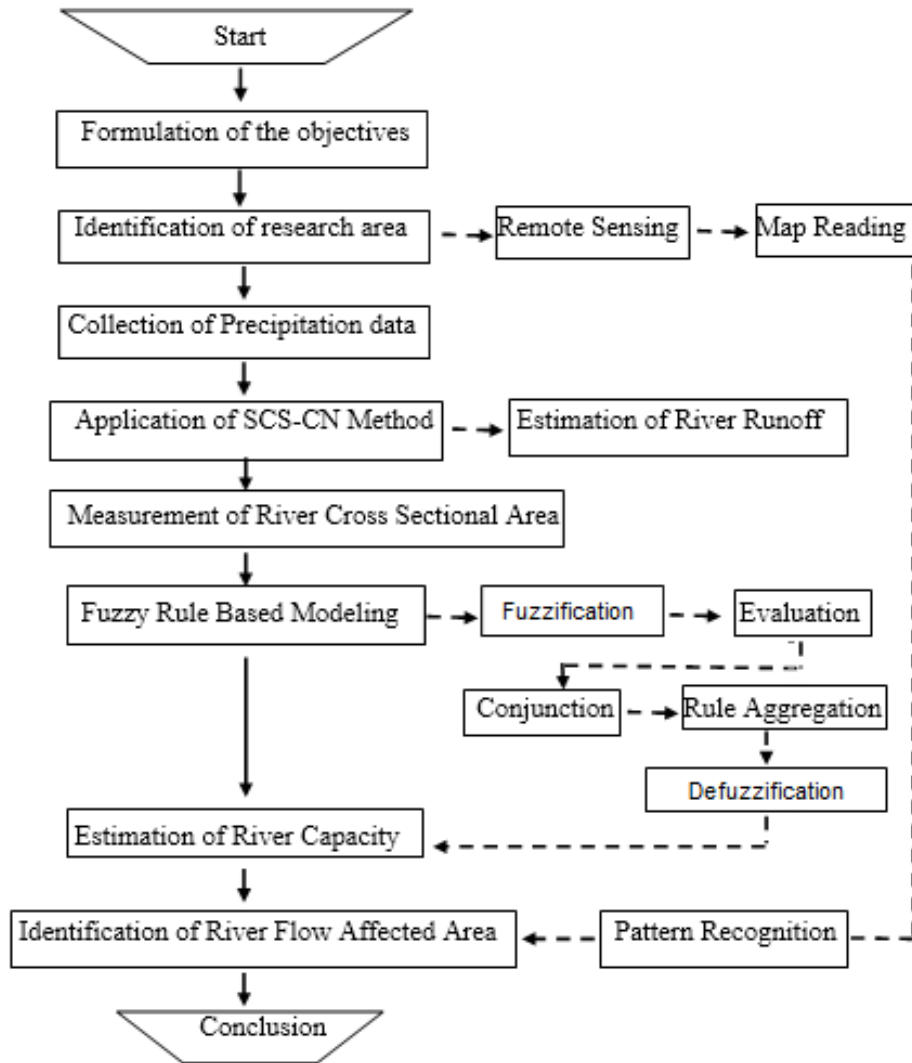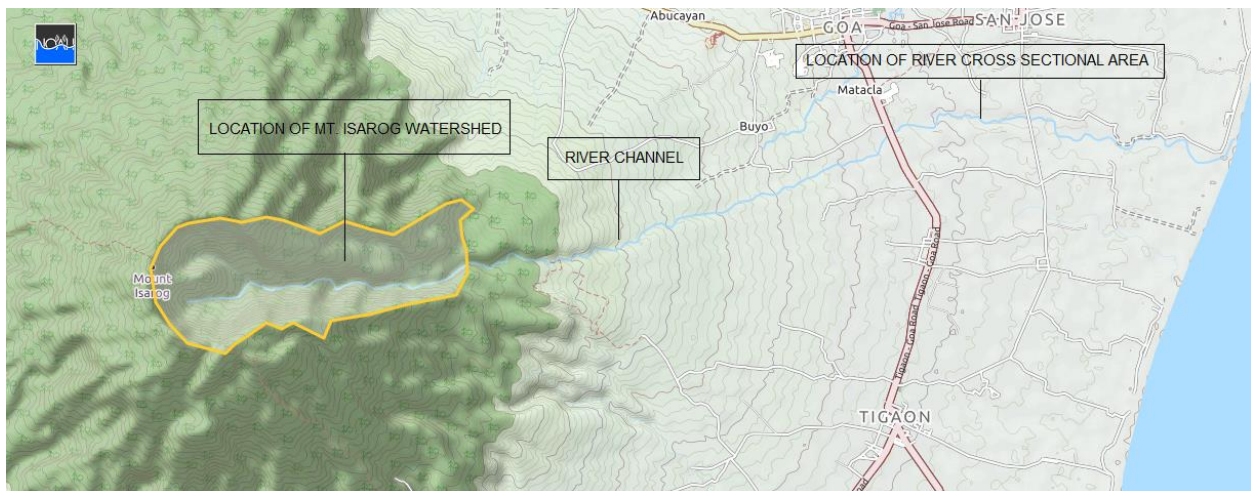
Fig. 1. The flowchart of this study.

**Fig. 2.** Location of the watershed and river cross sectional area.

Table 1
Date of event that peak precipitation and discharges happened.

Date	Precipitation		Discharge		
	P (mm)	P (in)	Q (in)	Q (mm)	Q (m³/day)
January 12	144	5.67	3.38	85.85	9,443.50
February 12	36	1.42	0.22	5.59	614.90
March 9	29	1.14	0.11	2.79	306.90
April 9	23	0.91	0.05	1.27	139.70
May 5	43	1.69	0.35	8.89	977.90
June 9	58	2.28	0.69	17.53	1,928.3
July 12	31	1.22	0.14	3.56	391.60
August 31	30	1.18	0.12	3.05	335.50
September 13	46	1.81	0.41	10.41	1,145.10
October 22	61	2.40	0.77	19.56	2,151.60
November 5	75	2.95	1.15	29.21	3213.10
December 29	298	11.73	9.05	229.87	25,285.7

The table reveals that peak precipitation occurred in December which was followed by January. The events are natural for these months are part of the rainy season. The lowest rainfall and discharge was in the month of April and is normal for it is part of the sunny season.

3.2. The fuzzy rule based system and discharge capacity of the river channel

In order to estimate the capacity of discharge that river channel cross section could accommodate, fuzzy rule based system was established. The process was centered on the size of the cross sectional area of the river and river discharge. The fuzzy expressions for cross sectional area of the river are small (S), medium (M) and large (L). The membership function for a river with cross sectional area of 45.00 m² is 0.25 small and 0.75 medium (see Figure 3). The fuzzy expressions for runoff water are extremely low with no overflow (ELNO), very low with no overflow (VLNO), Low with no overflow (LNO), High with probably no overflow (HWWO), Very High with overflow (VHO). This is followed by the generalized deductive reasoning scheme comprising the fuzzy if then rules that lends itself to model a highly nonlinear relationship existing between cross sectional area of the river and the water discharge values. Every rule is responsible for mapping some part of the input space to suitable part of the output space [26]. The fuzzy rule base for this model is molded by various statements (See Table 2).
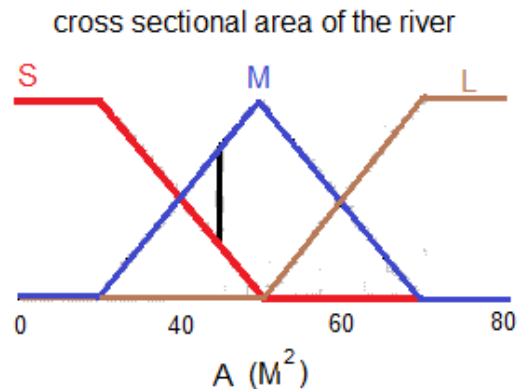

Fig. 3. Membership function of river cross section area variable.

Table 2
The statement of the fuzzy rule based model.

Rule	Statement
1	If the river cross section is M and runoff is extremely low, then no overflow (ELNO)
2	If the river cross section is M and runoff is very low, then no overflow (VLNO)
3	If the river cross section is M and runoff is low, then no overflow (LNO)
4	If the river cross section is M and runoff is high, then with or without overflow (HWWO)
5	If the river cross section is M and runoff is very high, then there is overflow (VHO)
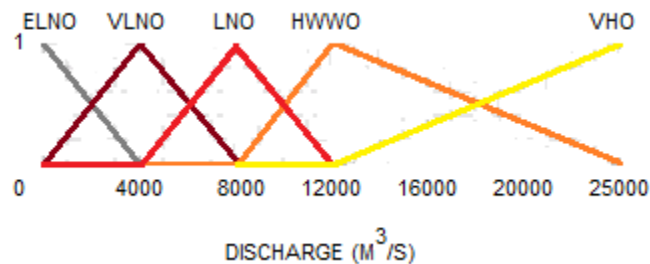
Fig. 4. Membership function for discharge variable.

Shown in Figure 4 is a model based from variables that defines fuzzy sets. The model was built to decompose linguistic variables into a set of terms which cover its universe of scope giving linguistic meaning to either the variables or the fuzzy sets. The membership function for discharge variable was illustrated.

.After fuzzy sets were evaluated, other procedures that were done are conjunction, implication and rule aggregation on which all rules that have been calculated are aggregated by joining with the linguistic connector to get the final fuzzy set output inclusively with the structure (See Figure 5). The final procedure is by defuzzification which was accomplished by computing the center of gravity.
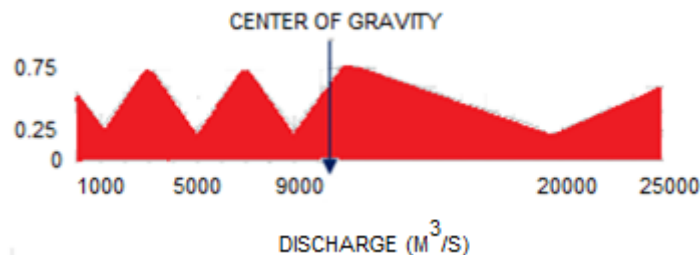
Fig. 5. Result of deffuzification process.

3.3. The channel overflow event

Defuzzification process was able to determine the capacity of the river channel with nearly medium size cross sectional area to transport discharge water. The result was used to estimate and describe the event of twenty four hour peak discharge of the months of year 2018.
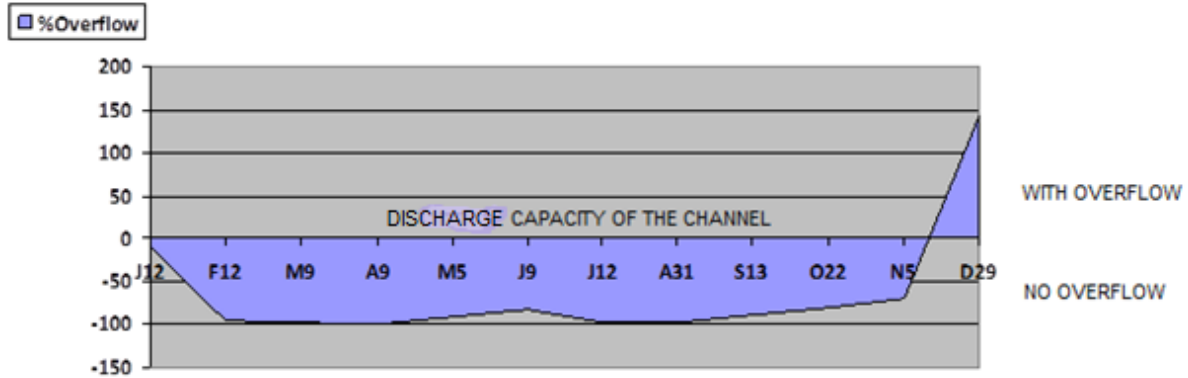
Fig. 6. Monthly highest discharge event.

The data revealed that the river channel cross section is sufficient to transport peak discharges from January to November. However, there was an overflow in the month of December which is very high compared to other events. The situation is distressing for failure of drainage capacity to flow river discharges could possibly be a factor of causing flood [27] and destruction. The result of the overflow could be traced on satellite images shown in Figure 7. The channel overflow in upper portion of the river channel started from coordinate 13.673962, 123.485475. Overflow on the lower portion of the channel started in coordinate 13.682830, 123.504392 (See Figure 8).

Fig. 7. Traces of overflow that occur on the upper portion of the river channel.

Fig. 8. Traces of overflow that occur on lower portion of the river channel.

4. Conclusion

The highest precipitation of 298 mm that happened in the month of December accumulated a river runoff of 229.87 mm or an equivalent of 25,285.70 m^3/s based from computation using SCS-CN method. The fuzzy logic based model system was formulated and ultimately was used to estimate the capacity of the river with almost a medium size cross sectional area of 45.00 m^2. It was found that the cross sectional area was not sufficient to accommodate the December extreme event causing overflow within the flood plain area. Traces of overflow could be seen in satellite images.

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