Fuzzy Logic for Watershed Assessment

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Abstract

Watershed assessment requires techniques capable of synthesizing large quantities of spatial information. Fuzzy logic is one approach for addressing this problem. Geographic information systems (GIS) have the capacity to represent and integrate several levels of information on watershed characteristics and condition. Spatial analyses can show the relative condition of a watershed or delineate zones requiring different levels of protection related to a set of activities. One of the disadvantages of techniques commonly used in these analyses (e.g. Boolean, Weighted Index, Analytical Hierarchy Process) is that they do not include the uncertainty of a given factor or in the final results, which can be addressed with a fuzzy logic approach. With fuzzy logic a fuzzy membership function is defined for each environmental factor, which defines a region where the inclusion or exclusion of the factor is unclear. This paper briefly reviews the approach and application of fuzzy logic to the Riparian Restoration Ranking (R3) System on several montane watersheds in Arizona.

Introduction

The underlying principle of watershed management is that there is a linkage between uplands and downstream areas (Brooks et al. 1997). Watershed management requires the synthesis of a vast array of spatial information to assess both upland and downstream impacts. Inventory and mapping of watershed properties and then classifying watersheds based on these properties have long been an important management tool.

Common products used in watershed management include maps delineating areas based on erosion potential, landslide hazard and flooding risk (U.S Forest Service 1980). A common application is to use mapping tools to identify the capability of areas to withstand different management activities without impairing watershed values. Other mapping activities include defining the relative condition or "health" of a watershed or assessing the need or potential for watershed or riparian rehabilitation (Falk et al. 1998; Forest Practices Code 1995; Sulaiman 1995).

Geographic Information Systems (GIS) are increasingly being used in watershed management (Guertin et al. 2000). GIS have the capacity to represent and synthesize different information layers of watershed characteristics resulting in a representation of the watershed based on a set of rules. Examples of GIS applications include assessing erosion potential (Warren et al. 1989), landslide potential (Burrough and McDonnell 1998; Carra et al. 1991; Davis and Keller 1997; Montgomery et al. 1997) and watershed classification (Itami and Cotter 1999; Sheng et al. 1997).

One of the disadvantages of the GIS techniques commonly used in these analyzes (e.g. Boolean, Weighted Index, Analytical Hierarchy Process) is that they do not include the uncertainty regarding a given factor, in regards to both measurement errors and its relative importance (Bonham-Carter 1994). Results from these analyses tend be discrete in nature (e.g. high, medium, or low erosion potential) and do not reflect or display the inherent spatial variability present in watersheds. For example, use of waterside zones (i.e. buffer strips) are a common best management practice utilized in watershed protection, but experts still disagree on the optimum width of the zones. With most GIS techniques a decision on the zone width must be made a *priori*, inherently restricting the resultant analysis.

This paper will examine the use of Fuzzy Logic Theory to assess and classify watersheds. The primary advantages of the fuzzy logic approach are: (1) its ability to account for uncertainty in regards to both measurement error and relative importance of an environmental variable; (2) that it is a relatively simple approach applicable to complex systems; (3) its robustness due to its ability to account for imprecision in input data; (4) its readily interpretable and communicable results; and (5) that it can be used to promote and facilitate user participation (Openshaw and Openshaw 1997). The paper will apply the fuzzy logic approach to the Riparian Restoration Ranking Systems (R3) System (Falk et al. 1998) and compare its results to the current procedures used by the R3 System.

Fuzzy Logic Approach

Watershed assessment usually starts with a collection of facts and observations of various character and origin. A primary aim of assessment is to delineate the need for further investigation or provide support to the decision making process. Observations and measurements in a watershed are often "rough" or can only be described qualitatively, as is often the case with historical knowledge. Moreover, the number of repeatable observations is often small, and traditional statistical methods of watershed assessment face serious challenges relating to assumptions inherent to a given technique.

Zadeh (1965) suggested another approach, fuzzy logic theory, to better cope with rough numerical and verbal descriptions. In classical set theory, membership in a given set is defined as either true or false (i.e. 1 or 0). This is the basis of many spatial classification techniques. However, membership in a fuzzy set is expressed on a continuous scale from 1 (full membership) to 0 (full non-membership), so individual measurements of an environmental factor may be defined according to their degree of membership in the set between 1 and 0.

For example, if we are interested in classifying a watershed based on its riparian restoration potential one environmental factor of interest is road density. Given a low road density, the potential for successful restoration is high. Likewise, if the road density is high the potential for successful restoration would be low because of persistent negative impacts associated with the roads. However, there are usually thresholds to consider. A small number of roads, up to a certain threshold, may exist in a watershed, yet the watershed would retain full membership in the high potential riparian restoration set (i.e. fuzzy value = 1). There is also a point where additional roads in an area, with an already high road density, will have little additional impact, and as such have full non-membership in the high potential riparian restoration set (i.e. fuzzy value = 0). Figure 1 illustrates a fuzzy membership function that could be developed for such a case. The environmental factor, x, would be road density. The values $B1$ and $B2$ represent the thresholds for full membership ($f(x) = 1$) and full non-membership ($f(x) = 0$), respectively. Between the thresholds lies the zone of partial membership represented mathematically as a fuzzy membership function that translates the environmental variable (road density) to a fuzzy score between 1 and 0. Note that the example in Figure 1 presents a linear relationship between the thresholds. This could be readily presented as a nonlinear relationship or complex function representing zones of degree of memberships (Openshaw and Openshaw 1997). The shape of the fuzzy membership function represents the relative influence of a change in the environmental variable on the objective. The threshold values represent the susceptibility of the watershed across a range of data. Both the function and threshold values could be defined through research, expert opinion, or a public participatory process.

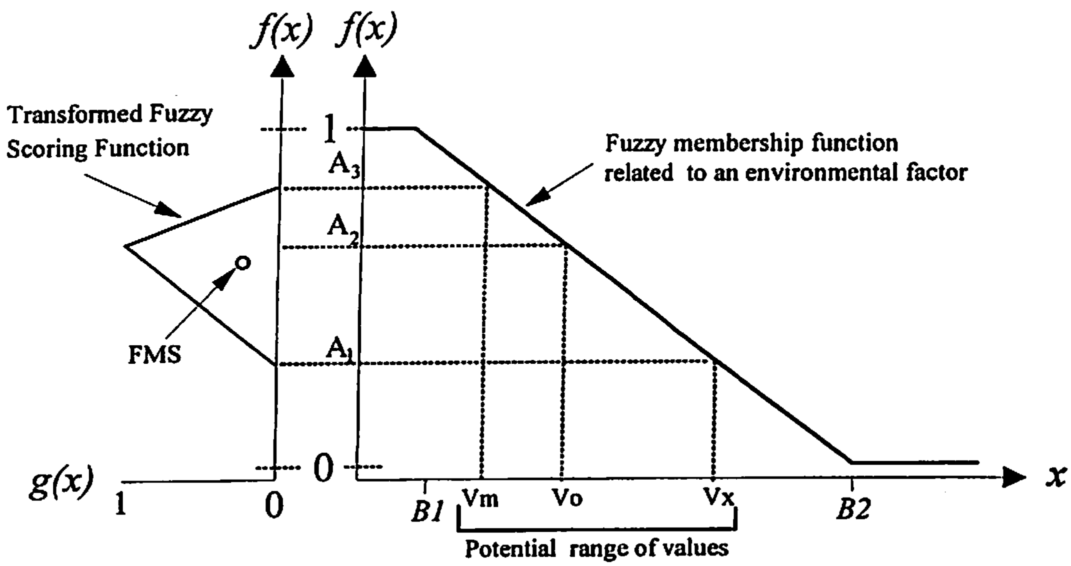

Figure 1. Transformation of the environmental variable *X* into the fuzzy score interval *f(x)* [0, 1] through a normalization function (fuzzy membership function). *B1* and *B2* are the threshold values. Vo represents the observed, Vm the expected minimum, and Vx the expected maximum value of the input variable, The values A1, A2 and A3 are the resultant fuzzy values for these input values. FMS, the fuzzy membership score, represents the center of mass of the transformed fuzzy scoring function, and is the composite fuzzy score for the given environmental variable.

The fuzzy logic approach used in this paper incorporates the level of uncertainty related to the measurement of the environmental factor (Bandemer and Gottwald 1995). This uncertainty could be due to instrument error, natural variability, user error, or lack of knowledge. The range of potential values is determined by defining the range of expected under- and over-estimation of the environmental factor (Figure 1; represented as Vx and Vm, respectively). As with the fuzzy membership function this range can be determined through research, expert opinion or a public participatory process.

Using the potential minimum, observed and potential maximum values for the environmental factor a transformed fuzzy scoring function is computed (Figure 1). First, fuzzy scores for Vm, Vo, and Vx are determined (A3, A2, and A1, respectively). The transformed fuzzy scoring function is represented as a triangle where $g(x) = 0$ at points A1 and A3, and $g(x) = 1$ at point A2. This transformation forms a normalized triangle, whose center of mass is quantified as the fuzzy membership score (FMS) for that factors shown in equation 1.

$$FMSi = A2 + [(A1 - A2) / 2] + [(A3 - [(A1 - A2) / 2] - A2) / 3] \quad (1)$$

If there is more than one environmental factor a composite fuzzy score (CFS) can be computed as the sum of the FMSi multipled by a weighting factor for n environmental factors:

$$CFS = \sum_{i=1}^{n} (Wi * FMSi) \quad (2)$$

where Wi is a weighting factor for the environmental factor, i. The sum of the weights must equal one. In this paper the variables were assigned equal weights.

Application

For illustration, the fuzzy logic approach was applied to the Riparian Restoration Ranking (R3) System (Falk et al. 1998) on the Upper Little Colorado River, three of its tributaries, and a tributary of the Black River in the White Mountains of Arizona (Figure 2). Composite fuzzy scores were computed for the five watersheds based on the R3 system.

The five watersheds included in this study are located on the Apache-Sitgreaves National Forest of east-central Arizona. Basalt and andesite flows form rolling topography to the east of Mount Baldy, an extinct volcano within the Apache-Sitgreaves. The climate of the Mount Baldy area has been classified as moist to subhumid (Merrill, 1970). Mean annual precipitation is approximately 76 cm, with half of the yearly precipitation falling during summer thunderstorms (Merrill, 1970). Although there are seasonal fluctuations in these streams, flow occurs year round. Elevation ranges from 2256 to 3474.5 meters (7402 to 11403 feet). Vegetation types in the study area range from open ponderosa pine forests at the lower elevations near Greer, Arizona, to spruce and fir forests on the upper flanks of Mount Baldy (Elmore, 1976). Vegetation cover consists of forests with small meadows on Mount Baldy and within the canyons, and large open meadows with patches of forest on the volcanic flows. Comprehensive GIS databases were constructed for the watersheds from information obtained from the U.S. Forest Service and Arizona State Department of Lands.

The R3 system developed by Falk et al. (1998) was designed to rank riparian areas and their associated watersheds for restoration potential and difficulty. The goal of the R3 is to assist watershed managers establish restoration priorities. Although it is desirable to restore all degraded riparian areas and associated watersheds, the purpose of the R3 is to assess the feasibility (or desirability) of restoring a system given its current conditions.

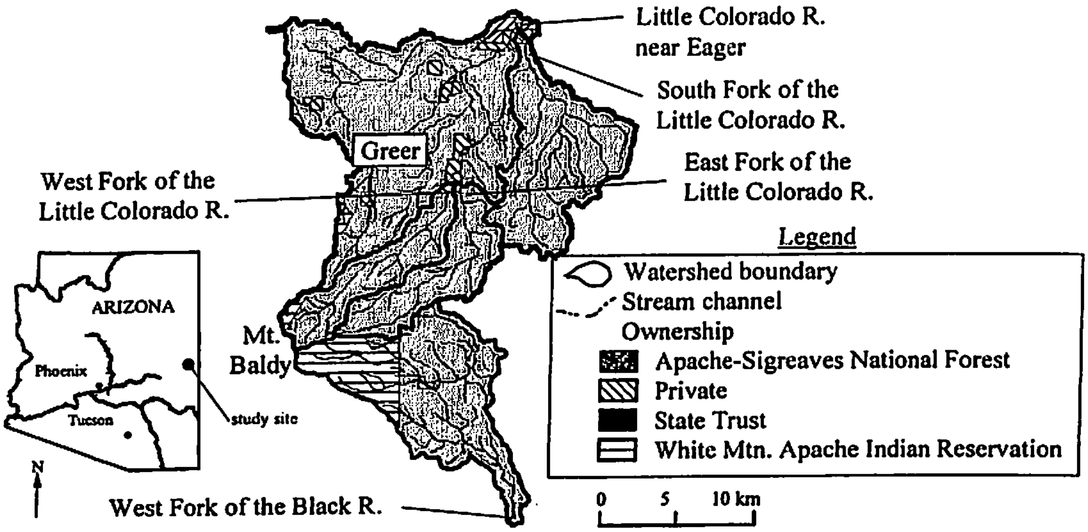

Figure 2. Locations of the study areas. The watersheds included in this study are indicated: the Upper Little Colorado River (LCR) near Eager (area = 277 km^2); South Fork of the LCR (65 km^2); West Fork of the LCR (35 km^2); East Fork of the LCR (36 km^2); and the West Fork of the Black River (73 km^2).

R3 makes the assessment by bringing together information concerning the *ecological condition* of the riparian area and its watershed and the *land use* in the same area. A simple numerical scoring system is used to indicate how different the current watershed condition is from the reference condition, and the extent to which land use practices are assumed to affect ecological condition. R3 then combines the scores into a numerical index, which the land manager can use to compare different watersheds for restoration priority and potential difficulty. The implementation of the R3 System discussed in this paper is presented from the point-of-view of the U.S. Forest Service as presented in Falk et al. (1997). R3 can be easily modified for other points-of-view.

This paper concentrates on the land use and management component of the R3 System. The land use and management component assesses the composite effects of 15 factors on riparian restoration potential. The factors are: (1) non-Forest Service ownership; (2) urbanization; (3) grazing: active allotments; (4) high impact recreation; (5) mining; (6) agriculture; (7) high-impact logging; (8) road and utility corridors; (9) altered fire regime; (10) groundwater withdrawal; (11) riparian recreation impacts; (12) riparian mining impacts; (13) water impoundments; (14) riparian grazing; and (15) roads in riparian areas. The first step of the procedure is to estimate the percentage of a watershed that is in each of the environmental factors. For example, in Table 1, which presents a summary of the results for the LCR watershed, 6.5% of the Upper Little Colorado Watershed was in Non-U.S. Forest

Table 1. Example of the R3 System and Fuzzy Logic Approach for the Upper Little Colorado Watershed in east-central Arizona.

	Percent Coverage			**Membership Function**		**Membership Score**			**FMS**
Environmental Factor	*Observed*	*Low Estimate*	*High Estimate*	*Full*	*Full-Non*	*Observed*	*Low Estimate*	*High Estimate*	*Center of Mass*
Non USFS Ownership	6.5	4.5	8.5	5	30	0.940	1.000	0.860	0.934
Urbanization	3.5	0.0	8.5	0	30	0.882	1.000	0.715	0.866
Grazing	83.1	71.6	100.0	10	50	0.000	0.000	0.000	0.000
High Impact Recreation	1.1	0.0	6.1	5	20	1.000	1.000	0.928	0.976
Mining	1.8	0.8	2.8	0	10	0.820	0.920	0.720	0.820
Agriculture	0.0	0.0	10.0	20	50	1.000	1.000	1.000	1.000
High Intensity Logging	1.3	0.0	3.3	30	70	1.000	1.000	1.000	1.000
Road & Utility Density	3.2	1.2	5.2	0	10	0.680	0.880	0.480	0.680
Altered Fire	98.2	88.2	100.0	30	60	0.000	0.000	0.000	0.000
Groundwater	0.0	0.0	20.0	5	15	1.000	1.000	0.000	0.667
Recreation Impacts	4.0	0.0	9.0	1	10	0.668	1.000	0.112	0.593
Impoundments	0.2	0.0	1.2	0	5	0.969	1.000	0.769	0.913
Floodplain Grazing	81.4	0.0	91.4	2	30	0.000	1.000	0.000	0.333
Roads & Buildings in Floodplains	6.2	4.2	8.2	0	20	0.689	0.789	0.589	0.689
R3 Composite Sum:	**290.5**								
							Composite Fuzzy Score:		**0.676**

Service ownership. From the U.S. Forest Service point-of-view, for riparian restoration it is more desirable to have complete control of the watershed. Areas outside their management control could jeopardize the success of a restoration effort. The percentages for each environment factor are then summed to create a composite score that can be compared to similar watersheds or the reference watershed. In the LCR example (Table 1), the composite score was 290.5. Lower composite scores indicate that a watershed is better suited for riparian restoration. The process of obtaining the percentages was automated in a GIS. However, discussion of the spatial analysis process is beyond the scope of this paper.

Table 1 also provides an example of the fuzzy logic approach. A small group of experts provided estimates of the potential uncertainty in estimating the watershed percentages and in defining the fuzzy membership thresholds. For example, the experts felt there was a potential +/- 2% error in estimating the percentage of non-U.S. Forest Service ownership given the available GIS data quality and resolution, resulting in a range of potential values from 4.5% to 8.5%. The experts also felt that non-U.S. Forest Service ownership below 5% was acceptable and would have little impact on potential riparian restoration. Therefore, watersheds with less than 5% non-ownership have full membership (fuzzy value = 1) in the high potential riparian restoration set. Likewise the experts felt that watersheds with over 30% non-U.S. Forest Service ownership would not be desirable for restoration because of the consequent lack of control. Thus, watersheds with greater than 30% non-ownership have full non-membership (fuzzy value = 0) in the high potential riparian restoration set. Using these values the FMS, the center of mass of the transformed fuzzy score set, for non-U.S. Forest Service ownership was computed to be 0.934. A high score such as this indicates that the environmental factor is close to full membership in the high potential riparian restoration set. Note that in this simple example the identity of the other land owners and their management objectives was not considered, a shortcoming that would need to be addressed in a full implementation.

The fuzzy membership scores were computed for 14 of the environmental factors (no information was found for the impacts of mines on riparian areas). The range of individual FMS's was 1.0 to 0.0, with grazing being the most limiting environmental factor. The composite fuzzy score for the Upper Little Colorado Watershed was 0.676 or relatively moderate membership in the high potential riparian restoration set.

Composite scores were computed for all five of the study watersheds using both the R3 Composite Sum and Fuzzy Composite Score techniques (Table 2). There are clear differences in the results between the two methods. There is a wide range (115 points) in the R3 Composite Sums, while the Composite Fuzzy Scores all show a moderate degree of membership in the high potential riparian restoration set. A difference in the order of the watershed rankings for restoration potential was also evident. The West Fork of the Black River had both the lowest R3 composite score of 200 (most desirable) and the lowest composite fuzzy score (least desirable). Such discrepancies in the rankings are a consequence of the form of the fuzzy membership functions. Recall that the R3 summation technique does not cut off the impact of a given variable based on a threshold; thus increasing the percent coverage of a variable causes the R3 score to increase directly. However, the fuzzy membership function collapses the impact of values that fall beyond either full non-membership ($f(x) = 0$) or full membership ($f(x) = 1$); note the presence of values of 0 and 1 in Table 1.

Therefore, fuzzy watershed assessment minimizes the impact of values that fall outside the range of the thresholds that define the fuzzy membership function.

One difficulty with the conventional R3 summation System is in the interpretation of the composite scores. Unless there is a datum to which scores can be compared, such as a reference watershed, it is difficult to assess whether these values represent a "good" or "poor" riparian restoration potential. It should be noted that identifying a truly representative reference watershed for the ideal condition that is comparable to other watersheds in a similar hydroclimatic region is difficult given natural variability and the extent of current disturbance.

Table 2: Comparison between the R3 System Composite Sums and the Fuzzy Logic Composite Scores for the study watersheds.

	R3 System	Fuzzy Logic Approach
Watershed	*Sum of Percentages*	*Composite Fuzzy Score*
Upper Little Colorado River (LCR) near Eager	290.5	0.676
South Fork of the LCR	315.0	0.671
West Fork of the LCR	265.0	0.671
East Fork of the LCR	267.0	0.694
West Fork of the Black River	200.0	0.632

In the above example all five watersheds are similar in terms of size, biophysical factors, and management activities, so it is not surprising that they have similar composite fuzzy scores. Let us suppose that the Upper Little Colorado River is to be heavily harvested (Table 1), and the environmental factors High Intensity Logging increased to 50% and Road and Utility Density increased to 15%. In this example, their individual fuzzy membership scores would both become zero and the new composite fuzzy score 0.534, which illustrates how management may affect the relative condition of the watershed.

The fuzzy logic approach provides values that are relatively easy to interpret (e.g. 1 = good and 0 = bad) and can be used for inter-basin comparison independent of a reference watershed. It should be noted that the composite score itself represents a relative measure of watershed condition which could be reclassified into discrete intervals. Uncertainties regarding input data are explicitly accounted for, thereby mitigating the impact of inaccuracies in the input data. Given that this approach requires the user to identify the range of acceptable values before beginning the analysis, an opportunity is created to incorporate user or expert participation in the process. Individual fuzzy membership scores can also help the manager identify which environmental factor is most limiting.

Summary

The fuzzy logic approach outlined in this paper can be a useful tool for watershed assessment and classification, providing an index value that is easy to interpret and explain. The uncertainty regarding the measurement of the environmental variables can be accounted for in the process. Importantly, the approach allows for the development of a complex system for estimating the responses between management goals and the environmental factors. The development of these relationships, or fuzzy membership functions, does not require extensive information to quantify the relationship but can be created using more qualitative information based on user or expert opinion and experience. Since the approach breaks the problem down to its basic components or processes, it removes the need to identify a reference datum.

Another advantage of the fuzzy logic approach not presented in this paper is the ability to assess the watershed condition at different scales. A composite fuzzy score can be computed for subwatersheds or points along a stream, showing a gradient of membership in space. Consequently, areas within a larger watershed that are either favorable (i.e. composite fuzzy scores approaching one) or unfavorable can be identified. Within a GIS framework this allows for the creation of maps that show the gradual change in relative condition and illustrate the potential uncertainty.

The fuzzy logic approach is not a panacea, as it still requires good data, hard work, and knowledge of the system in order to be successful. However, its advantages should make it an important watershed assessment and classification tool in the future.

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