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Fuzzy Hydrologic Model in Tropical Watershed

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1. Introduction

Natural elements such as soil, geology and vegetation are usually represented as map classes, whose boundaries are sharply defined. However not all entries in geo-objects datasets are sharp and this is true both for their attribute values as well as for their spatial distribution (Burrough, 1996).

This traditional representation between geo-objects is considered as an oversimplification of a more complex pattern. In some conditions, these boundaries are recognized more easily because are associated to significant and abrupt land changes, such as situations in which the boundaries are located in river banks, in geologic phenomenon (intrusions, flaws, fractures) or associated with sudden relief variations (Burrough, 1986). Apart from these situations, the boundaries are associated to uncertainties caused by limited observations (Hadzilacos, 1996). In all these cases, fuzzy methods are more suitable than boolean logic.

Zadeh (1965) developed fuzzy set theory allowing the mathematical modeling in zones of imprecisions and uncertainties. Fuzzy set theory is a generalization of the boolean logic to situations where data are modelled by entities whose attributes have zones of gradual transition, rather than sharp boundaries. Studies of natural phenomena and natural objects demonstrated that the use of boolean logic is an inadequate method and brings much inferior results (Burrough, 1986).

The objective of this study was to develop a fuzzy rule-based modelling to predict runoff in a watershed using the Soil Conservation Service Curve Number (SCSCN) model (SCS, 1972).

Although the SCSCN model was developed primarily based on small watersheds, it can be applied in medium and large watersheds, with a diversified variety of soils and vegetation, if integrated to a geographical information system (GIS) (Johnson & Miller, 1997; Thompson, 1999).

2. Study area

The study area is the Quilombo River watershed, located in Ribeira Valley, South of the State of São Paulo, Brazil (Fig. 1). The land-cover of the area is composed of Atlantic forest (dominant) and pasture. The choice to study this watershed was driven by the availability of soil map, rain record gage, and stream discharge record gage.
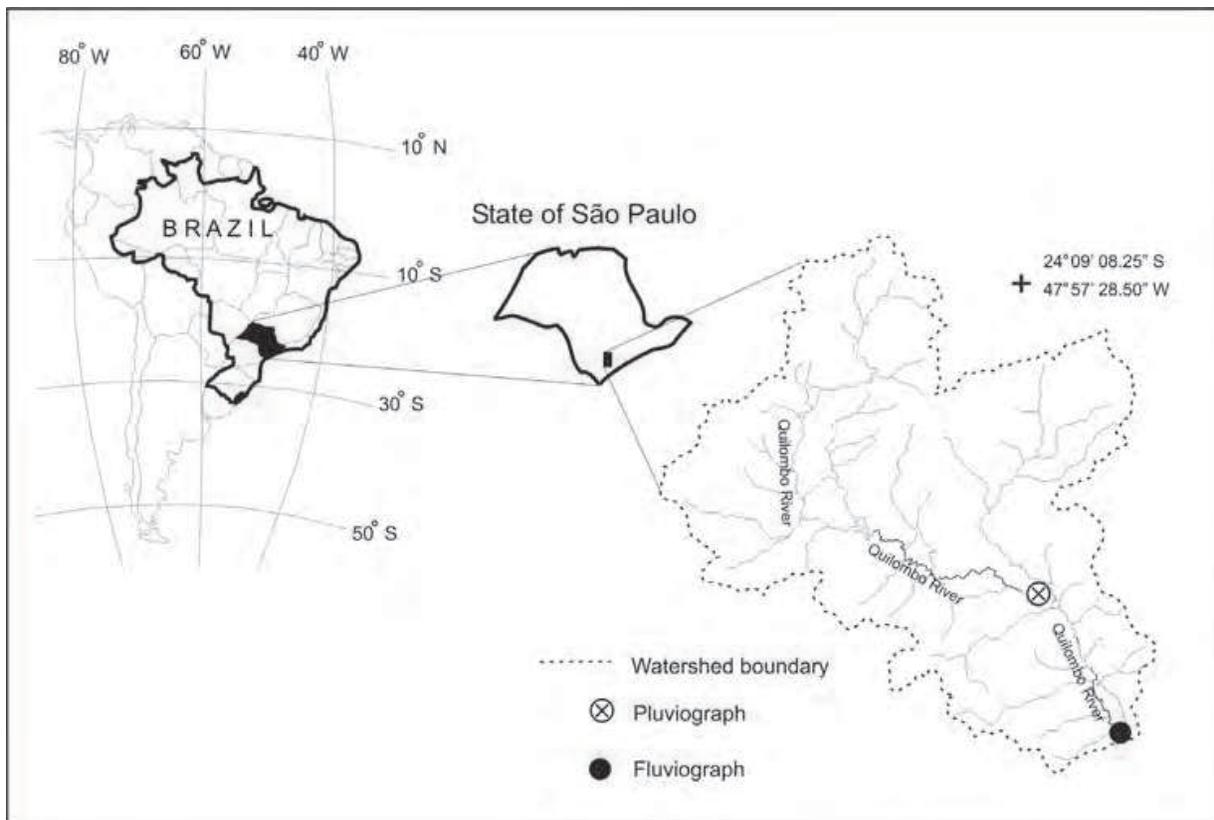
Fig. 1. Locality map

3. Fuzzy theory

A fuzzy set is defined mathematically as follows: if X = {x} is a finite set (for space) of points, then the fuzzy set A in X is the set of ordered pairs:

$$A = \{x, \mu_A(x)\} \quad x \in X \tag{1}$$

where $\mu_A(x)$ is known as the grade of membership of x in A and $x \in X$ mean that x is contained in X. For all A, $\mu_A(x)$ represents the grade of membership of x in A and is a real number in the interval [0, 1], with 1 representing full membership of the set and 0 non-membership (Zadeh, 1965). In practice, X = { $x_1, x_2 \ldots, x_n$) and the Eq. (1) can be written as:

$$A = \{x_1, \mu_A(x_1); x_2, \mu_A(x_2); \ldots ; x_n, \mu_A(x_n)\} \tag{2}$$

4. The Soil Conservation Service Curve Number (SCSCN) hydrologic model

The SCSCN model is a well known archetype for estimating the storm runoff depth from storm rainfall depth for watershed and thus, stream flow, infiltration, soil moisture content and transport of sediments. Therefore, the model can assist hydraulic projects, soil conservation projects and flood control (SCS, 1972; Engel et al., 1993; Mack, 1995; Johnson & Miller, 1997; Thompson, 1999; Pullar & Springer, 2000;
In the SCSCN model, the physical characteristics of the watershed, such as hydrologic soil group (HGS), land cover and antecedent moisture conditions, are important because these characteristics determine the curve number (CN) parameter that estimate the runoff from a

rain event. The CN ranges from 0 to 100, where larger CN represents greater proportion of surface runoff.

Basically, four steps are necessary to evaluate runoff from a rainfall by the SCSCN model: (i) to determine the hydrologic soil group (Table 1); (ii) to determine the five-day antecedent moisture condition of the soil from the precipitation record; (iii) to determine the runoff CN (on the basis of land cover, soil treatment, plus hydrologic condition and hydrologic soil group of the soil); and (iv) to calculate the runoff volume for one rain event. Concepts related to these four main steps are given below.

HSG	Characteristics
A	Soils with high infiltration rates
B	Soils with moderate infiltration rates
C	Soils with low infiltration rates
D	Soils with very low infiltration rates

Table 1. Hydrologic soil group (HSG) according to SCSCN model

In this model, the soils are classified to one of four HSG (A, B, C or D) defined by the SCS. This classification was accomplished by the analysis of the infiltration capacity of the soil. The description of each group, according to SCS (1972) and Rawls et al. (1992), is listed in Table 1.

In the SCSCN model, the watershed surface setting is assessed as a function of land cover, type of soil treatment and soil hydrologic condition. Land cover varies with landuse and can include key categories such as forests, swamps, pasture, bare soil, impermeable areas, etc. The soil treatment is related to automated farming practices (plantation along topographic contour lines and terraces) and management practices (pasture control, crop rotation and reduction). The association between landuse and the type of soil treatment is named class. Some examples of classes are: cereal plantations on topographic contour lines; dense forests; dense pasture, flat bare soil, paved highways, etc.

The association between specific HSG, land cover and type of soil treatment is referred to as soil-cover hydrologic complex, for which the CN attribute can be derived from the specialized literature (SCS, 1972; Rawls et al., 1992; Pilgrim & Cordery, 1993).

Antecedent Moisture Conditions (AMC) are related to the soil moisture due to accumulated rain, but considering the five last days that precede a particular rain event. There are three types of AMC: AMC I = soil is dry; AMC II = soil moisture is medium; and AMC III = soil is saturated in water.

The CNs were firstly obtained by measures made in a great number of watersheds for AMC II. The CN derived for AMC II can be converted to AMC I or AMC III through a transfer table provided by SCS (SCS, 1972).

The runoff begins when the portion of lost rain by infiltration, evapotranspiration, interception and depression storage, denominated initial abstractions, is less than the total precipitation. The runoff equation defined by SCS and detailed on the National Engineering Handbook (SCS, 1972) is the following:

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \tag{3}$$

where Q is the direct runoff or excess precipitation, P is the precipitation, S is potential maximum storage in the watershed after beginning of the runoff .

The CN parameter relates to S (mm) as:

$$S = \frac{25,400}{CN} - 254 \tag{4}$$

5. Model implementation

5.1 Landuse map

The land use map was obtained by image processing of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data (Abrams, 2000). Firstly, the ASTER image was compensated for atmospheric effects and converted into surface reflectance, through the Atmospheric Correction Now (ACORN) software, which involves a MODTRAN4-based method for radiative transfer calculation (Imspec, 2001). The Leaf Pigment Index (LPI) (Almeida & Souza Filho, 2004) was then calculated using ASTER reflectance data to represent the continuous surface associated to the vegetation coverage of the study area (Fig. 2). The LPI was calculated by:

$$LPI = (ASTER\ 1)\ /\ (ASTER\ 2) \tag{5}$$

where ASTER 1 is the band 1 (0.52-0.60 m - visible green) and ASTER 2 is the band 2 (0.63-0.69 m - visible red). The LPI indicates the amount of chlorophyll in plant foliage – higher index values highlight areas in the image where photosyntetically active vegetation is denser. Other vegetation indices such as the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1974) and the Moisture Stress Index (MSI) (Rock et al., 1986) were also tested, but the LPI showed to best represent the vegetation cover of the study area when the results were confronted with field observations. The map generated with LPI was converted to ASCII format, compatible with PCRaster EML.

5.2 Soil map

Soil data of the Quilombo River watershed were extracted from the soil map of Ribeira do Iguape Region at 1/100,000 scale (Sakai et al., 1983). Basically, the watershed is composed of four soil types: latosol, podzolic, inceptisol and organic soils. The soil map, originally in paper format, was converted to digital vector data. These vector data were transformed to raster data at 15 m resolution. The raster map was further converted to ASCII format.

The runoff estimate was obtained through the SCSCN model based on the hydrologic soil groups defined by the USA Soil Conservation Service, where the soil is classified into one of four different categories, ranging from A to D.

An important characteristic of the tropical soils in the São Paulo State is the fact that the clay-rich soils provide high infiltration rates (Lombardi-Neto et al., 1991). Another particular aspect of the studied watershed is that the organic soils are found in the bottom of the valleys and have high moisture content (Barreto-Neto, 2004). Based on these soil characteristics, the soil map was reclassified in agreement with the hydrologic soil groups (Table 2 and Fig. 3).
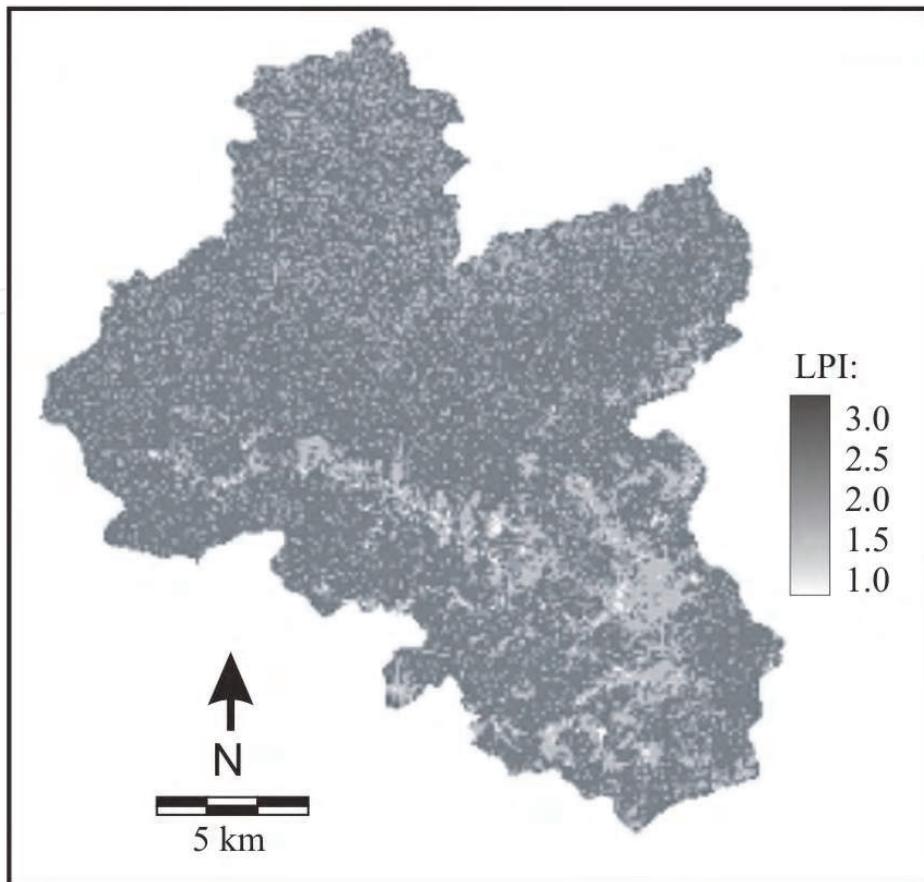
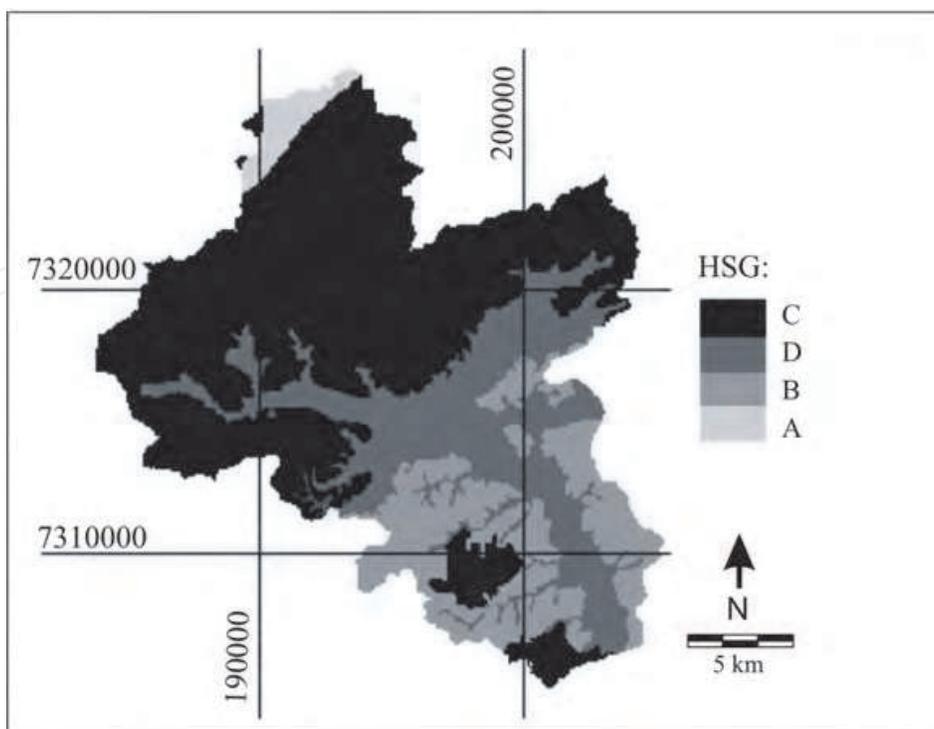Fig. 2. Leaf Pigment Index (LPI) map

Fig. 3. Hydrologic Soil Group (HGS) map

Soil types	% of area	HSG
Latosol	2.3	A
Podzolic	17.7	B
Inceptisol	56.3	C
Organic	23.7	D

Table 2. Soil types, % area in the watershed and their respective Hydrologic Soil Group (HGS) according to Lombardi- Neto et al. (1991) and Embrapa (1999)

5.3 Fuzzy SCSCN model

For the developed model, each input variable was coded, fuzzified and, subsequently, input into the fuzzy inference system for decision making, using the PCRaster EML (Wesseling et al., 1996). The implementation of the computer model followed three steps: (i) the soil and cover maps were transformed in a fuzzy set using the membership functions (linear and bell-shaped); (ii) using the fuzzy inference system, the CN map was generated based in the fuzzy soil map and the fuzzy cover map (both developed in the previous steps); (iii) runoff calculation.

5.3.1 Fuzzy soil map

Using the methods of fuzzy logic on polygon boundaries makes it simple to incorporate information about the nature of the boundaries. In this paper, the map-unit approach described for Burrough and McDonnell (1998) was employed. This approach assumes that the width of the transition zone is the same in all map boundaries. Information about the type of boundary was converted to parameters for two fuzzy membership functions (linear and bell-shaped) (Fig. 4), which were applied to the distance from the drawn boundary.
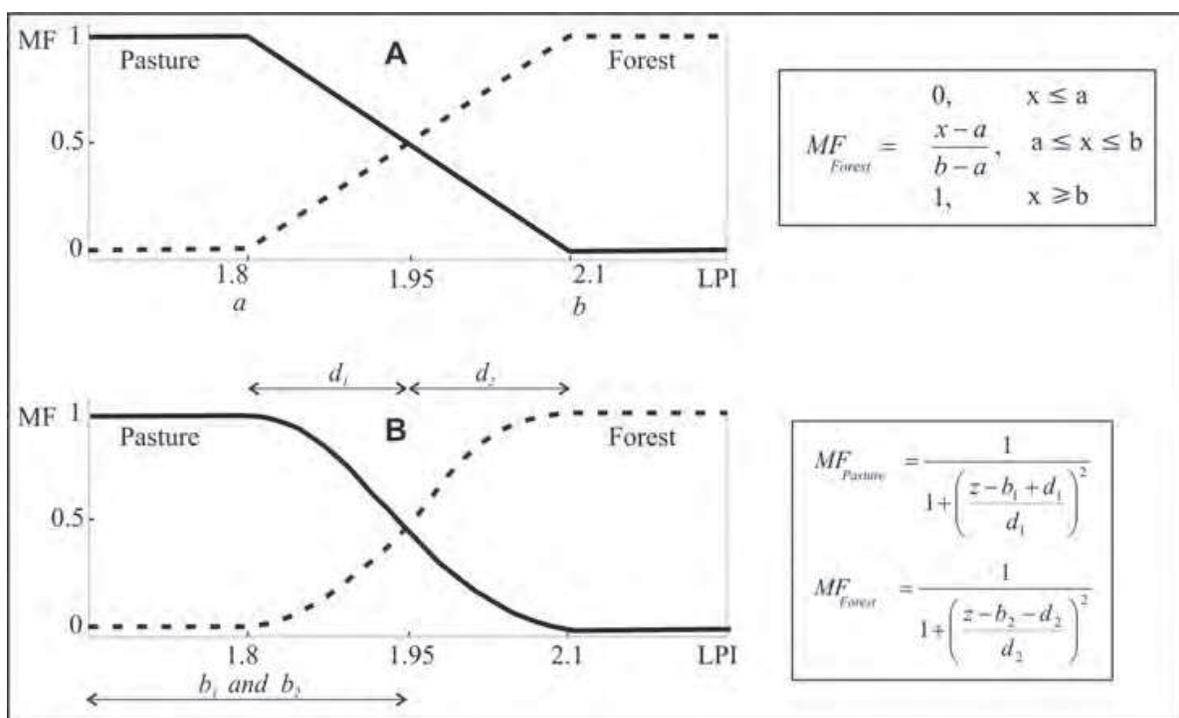

Fig. 4. Membership functions: (A) linear; (B) bell-shaped

The width of the transition zones was chosen based in the scale of the map, according to indications provided by Lagacherie et al. (1996) and Burrough and McDonnell (1998). Burrough and McDonnell (1998) exemplified that a sharp boundary drawn as a 0.2 mm-thick line on a 1:25,000 scale map covers 50 m (25 m to the right and 25 m to the left from drawn boundary) and a diffuse boundary at the same scale might extend over 500 m. In this study, sharp boundaries were drawn as a 1 mm-thick line on a 1:100,000 scale map, so that the width of the spatial transition zone centered over the drawn boundary location was 200 m. Only the uncertainty related to the drawn boundaries of the map was used, although the transition zones verified in the field show larger extensions.

In order to model fuzzy transition zones, the computer model involved the following steps: (i) separation of each soil unit (polygon boundary) in different map layers; (ii) isotropic spread of the boundary of each polygon (inside and outside the polygon); (iii) application of a membership function. Each soil unit was considered as a fuzzy set A = {x, $\mu_A(x)$}. In this case, x denotes a point in geographic space that belongs to A, and $\mu_A(x)$ is a number that ranges from 0 to 1 and reflects the grade of membership of x in A. The fuzziness of the boundary between soil units A and B were indicated by both distributions of grades of membership, $\mu_A(x)$ and $\mu_B(x)$ (Fig. 5). Points located far enough from the boundary have either $\mu_A(x) = 1$ and $\mu_B(x) = 0$ (if x is contained in A) or $\mu_B(x) = 1$ and $\mu_A(x) = 0$ (if x is contained in B). Points located close to the boundary $\mu_A(x)$ and $\mu_B(x)$ have values between 0 and 1; (iv) the procedure was repeated for each soil unit, yielding a soil boundary fuzziness map for each soil unit. The width of the transition zone can be defined by the user before the computer program is run. Fig. 6 and Fig. 7 show the boundary of organic soil using the fuzzy and boolean model, respectively.
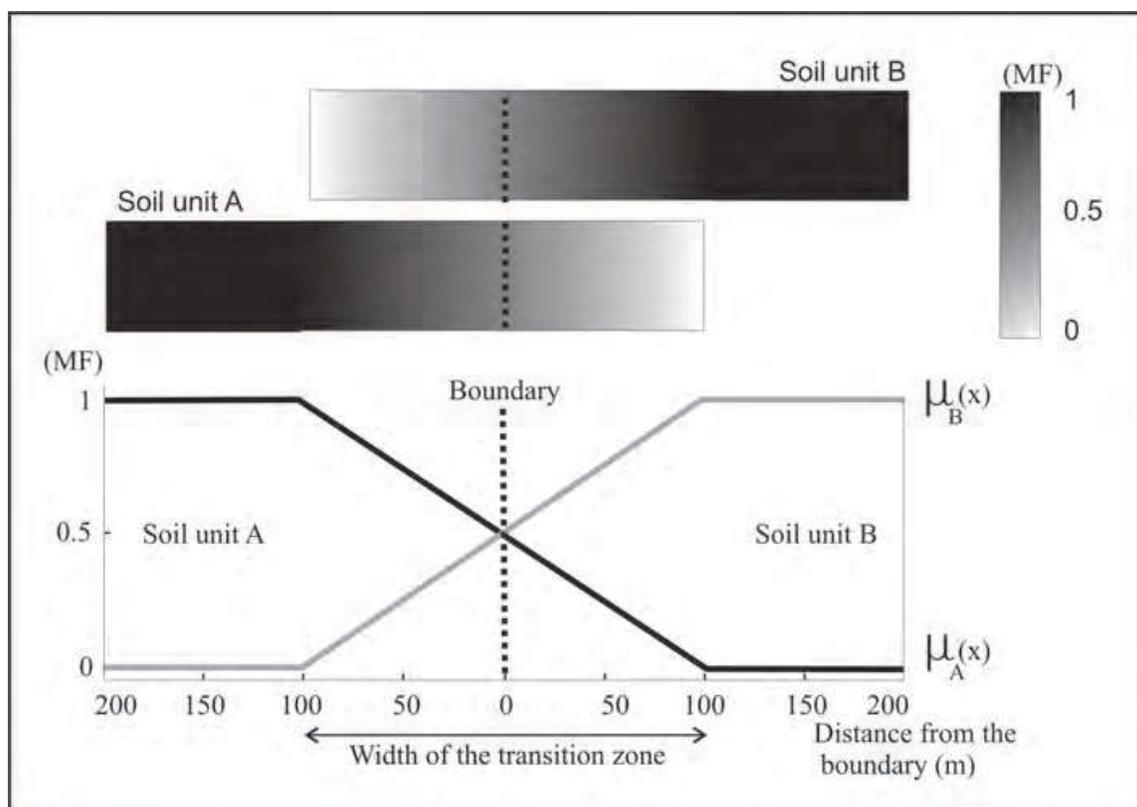

Fig. 5. Linear membership function and illustration of the methodology employed in the conversion of crispy soil data to fuzzy soil data
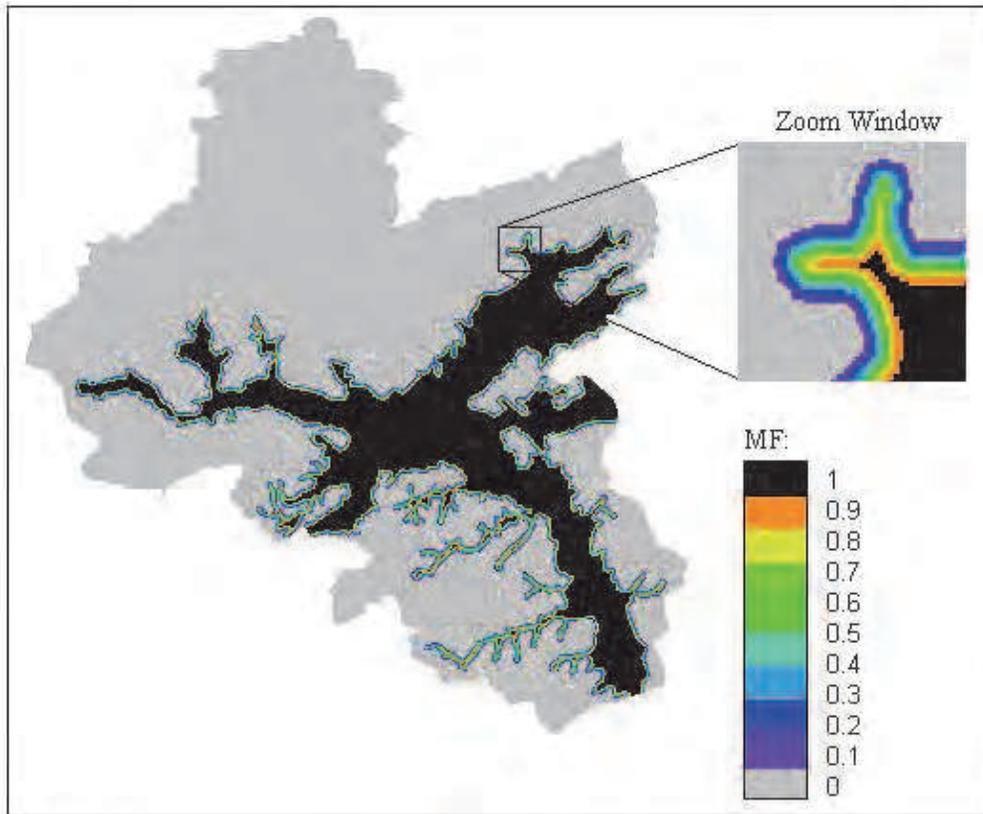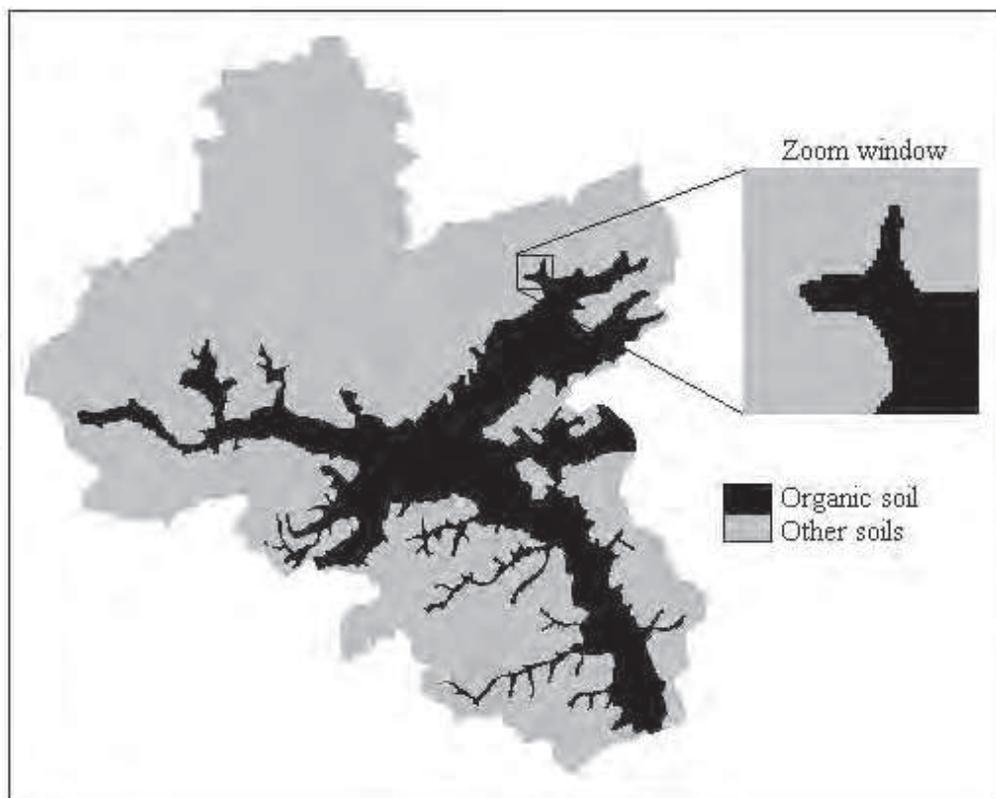
Fig. 6. Organic soil map with fuzzy boundaries

Fig. 7. Organic soil map with Boolean boundaries

5.3.2 Fuzzy land cover map

The fuzzy feature of the LPI map (land cover map) was calculated by the membership functions illustrated in Fig. 4. Field observations allowed the identification of transition zones on the vegetation cover (forest and pasture). The transition zones are covered by brushwood, as well as by degraded forest with grass fields. The diffuse boundaries observed in field were identified on the LPI map, so allowing proper membership function parameters to be used. This procedure generated four fuzzy maps: forest and pasture fuzzy maps using linear and bell-shaped membership functions.

5.3.3 Fuzzy rule-based modeling

In the fuzzy rule-based modeling, the relationships between variables are represented by means of fuzzy **if-then** rules that assume the form:

$$\textbf{If } x \text{ is } A \textbf{ then } y \text{ is } B \tag{6}$$

where x and y are linguistic variables, A and B are linguistic constants. The if-part of the rule "x is A" is named the antecedent, while the then-part of the rule "y is B" is named the consequent.

In this study, the Sugeno's method of fuzzy inference (Sugeno, 1985) was used to calculate the CN of all cells in the watershed map. In this method the antecedent is a fuzzy proposition and the consequent is a crisp function. Two typical fuzzy rules used in a Sugeno fuzzy model will be demonstrated as an example:

$$\textbf{If } x_1 \text{ is } A_{11} \textbf{ and } x_2 \text{ is } A_{12} \textbf{ then } y \text{ is } B_1 \tag{7}$$

$$\textbf{If } x_1 \text{ is } A_{21} \textbf{ and } x_2 \text{ is } A_{22} \textbf{ then } y \text{ is } B_2 \tag{8}$$

where x_i (i = 1, 2) is an input variable (e.g. soil, vegetation), y is an output variable (e.g. CN parameter), A_{ij} (i = 1, 2 and j = 1, 2) is a fuzzy set (e.g. high infiltration capacity, forest), and B_i is a number that represents the consequent of the rule.

If x_1^0 and x_2^0 are values assumed by x_1 and x_2 and $A_{ij}(x_i^0)$ the grade of pertinence then the consequent value (crisp function) is W_1 and W_2 :

$$W_1 = \min(A_{11}(x_1^0), A_{12}(x_2^0)) \tag{9}$$

$$W_2 = \min(A_{21}(x_1^0), A_{22}(x_2^0)) \tag{10}$$

where "min" denotes "minimum value of". The global output y^0, that can be the CN parameter, is calculated by equation (11) (Kruse et al, 1994; Burrough, 1998):

$$y^0 = (W_1 B_1 + W_2 B_2)/(W_1 + W_2) \tag{11}$$

The fuzzy inference system of the Fuzzy SCSCN model was accomplished through the following steps: (i) transformation of the input data in a fuzzy set; (ii) application of the fuzzy rules (Table 3); (iii) computation of the information associated to transition zones on different soil and vegetation map units, using the Sugeno's method; (iv) generation of CN raster maps with the CN values of all pixels of the studied watershed (Fig. 8); and (v) runoff calculation.
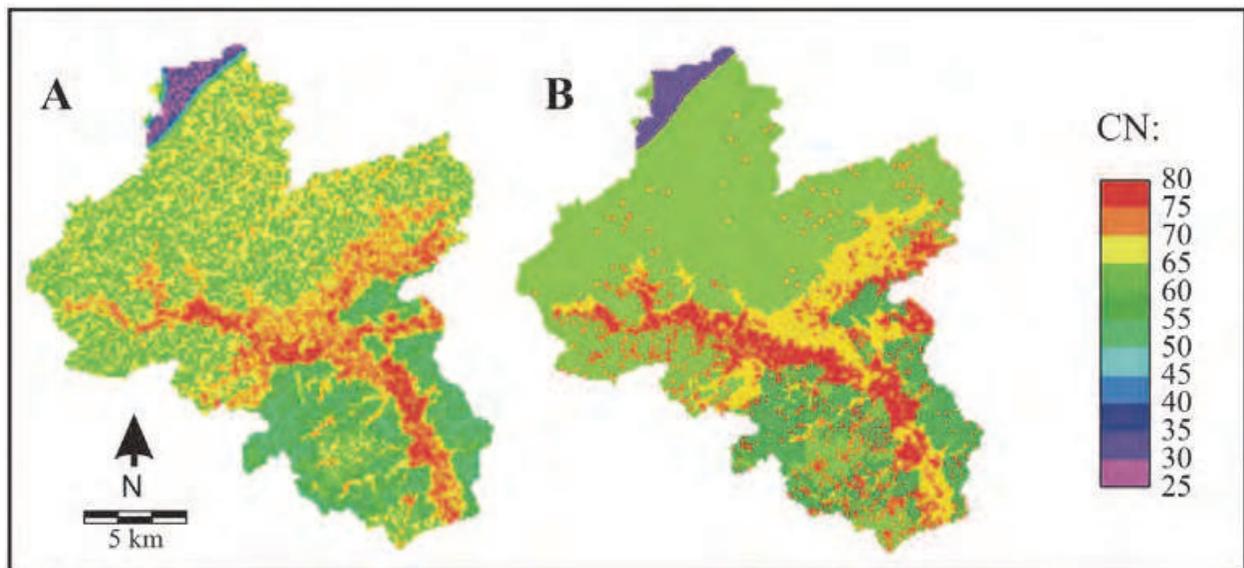
Fig. 8. CN maps obtained by the Fuzzy SCSCN model (A) and by the standard SCSCN model (B)

Rule no. (R_i)	*If*	HSG	*and*	LPI	*Then*	CN
R_1	*If*	D (*v. low inf.*)	*and*	pasture	*then*	80 (*v. high*)
R_2	*If*	D (*v. low inf.*)	*and*	forest	*then*	69 (*medium-high*)
R_3	*If*	C (*low inf.*)	*and*	pasture	*then*	74 (*High*)
R_4	*If*	C (*low inf.*)	*and*	forest	*then*	62 (*Medium*)
R_5	*If*	A (*high inf.*)	*and*	pasture	*then*	39 (*medium-low*)
R_6	*If*	A (*high inf.*)	*and*	forest	*then*	26 (*Low*)
R_7	*If*	B (*moderate inf.*)	*and*	pasture	*then*	61 (*Medium*)
R_8	*If*	B (*moderate inf.*)	*and*	forest	*then*	52 (*medium-low*)

Table 3. Fuzzy rule-based model for providing the *CN* parameters for the study area.

6. Result discussions

The CNs used here were selected on the basis of calibrations between modeled and observed runoffs. Key characteristics of the watershed, chiefly the hydrologic soil group, land cover and antecedent moisture conditions, plus CN tables available in the literature (e.g., SCS 1972; Thompson 1999), guided the CN selection. Once the CNs were selected, the runoff modelling was tested through a comparison between the modeled runoff depth and the recorded runoff depth observed in field. The validation of the CNs for the Quilombo River watershed was carried out for 16 rain events (Table 4). The results indicate that the modeled and the observed runoffs are akin and, therefore, the employed CNs proved suitable.

Event	rain (mm)	Recorded runoff (mm)	Runoff for Boolean SCSCN model (mm)	Runoff for Fuzzy SCSCN model (mm)	
				Linear membership function	Bell-shaped membership function
rain 1	5.5	2.1	0	0	0
rain 2	14	2.4	0	0	0
rain 3	21.2	3.4	0	0	0
rain 4	27.4	4.5	0.2	0	0
rain 5	32.8	5	0	1	1
rain 6	35.5	5	1.0	1	1
rain 7	45	7	2	3	3
rain 8	46	7	2	3	3
rain 9	56.5	12.6	5	6	6
rain 10	71.6	14	10	12.3	12.3
rain 11	87.0	19	16.6	18.4	18.6
rain 12	122.6	40	31	37	37
rain 13	134	49	43.2	50	50
rain 14	140.2	56	53	57	57
rain 15	150	59	54	58	58
rain 16	162	62	59	61.5	61.7

Table 4. Simulated runoff with the Boolean SCSCN and with the Fuzzy SCSCN using sixteen rain events

Runoff simulations with the Fuzzy SCSCN model were accomplished using recorded precipitation data in the watershed (Table 4). Runoff modeling was also carried out using soil and vegetation cover data in Boolean format. The notion here was to compare the results derived from conventional SCSCN model and the Fuzzy SCSCN model, as presented in Table 4.

Figure 8 portrays two maps with the spatial distribution of the CNs calculated for the Fuzzy SCSCN model and for the boolean SCSCN model. These CN maps represent the capacity of the land to produce surface runoff from a rain event. It is clear that there is a greater variety of values of the parameter CN when it is calculated by the Fuzzy SCS model. Using the boolean SCSCN model it was possible to achieve only 8 CNs, whereas a larger range of CNs was yielded with the fuzzy SCSCN.

The simulated runoff values derived from the Fuzzy SCSCN model were closer to measured runoff values in the watershed than the simulated runoff values yielded from the Boolean SCSCN model (Table 4). The better performance reached by the fuzzy model signifies that it can conveniently express natural phenomena, including zones of imprecision and/or uncertainties like transition zones among soil types and vegetation cover. Table 4 shows that the runoff data calculated by the models (from rain 1 to rain 9) is not in agreement with the

runoff recorded in the field. This can be explained by the fact that the SCSCN model is inappropriate for estimating the storm runoff depth from small storm rainfall depth (SCS, 1972).

The choice of membership function employed in the Fuzzy SCSCN model, either linear or bell-shaped, showed no significant variation in the simulated runoff. The observed equivalence in the model using these membership functions can be explicated by four factors: (i) both functions are very similar in shape (Fig. 4); (ii) the map scale (1/100,000) is small; (iii) the watershed is medium-sized (270 km²) and this imparted a low runoff variability; and (iv) the transition area is of limited width (200 m).

7. Conclusions

A methodology for runoff modeling using fuzzy sets, fuzzy membership functions and fuzzy rules was presented in this paper. The computer model was created within a GIS environment and its use can be extended to other watersheds in Brazil by simple changes on the database.

Fuzzy logic has a great potential in hydrologic sciences. The incorporation of the fuzzy theory to the SCSCN model allowed a better representation of natural phenomena because fuzzy theory considers the transition zones among geo-objects, which differs from the boolean logic that considers such boundaries as crisp. The calculated runoff by fuzzy model was closer from the measured runoff than the calculated runoff by the boolean model, confirming the adequacy of the fuzzy theory in modeling natural phenomena.

The Fuzzy SCSCN model can be used as a tool for predicting runoff and, consequently, soil erosion and quality of water in watersheds. The model is relatively inexpensive because the PCRaster program, where the script is run, is freeware. The program developed here can produce fuzzy boundaries with different widths and can be used with numerous membership functions by simple changes in program script.

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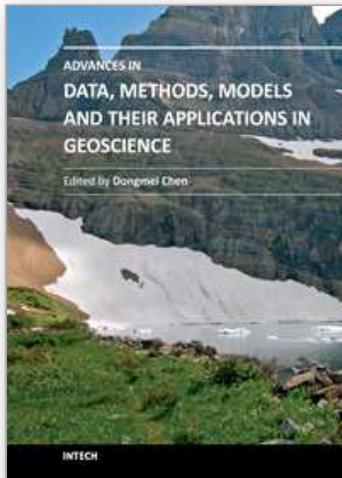
Advances in Data, Methods, Models and Their Applications in Geoscience

Edited by Dr. DongMei Chen

With growing attention on global environmental and climate change, geoscience has experienced rapid change and development in the last three decades. Many new data, methods and modeling techniques have been developed and applied in various aspects of geoscience. The chapters collected in this book present an excellent profile of the current state of various data, analysis methods and modeling techniques, and demonstrate their applications from hydrology, geology and paleogeomorphology, to geophysics, environmental and climate change. The wide range methods and techniques covered in the book include information systems and technology, global position system (GPS), digital sediment core image analysis, fuzzy set theory for hydrology, spatial interpolation, spectral analysis of geophysical data, GIS-based hydrological models, high resolution geological models, 3D sedimentology, change detection from remote sensing, etc. Besides two comprehensive review articles, most chapters focus on in-depth studies of a particular method or technique.

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