A METHODOLOGY FOR IMPERVIOUS COVER ESTIMATION IN URBAN DEVELOPMENT USING FUZZY SET THEORY

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ABSTRACT

The amount of urban runoff and its impacts on stream conditions and water quality are linked to the percent area of impervious surfaces within a watershed. Principle of a new methodology for the estimation of urban watershed imperviousness based on land use analysis is presented. The proposed approach is able to take into account uncertainty and fuzziness inherent in the available data used for impervious surface estimation. The uncertainty and fuzziness modelling are achieved by using if-then rules and fuzzy set analysis. Numerical application is presented to show the applicability of the proposed methodology.

Keywords: imperviousness estimation, land use/land cover, fuzzy sets, fuzzy inference

INTRODUCTION

Impervious cover prevents the infiltration of rainfall into the soil. This includes roofed structures, sidewalks, driveways, roads, and parking lots. A number of researchers have found that the amount of urban runoff is linked to the percent area of impervious surfaces within a watershed (Schueler, 1994; Arnold and Gibbons, 1996). Research also shows a clear correlation between the percent of impervious surface in a watershed and the degree of stream impairment observed (Schueler, 1994; May *et al*., 1997; Bannerman *et al*., 1993; Booth, 1991; Booth *et al*., 1996).

Limiting the amount of impervious surface in a watershed is an important component of overall watershed management. Water resource and land use managers need to be able to determine the existing percent imperviousness in order to develop appropriate watershed management and pollution mitigation plans. While much research has focused on determining the relationship between watershed impervious surface coverage and water resource impacts, little work has been done to develop methods to measure impervious surfaces at the watershed scale (Cappiella and Brown, 2001).

Generally, there are two approaches commonly used to evaluate the impervious cover (Prisloe *et al*., 2000):

1- The direct measurement approach: This is actually a physical measurement of impervious cover. The areas of all rooftops, streets, sidewalks, parking lots, and other impervious areas are measured in a subwatershed. The data is derived from actual on site survey, 'drive-by' estimation, aerial photography, or satellite imagery. Direct measurement is the most accurate method. However, it is the most expensive and time-consuming method of determining impervious cover and has very limited use for determining future impervious cover.

2- The land use approach: This approach estimates watershed imperviousness based on specific land use categories, such as low density residential, commercial, *etc.* (Cappiella and Brown, 2001; Turner and Meyer, 1991). Each land use category (*i.e.* commercial, industrial, residential, etc) can be assigned an average percent impervious cover, based on data from direct measurement studies done elsewhere or on a small portion of the study area. This approach has the advantage to be easy to build and can also be used to forecast future impervious cover at build-out by evaluating the various zoning types within the watershed and equating to a corresponding existing land use impervious cover. However, methods of this approach suffer from the lack of accuracy due to the uncertainty and fuzziness inherent in the available data used for the estimation of watershed imperviousness.

There is a need for tools to calculate watershed imperviousness that use well-documented methods and that achieve an acceptable level of accuracy by taking into account uncertainty and fuzziness inherent in the available data. These are the guiding principles behind the development of the new approach for the watershed imperviousness estimation presented in this research.

This paper presents a new impervious cover estimation methodology which allows the analyst to take into account the uncertainty inherent in the structure of information by using the fuzzy set theory. The fuzzy set and fuzzy logic provide methods for handling uncertainty and imprecision and manipulating information expressed with human words efficiently (Zadeh, 1975). This technology can be used to make a decision from vague or imprecise data since it does not require the precise specifications required by traditional computing techniques. This paper examines the application of the fuzzy inference mechanism to develop an approach for proper determination of impervious cover from uncertain and imprecise land use categories information.

The paper is organized as follows. Section 2 introduces the fuzzy inference system and the necessary elements of knowledge for impervious cover coefficient estimation. Section 3 presents an approach based on if-then rules and fuzzy inference concepts to develop the urban imperviousness estimation. An example illustrating the developed approach is presented in Section 4. Section 5 concludes this paper.

METHODOLOGY FOR IMPERVIOUS COVER ESTIMATION IN URBAN DEVELOPMENT

The percent of impervious surface varied based on the land use category and the degree of urbanization of the city or town (Brown, 2000; Sleavin, 1999). The first step of the proposed method is to define the elements of knowledge that will be used to estimate the impervious cover. These elements are related to a good knowledge of the land use. The following variables or parameters represent an example of them:

- Density of residential land use
- Density of commercial land use
- Density of industrial land use
- Density of institutional land use
- Density of mixed urban land use
- Density of utilities land use
- Density of transitional land use
- Density of bare land use

The description of these land use categories is presented in Table 1.

N.B.: Permeable soil surface as for example agricultural land use, forest, natural lakes, preserved open space, parkland, recreation areas, golf courses, etc are assumed to have impervious cover coefficient equal zero.

This approach is based on the derivation of an impervious cover coefficient for each land use category and calculating watershed imperviousness by multiplying the area of each land cover category by the impervious cover coefficients derived for each land cover type.

One can write:

$$IC_{cat} = f\,(\text{land use category})$$

Where:

IC_{cat} = the impervious cover coefficient for a land cover type
f = function to be determined

Considering the uncertainty inherent in quantifying elements that contribute to the estimation of impervious cover for each land use category and considering the difficulty of the identification of the function (f), it was preferred to explore a fuzzy reasoning approach (Karnib *et al*., 2002; Yan *et al*., 1991; Kim, 1990; Han and Tschangho, 1997). The idea of fuzzy reasoning is to express the modelling of the system in a simple, natural-language-like form. Instead of ordinary functional relationships, fuzzy inference rules are used. To construct a model for fuzzy reasoning, the range of each variable is divided into k linguistic values, for example *low, medium* and *high* as shown in Figure 1. Each of these linguistic values is represented by fuzzy set and its membership function $\mu(x)$, which can take values between 0 and 1 (Mizumoto 1988; Mamdani 1977; Zadeh 1975). In this study, we have used fuzzy sets of the trapezoidal type; in this mode of representation, the membership function is defined by 5 parameters (m, n, α, β, h) and two functions L (left) and R (right) (Figure 2).

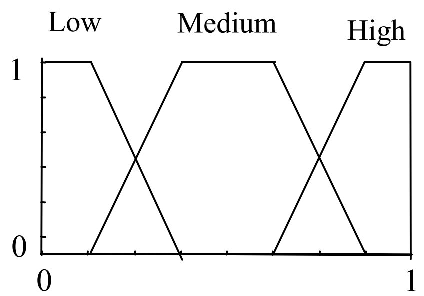

Figure 1. Density of a land use category.

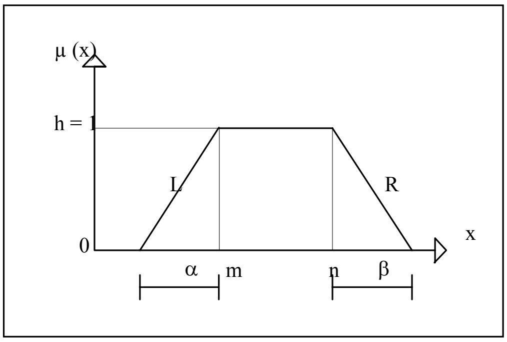

Figure 2. Fuzzy set of a trapezoidal type.

The first type of uncertainty, which is the imperfect information, can be expressed in the concept of fuzzy sets themselves (Parkinson and Duerre, 1993). For example, if we consider the fuzzy set *low* and variable *Density of Residential Land Use* (*DRLU*), to what degree do we believe that *DRLU* is *low*? *μ(DRLU* = 25%) = 0.5 means that the value 25% for *DRLU* can be said to be *low* to the extent 0.5.

In addition to fuzzy sets, inference rules are also defined. The fuzzy inference rule can process the second type of uncertainty relates to the imperfection of rules (Ramsey et. al., 1986). For example, if we consider the following rule: if *density of residential land use* is *low* then *impervious cover coefficient* is *average*, to what degree do we believe that the *impervious cover coefficient* should be *average* given that the *density of residential land use* is *low*? This type of uncertainty could be expressed by the concepts of fuzzy inference (Mamdani, 1977).

The fuzzy inference allows to determine the outputs of the system from fuzzy inputs and fuzzy rules. The principle of fuzzy inference is based on Mamdani method (Mamdani, 1976) (Tong Tong, 1995). We present here an illustration of the method on an example of two input variables and one output variable (Figure 3):
Let us take the following two rules:

If X_1 *is* A_{11} *and* X_2 *is* A_{12} then Y *is* B_1
If X_1 *is* A_{21} *and* X_2 *is* A_{22} then Y *is* B_2

The elements A_{11}, A_{21}, A_{12}, A_{22} are the fuzzy qualification (*low, medium, high*) of premises X_1 and X_2 (which are the measured values in our case), B_1 and B_2 are the fuzzy qualification of the output Y (which is the impervious cover coefficient in our case) which have respectively the following membership functions:

$\mu_{A11}(x_1)$, $\mu_{A21}(x_1)$, $\mu_{A12}(x_2)$, $\mu_{A22}(x_2)$, $\mu_{B1}(y)$ *and* $\mu_{B2}(y)$.

In practice if x_{01} and x_{02} represent values attributed to X_1 and X_2, then the characteristics of the output (or conclusions of rules) become $\mu_{B'1}(y)$ and $\mu_{B'2}(y)$; they are calculated from the previous membership functions.

By applying the inference method of Mamdani, we can write:

$$\beta_1 = min\ [\mu_{A11}(x_{01}), \mu_{A12}(x_{02})] \quad (1)$$

and

$$\beta_2 = min\ [\mu_{A21}(x_{01}), \mu_{A22}(x_{02})] \quad (2)$$

The results of the two rules inference (the possibilities that Y been $B'1$ and Y been $B'2$) are calculated by :

$$\mu_{B'1}(y) = min\ (\beta_1, \mu_{B1}(y)) \quad (3)$$

$$\mu_{B'2}(y) = min\ (\beta_2, \mu_{B2}(y)) \quad (4)$$

The global fuzzy output (B^*) is given by the maximum of the previous function :

$$\mu_{B^*}(y) = max\ [\mu_{B'1}(y), \mu_{B'2}(y)]\ \forall\ y \in \Re \quad (5)$$

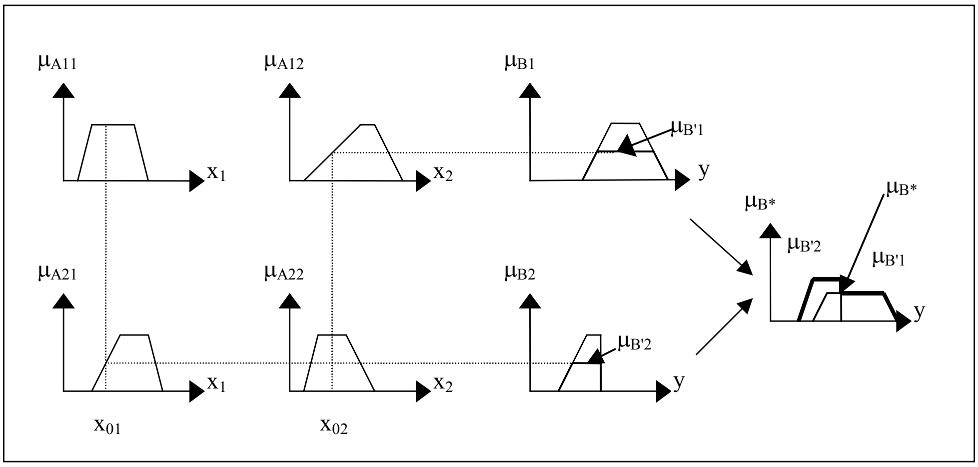

Figure 3. Graphical representation of the Mamdani method.

Steps of reasoning

The principle of fuzzy inference goes through the following steps:

1- Fuzzify inputs: Resolve all fuzzy statements in the antecedent to a degree of membership between 0 and 1. If there is only one part to the antecedent, this is the degree of support for the rule.

2- Apply fuzzy operator to multiple part antecedents: If there are multiple parts to the antecedent, apply fuzzy logic operator *min* and resolve the antecedent to a single number between 0 and 1. This is the degree of support for the rule.

3- Apply implication method: Use the degree of support for the entire rule to shape the output fuzzy set. The consequent of a fuzzy rule assigns an entire fuzzy set to the output. This fuzzy set is represented by a membership function that is chosen to indicate the qualities of the consequent. If the antecedent is only partially true, (i.e., is assigned a value less than 1), then the output fuzzy set is truncated according to the implication method.

4- Aggregate all outputs: Aggregation is the process by which the fuzzy sets that represent the outputs of each rule for each impervious cover coefficient (for each land use category) are combined into a single fuzzy set. The input of the aggregation process is the list of truncated output functions returned by the implication process for each rule. Notice that as long as the aggregation method is commutative (which it always should be), then the order in which the rules are executed is unimportant.

In this study we use a simpler 1 - 1 rule scheme, this can improve the clarity of the rule structure. Nevertheless, the rule antecedent in the proposed inference system can have one or multiple parts. All parts of the antecedent are calculated simultaneously and resolved to a single number between 0 and 1 by using the application of fuzzy operator and implication method.

In the following section we present the application of this rules inference method to the estimation of the impervious cover coefficient.

DEVELOPMENT OF FUZZY INFERENCE SYSTEM FOR THE ESTIMATION OF IMPERVIOUS COVER COEFFICIENT

In this section we will present the fuzzy inference system that allows the determination of the impervious cover coefficient using the method presented in section 2. This system has been implemented in the 'MATLAB' environment (Roger Jang and Gulley, 1995).

The basic structure of the system is presented in Figure 4.

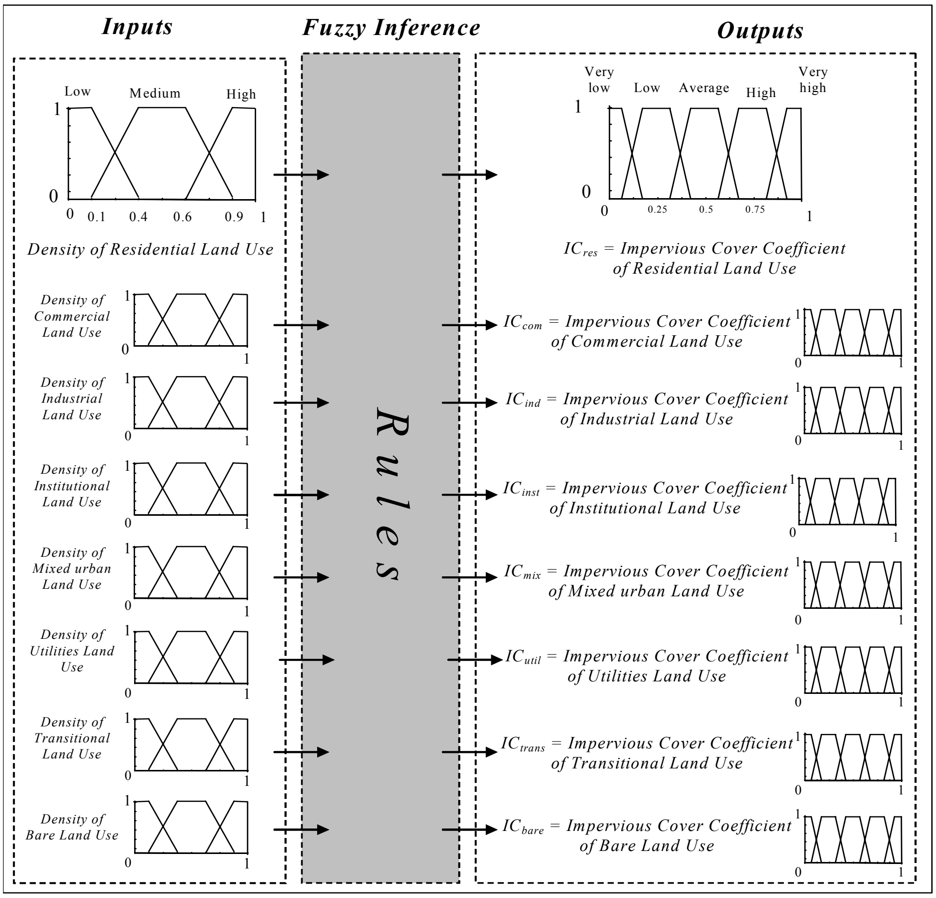

Figure 4. The basic structure of the fuzzy inference system.

The analyst must determine for each land use category, depending on the nature of this, the input variables which take values between 0 and 1 raging from the low to high density of land use category. Table 1 presents a guide to set these values.

TABLE 1
Description of the Different Land Use Categories

Density of land use	Description	Low density	High density
Residential L.U.	Lands containing structures used for human habitation, including associated yards and parking areas.	Lands used for housing residents in single-family dwelling units.	All lands devoted to housing more than one family on a permanent or semipermanent basis and their associated grounds.
Commercial L.U.	Areas used primarily for the sale of products and services, including associated yards and parking areas.	Includes individual stores and services of various sizes and associated grounds and parking. Includes small movie theaters, gas stations and auto repair shops	Includes shopping malls, retail "outlet centers," and "superstores" that draw clientele from a regional area.
Industrial L.U.	Manufacturing and industrial parks, including associated warehouses, storage yards, research laboratories, and parking areas.	They are generally "individual" and "clean" industries that do not produce large amounts of waste materials.	Use this category for heavy industry where lots of warehouses, storage yards, research laboratories, and parking areas are used.
Institutional L.U.	Specialized government or private features that meet the educational, religious, medical, governmental, protective, and correctional needs of the public. Parking lots and associated grounds are included.	Includes individual buildings and associated grounds and parking.	Consists of extremely large single buildings or a complex of large buildings and their parking lots.
Mixed Urban L.U.	Developed areas with a mixture of residential and nonresidential features. This category is used when more than one-third of the features in an area do not fit into a single category.	Includes a mixture of single family dwelling units and individual nonresidential features	Includes a mixture of multiple dwelling units and complex of nonresidential large buildings.
Utilities L.U.	Structures or facilities and associated grounds used for railroads, airports, ports, power generation, communications, treatment or storage of drinking water, waste management etc.	Includes individual buildings and associated grounds and parking.	Consists of extremely large single buildings or a complex of large buildings and their parking lots.
Transitional L.U.	Areas dynamically changing to another land use/land cover. Includes all construction areas and urban renewal areas that are in a state of transition.	Depends on the nature of the original land cover, the new land cover and the transition progress percentage.	Depends on the nature of the original land cover, the new land cover and the transition progress percentage.
Bare L.U.	Undeveloped areas of Earth not covered by water that Earth's surface may be composed of bare soil, rock, sand, gravel, salt deposits, or mud.	Depends on the nature of the soil cover.	Depends on the nature of the soil cover.

In this study, a set of 24 rules (presented in table 2) are used to show the applicability of the proposed system on a real case study. These rules are subject to refinement in parallel with the adjustment of membership functions for the input and output parameters.

TABLE 2
The Rules Used for the Application of the Proposed Fuzzy Inference System

If	*Density of residential land use*	is	Low	then	IC_{res}	is	Average
			Medium				*High*
			High				*Very high*
If	*Density of commercial land use*	is	*Low*	then	IC_{com}	is	*Average*
			Medium				*High*
			High				*Very high*
If	*Density of industrial land use*	is	*Low*	then	IC_{ind}	is	*Average*
			Medium				*High*
			High				*Very high*
If	*Density of institutional land use*	is	*Low*	then	IC_{inst}	is	*Average*
			Medium				*High*
			High				*Very high*
If	*Density of mixed urban land use*	is	*Low*	then	IC_{mix}	is	*Average*
			Medium				*High*
			High				*Very high*
If	*Density of utilities land use*	is	*Low*	then	IC_{util}	is	*Low*
			Medium				*Average*
			High				*High*
If	*Density of transitional land use*	is	*Low*	then	IC_{trans}	is	*Low*
			Medium				*Average*
			High				*High*
If	*Density of bare land use*	is	*Low*	then	IC_{bare}	is	*Very low*
			Medium				*Low*
			High				*Average*

Before presenting the steps of reasoning of the system, the following remarks must be noted:

- The information regarding input variables of the system are determined by the analysts and the planners depending on their knowledge of their cities or towns.

- The proposed approach has been designed to accept a variety of land use and land cover source information, as well as locally-calibrated impervious cover coefficients.

The calculation of the (IC_{cat}) value for each land use category goes through the steps defined in the previous section.

The outputs of the proposed fuzzy inference system are impervious cover coefficients (percentage) IC_{cat} for each land use category. These results are non normalized fuzzy impervious cover coefficients.

The impervious surface of each land use category is then calculated by:

$$IS_{cat} = IC_{cat} * A_{cat} \tag{6}$$

Where:

IS_{cat} = Impervious surface of a given land use category
A_{cat} = Area of the land use category

The watershed total imperviousness is calculated by:

$$IS = \sum IS_{cat} \tag{7}$$

The average impervious cover coefficient (percentage) IC_{av} for the total area under consideration could be calculated by :

$$IC_{av} = IS \,/\, A_t \tag{8}$$

Where:

$$A_t = \sum A_{cat}$$

The calculation of the watershed total imperviousness (IS) as presented in equation (7) necessitates to make the summation of non normalized fuzzy sets. Giachetti and Young, 1997 and Dubois and Prade, 1985 gave overviews of approaches to performing fuzzy arithmetic. The most appropriate method for summation of non normalized fuzzy sets is to perform interval arithmetic at discrete α-cuts on the fuzzy numbers. As such they can operate on any membership function. The approach is to discretize the membership functions into closed intervals at each α-cut, then perform interval arithmetic at that α-cut. The results are combined and the output is a discretized membership function. This method has a drawback in its computational complexity which is function of the number of discretized points. Another simple method was proposed by (Dubois and Prade, 1985) which could be used to perform fuzzy summation on any trapezoidal shape (normalized or non normalized) as follows:

Given two trapezoidal fuzzy sets $s_i = (m_i, n_i, \alpha_i, \beta_i, h_i)$ and $s_j = (m_j, n_j, \alpha_j, \beta_j, h_j)$. The fuzzy quantity $(s_i + s_j)$ is a trapezoidal fuzzy set (m, n, α, β, h) where:

$$h = \min(h_i, h_j);$$

$$\alpha = h \cdot \left(\frac{\alpha_i}{h_i} + \frac{\alpha_j}{h_j}\right); \qquad \beta = h \cdot \left(\frac{\beta_i}{h_i} + \frac{\beta_j}{h_j}\right);$$

$$m = m_i + m_j - \alpha_i - \alpha_j + \alpha; \qquad n = n_i + n_j + \beta_i + \beta_j - \beta$$

In this study, we approximate any resulting fuzzy set to a trapezoidal set (Romaniuk, 1993) in order to use the described Dubois and Prade method.

The result obtained for (IS) is a non normalized trapezoidal fuzzy set value of the total imperviousness. The analyst could keep the fuzzy nature of this value for further applications in urban planning where uncertainty and fuzziness are inherent in other urban elements of knowledge. However, if a crisp value of (*IS*) is sufficient for a given application, we could use the centroid calculation of fuzzy sets (defuzzification), which returns the centre of the functions $\mu(x)$. Given the fuzzy functions $\mu(x)$, x_0 is the centroid point:

$$x_0 = \frac{\int \mu(x)x\,dx}{\int \mu(x)\,dx} \qquad (9)$$

ILLUSTRATIVE EXAMPLE OF APPLICATION

This section describes an application of the system to an example of impervious cover estimation in order to examine the various steps of our methodology in an actual case.

The study concerns the estimation of the impervious cover of the 3.5 Km^2 of the southern suburbs of Beirut City watershed. The estimation of the impervious cover of southern suburbs watershed was processed in order to provide to the municipal and watershed planners with a tool to evaluate the impacts of development on the environment.

The values of the input variables are determined depending on the nature of the existing urban land use of the region and they are presented in table 3.

TABLE 3
Values of the Input Parameters

	Density	Area (Km^2)
Residential land use	0.75	1.5
Commercial land use	0.2	0.3
Industrial land use	0	0
Institutional land use	0.5	0.2
Mixed Urban land use	0.5	0.4
Utilities land use	0.25	0.1
Transitional land use	0.4	1
Bare land use	-	0
Pervious land	-	0

The application of these values in the proposed fuzzy inference system leads to the fuzzy impervious cover coefficients for each land use category. The obtained results are presented in Figure 5.

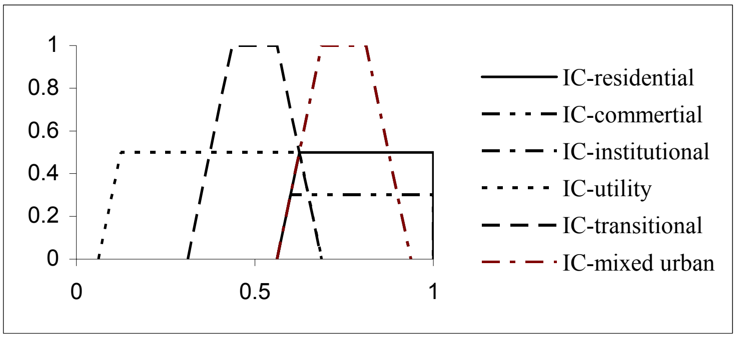

Figure 5. Graphical representation of fuzzy impervious cover coefficients.

These results could be then used to estimate the total imperviousness and the average impervious cover coefficient of the entire watershed under consideration by using equations 6, 7 and 8. The obtained results are presented in figures 6 and 7.

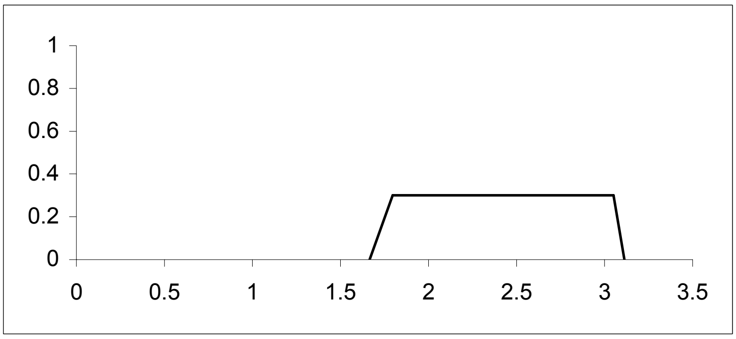

Figure 6. Graphical representation of the total fuzzy imperviousness *IS* (Km^2).

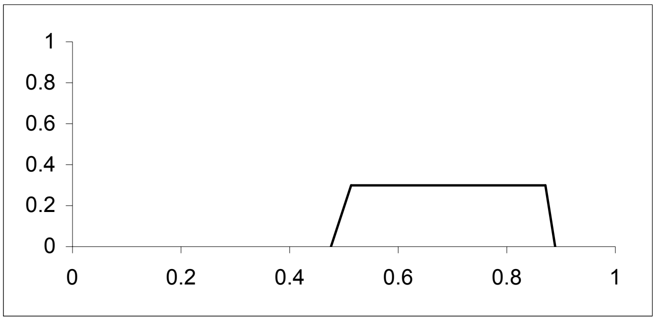

Figure 7: Graphical representation of the average fuzzy impervious cover coefficient IC_{av} (%).

These fuzzy results can then be used by water resource and land use managers in order to develop appropriate watershed management and pollution mitigation plans where other fuzzy parameter could be introduced. However, when crisp values of total imperviousness and impervious cover coefficient are sufficient for managers, the obtained fuzzy values could then be defuzzified using equation (9) which leads to total impervious surface IS = 2.4 Km^2 and average impervious coefficient IC_{av} = 68.5 %.

CONCLUSION AND FURTHER DEVELOPMENT

The watershed imperviousness is directly linked to the amount of urban runoff and its impact on stream conditions and water quality. Water resource and land use managers need to be able to determine the existing percent imperviousness in order to develop appropriate watershed management and pollution mitigation plans. The direct measurement method for the estimation of the impervious cover coefficient suffers from being expensive and time-consuming method and has very limited use for determining future impervious cover. However, methods based on land use analysis have the advantage of being easy to build and can also be used to forecast future impervious cover. The difficulty encountered stem from the lack of accuracy due to the uncertainty and fuzziness inherent in the available data used for the estimation of watershed imperviousness. A method has been proposed here which allows the evaluation of watershed imperviousness based on land use system approach using if-then rules and fuzzy inference concepts. The method allows each land use category to be quantified in terms of its impervious cover coefficient.

This method may also be used for other applications such as the estimation of the runoff coefficient by taking into account uncertainties related to the land cover in urban areas. This method allows also a new opportunity in watershed management by taking into account the qualitative and quantitative knowledge of land covers of urban areas.

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