PERFORMANCE EVALUATION OF IRRIGATION TECHNIQUES THROUGH THE IMPLEMENTATION OF A FUZZY LOGIC SYSTEM

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ABSTRACT

This paper presents a new methodology for evaluating the performance of irrigation systems, taking into account indicators of efficient use of water resources and tools for intelligent systems such as fuzzy logic. The objective was to propose a fuzzy logic system as a tool to evaluate the performance of irrigation systems, from a set of indicators of efficiency of water use. The system was validated for the cultivation of cocoa (*Theobroma cacao*) in the climatic conditions of the north part of Huila state, Colombia. Treatments (T) were: T1: drip irrigation, T2: surface irrigation, T3: control without irrigation. The experimental design was completely randomized block with three replicates per treatment. The Fuzzy Logic Toolbox of Matlab (*MathWorks*) was used to implement the fuzzy logic system. The output variable of the system was the performance of the irrigation system (%) and the input variables were index rate income from irrigated area cultivated ($ ha^{-1}) and the Relative water supply. The results of the study show that cocoa cultivation and under the climatic conditions of the north of Huila, the technique of surface irrigation performance has a "High" (91.3%), on the contrary treatment without irrigation presents a performance "Low" (17%) and drip irrigation has a performance "Medium" (50%). This type of system as implemented in the agricultural sector and specifically in the evaluation of irrigation systems tools are innovative and can help decision making of professionals in such sector.

Keywords: irrigation techniques, cocoa (Theobroma cacao), fuzzy logic, mamdani type system, dry areas, irrigation water use efficiency.

1. INTRODUCTION

Cocoa (Theobroma cacao) is one of the most important perennial type cultivation in the world, with an estimate world production of 3.6 million of tons (FAO, 2012). In Colombia the national yield of cocoa is estimated at 34.929 tons (DANE, 2011). However, the mean yields of cocoa in Colombia are very low, 0.48 t ha^{-1} (Espinal, *et al*., 2005), while in the world the commercial yields are between 1.5 - 2.7 t ha^{-1} (Diczbalis, *et al*., 2010). This figures show the technological gap existing in the Cocoa cultivation in Colombia. At regional level, Huila has a menace regarding food production due to a decrease in rainfall intensity mainly in the north part. According to projections of the Second Communication of the Climate Change of IDEAM, the northern part of Huila will have a decrease of 30% in rainfall. In other words and according to climate change scenarios formulated by the Intergovernmental Panel on Climate Change - IPCC (Scenario A2), Huila will be drier than it is today. Nowadays, the northern part of Huila has a mean rainfall of 900 mm year^{-1} and according to projections rainfall would be of 630 mm year^{-1} which may speed up the expansion of dry area. In this context, Huila will have to adapt itself to new climate conditions improving its management strategies of water resource (Ruiz, 2010). Inadequate management of water - soil resources in agriculture and the uncertainty about climate changes pose a risk to food safety of peoples (Steduto, *et. al*., 2012). Therefore, it is necessary to implement irrigation systems and efficiently used strategies of water resource to assure food safety in regions and environment sustainability (Villalobos, *et al*., 2000).

Northern part of Huila has a bimodal rainfall regime, mean temperatures are over 28°C, relative humidity is 64%, precipitation of 9000 mm year^{-1}, evaporation of 2000 mm year^{-1} (Olaya, 2006). A limiting factor of cocoa production is water resource availability. Nevertheless, at present market provides different irrigation technologies that are widely adopted in the world but these technologies are of little acceptance in Colombian and specifically in cocoa crop, sometimes because of lack of knowledge, for economic reasons, etc. Notwithstanding, farmers worldwide receive an economic benefit when implementing an irrigation system (Moreno, *et al*., 2000). For instance, Lee (1975) carried out an irrigation experiment with cocoa in Malawi and found a mean yield of 2200 kg ha^{-1}. In turn, Hutcheon *et al*. (1973) had yield increase by 12, 17 and 40% in an experiment in Ghana - Africa. Likewise, Huan *et al*. (1986) reported results of a drip irrigation experiment in Malaysia, and found a yield increase from 1500 to 2400 kg ha^{-1}, that is to say, an increase of 60% in production. Irrigation technology advancements represent a decrease in water and energy for farmers, reduction of management practices of irrigation system and an increase in cultivation yield (Golden and Peterson, 2006). Despite this, irrigation technologies require an evaluation and subsequent adaptation to local conditions. It is here where performance rates of irrigation systems are of importance. An adequate performance evaluation of irrigation technologies reveals management strategies in the evaluated systems.

In fact, the International Water Management Institute (IWMI) proposed a set of nine indicators to

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compare the agricultural irrigation systems (Molden *et al*., 1998). Furthermore IWMI methodology was modified by Sanchez *et al*. (2006) and it was implemented in different Mexican cultivations. Garcia (2007) also proposed a methodology to make an economic evaluation of irrigation systems but including the irrigation water efficiency variable; this methodology was implemented in fruit trees. On the other hand, approximations to modeling studies have required and require nowadays new abstractions allowing to improve our nature predictive skills and consequently strive for a sustainable development (Obregon, 2001). The application of the so-called intelligent systems in Agricultural Sciences studies is relatively recent in comparison to other knowledge areas like electronic engineering, electric engineering, mechatronics and telecommunications. Huang *et al*. (2010) sustain that intelligent systems are an integration of biological structures with computing techniques. These systems are used to reach handling, robustness and low cost solutions with some degree of tolerance and imprecision, uncertainty and approximations. These characteristics make intelligent systems capable of solving problems which are not efficiently solved by conventional tools. According to Kosko (1992) accelerated progress in computer technology is an important support to implement artificial intelligence in several real world applications, using smart technologies such as: expert systems, fuzzy systems (FS), artificial neural networks (ANN), genetic algorithms (GA) and approximations of chaos theory, decision trees, among others. In agricultural sciences worldwide fuzzy logic is used for modeling and prediction, control, classification, fuzzy clustering, rule-based inference, multisensory data fusion, optimization (Huang *et al*., 2010). Moreover, in the cultivation of cocoa only the development of a multimedia application of web access to irrigation control was found; this experience uses decision trees to schedule irrigation in Ecuador. (Alvarado *et al*., 2012).

Finally, this study was aimed at implementing a fuzzy logic system as a tool to evaluate the performance of irrigation systems from a set of indicators of efficient water use. The system was validated at potential level for three irrigation treatments in cacao planting under climatic conditions of the northern area of Huila.In this paper, T and wedge geometry conditions, wedge angles and well locations were simulated to observe pressure behavior and identify unique characteristics for each system so an analytical methodology using the log-log plot of the pressure and pressure the derivative versus time is formulated and successfully tested with simulated cases.

2. MATERIALS AND METHODS

This study was carried out in 2013 in the northern part of Huila, municipality of Baraya, in a rural area called La Unión, farm San Jose. The experimental place is at 3° 16’ N y 74° 56’ W, at 561 m.a.s.l, in an 8 year cocoa cultivation. Vegetable materials like ISC-31, ISC-60 and ISC-51 were identified, with a 3 x 3m three-small balls planting system, and a mean yield of 400 kg ha^{-1}. Soil of alluvial valleys of dry and very dry climate (VX); correspond to kind of relief of small farms, terraces and slopes that are formed from alluviums of varying granulometry. Topography ranges from flat to gently undulate, with slopes ranging from 0.3% and 7%, texture is sandy loam with moderate depth and average density is 1.46 g cm^{-3}. Field capacity and permanent wilting point are 33.71% and 15.21%, respectively. The soil has good internal and external drainage and good effective depth.

2.1. Water balance

Climatic data were taken from Santo Domingo weather station run by IDEAM. To estimate water balance it was used multiannual monthly mean precipitation, effective precipitation, evaporation, evotranspiration and Kc Coefficient of cultivation (Allen, *et al.* 1998). Treatments (T) were: T1: drip irrigation, T2: surface irrigation, T3: control without irrigation. The experimental design was fully-randomized blocks with three replicates per treatment. Initially applied irrigation was 5 mm d^{-1}.

2.2. Yield estimate

To quantify harvest ripe corncobs were counted in each tree. After six-month monitoring, irrigation impact on long-term cocoa yield was projected, according to Cocoa Federation - Regional Huila technicians’ knowledge (Table-1).

2.3. Indicators for comparing performance of irrigated agricultural systems

Evaluation of irrigation systems performance helps in the identification of irrigation infrastructure needs, detection of technology and research transfer needs and the improving of the operation of the system (Moreno, *et al*. 2000; Sánchez, *et al*. 2006). According to Molden *et al.* (1998) a set of indicators is presented. These indicators show the product of the cultivation per unit of water and land which are the basis for comparing productive and economic performance of the irrigation systems evaluated.

2.3.1. Output per cropped area (I_{ac})

The importance of this rate lies in knowing the productivity of agricultural area evaluated.

$$I_{ac} = \frac{R}{A} \qquad (1)$$

2.3.2. Relative water supply (RAW)

It is an index that quantifies the relation between offer and demand of water. This value is the opposite of the traditional term. “Efficiency of water use - EUA” It shows a neutral overview of relation between amount of water supplied and amount used for production of cultivation (Sánchez, *et al*., 2006).

$$RWS = \frac{V}{E_t} \qquad (2)$$

2.4. Design of fuzzy logic system

When input information is not precise, vague, incomplete, ambiguous or noisy, fuzzy logic is a tool that allows arriving at a conclusion in a simple way, trying to simulate expert knowledge of a human being. The procedure began choosing input variables for the system (indexes), analyzing available indexes and selecting: Output per cropped area (IGAR) and Relative water supply (RWS). It was also selected the output variable of the system: irrigation system performance, for each of the system variables it was established an action range according to literature review. Then, qualitative labels were defined per each range of the system variables. Definition of labels followed criteria of simplicity and ease in order to facilitate the acquisition of the system rules. To formulate rules of fuzzy system it was conducted interviews addressed to an expert on the subject, constructing scenarios where possibilities of input variables are combined. Later, it was used Toolbox Fuzzy Logic de Matlab to structure the fuzzy logic system, where membership, ranges, active rules functions were chosen; likewise, response functions are analyzed and the system is verified. Moreover, pilot tests are performed to evaluate predictive capacity of the model through controlled experiments.

3. RESULTS

3.1. Water balance

Figure-1 shows a pattern characterized by occurrence of two rainy periods and two dry periods. These precipitation patterns are typical of northern part of Huila. The first rainy period is less intense than the second one.

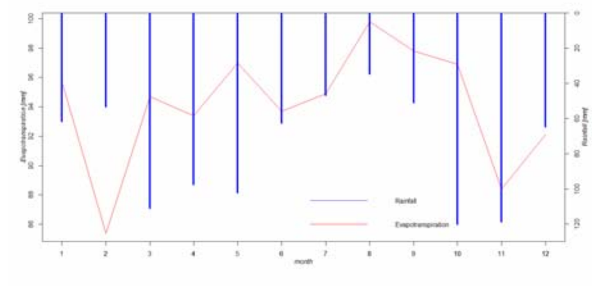

Figure-1. Climatic water balance of Baraya, Huila, Colombia.

Rainy season of year begins in March and goes to May, being more prolonged and homogenous, with rainfall less than in the second period; monthly average values ranging between 97 mm and 112 mm. The second period of heavy rain takes place in October and November, being shorter and heavy; with monthly average values ranging between 118 and 120 mm. The first dry period or summer is less intense than the second one and begins in December and goes to the end of February, with average values of monthly rainfall ranging between 53 mm and 64 mm; next drought period begins in June and ends in September, with monthly average rainfalls ranging between 34 mm and 62 mm. Total multiannual rainfall of season shows a value of 924 mm. October has the highest rainfall, with a value of 120.16 mm, August has the lowest rainfall, with a value of 34.67 mm. Periods of water deficit coincide with drought periods. The first deficit period is from December to February and the second one from June to September which is more intense and longer.

3.2. Efficiency rates of water use in the north of Huila

Efficiency indicators of water use (Table-1) were applied to climatic conditions of northern area of Huila. Values are estimated unitarily per hectare per year. Production data are annual average values reported in the Agricultural Statistical Yearbook 2012.

Table-1. Rates estimate of water use efficiency in the north of Huila.

Input data	**T1: Drip Irrigation**	**T2: Surface Irrigation**	**T3: Without irrigation**
Irrigation crop area (ha)	1	1	1
*Production ($):	$6, 776, 700	$3, 430, 000	$2, 450, 000
Crop demand (m^3):	24,200	54, 450	10, 310
Implementation cost por hectare	$5, 925, 000**	$611, 000	$0
Total water supply (m^3):	21, 780	21, 780	21, 780
Estimate of indexes			
Output per cropped area ($ ha^{-1})	6, 776, 700	3, 430 ,000	2, 450, 000
Relative water supply ()	1.11	2.50	0.47

*Cocoa production data estimated by Mr. Rafael Maecha FEDECACAO Technical Coordinator. The value of kg of cocoa was assumed to $ 4900 ** Cost evaluated for the irrigation system for micro-hose (Chavarro, 2013).

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In Table-1 there is a difference between income rate indexes per area of irrigation cultivated, especially between T1: drip irrigation and T2: surface irrigation, which is two times higher. In that sense, the surface irrigation option would have a higher profit margin, specifically, if high costs of implementation of drip irrigation are taken into account. Regarding Relative water supply (RWS), values less than unit show the deficiency of water to satisfy water requirements of cultivation; therefore, it was not reached maximum performance per surface unit. A high value of RWS means high losses by conduction or there is excessive watering, which is evidenced in the surface irrigation treatment. On the contrary, a RWS less than 1 means the need to assist the system by using pumping to meet demand (Sánchez, *et al.* 2006). It also may means that water offer available in the area does not meet the water requirements of cocoa cultivation which is evident in the north of Huila. In this regard, it would be necessary to implement an irrigation system if the cultivation has stress symptoms or shift cultivation by one more resistant to water stress.

3.3. Implementation of fuzzy logic system

A Mamdani-type fuzzy logic system was designed based on the tool Fuzzy Logic Toolbox of Matlab to evaluate the performance of the irrigation system according to the index of Output per cropped area (IGAR) and Relative water supply (RWS) for the cocoa cultivation in climatic conditions of the north of Huila (Figure-2).

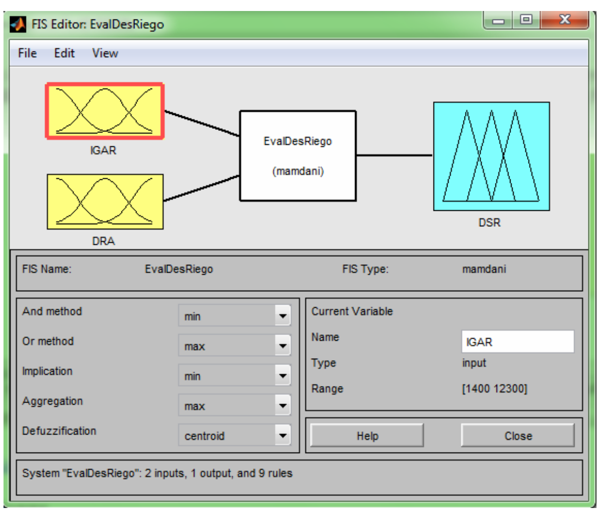

Figure-2. Fuzzy inference system to evaluate the irrigation system performance.

3.3.1. Input variables

The selected input variables were expressed in linguistic labels, discourse or range universe was defined, membership functions and subranges (Table-2) based on expert knowledge.

Table-2. Characteristics of input variables of fuzzy logic.

Input variable	Index of income rate per area of irrigation cultivated (IRIA) [$ ha^{-1}]	Relative water supply (RWS) []
Range:	1400- 12250*	0-5
Classification:	BAJO: 1470 -2935	BAJO: 0.1 - 0.99
	MEDIO: 2940 - 8815	MEDIO: 1 - 2
	ALTO: 8820 - 12250	ALTO: 2.1 - 4
Membership function:	Triangular	Triangular

*Values in thousands

Triangular-type membership functions were selected for fuzzy system because they adequately represent the discourse universe and are easy to implement. Moreover, they only need three parameters: lower limit, upper and a modal value.

3.3.2. Output variables

As in input variables, output variables were expressed in linguistic labels, discourse universe or range was defined; membership functions and subranges (Table-3).

Table-3. Characteristics of output variables of fuzzy system.

Output variable	Irrigation system performance (ISP)
Range	0 - 100 %
Classification:	LOW: 10 - 49
	MEDIUM: 50 - 79
	HIGH: 80 - 99
Membership function:	Triangular

Figure-3 shows an example of interface to define characteristics for output variable, performance of the irrigation system.

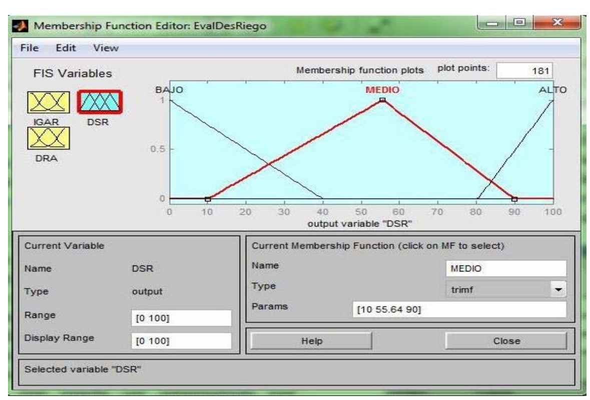

Figure-3. Functions of membership of output variable DSR.

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Defining the performance of the irrigation system is a complex task due to the great amount of variables involved (costs, production increase, water efficiency, energy efficiency, etc.); nevertheless, in this work it was selected the economic aspect, that is to say, the impact of irrigation system on production increase and on the other side, the Relative water supply, which is an indicator of water efficiency. Moreover, it is necessary to say that labeling the system output in only three options (high, medium and low) is very limited due to the system complexity. However, it facilitates interpretation of results and the making of rules for the fuzzy system. According to the above mentioned statements, performance of system of high irrigation can be interpreted as the one that efficiently uses the water resource and maximizes the increase in production and hence increase in economic income for farmers. On the contrary, performance of system of low irrigation is one that does not use efficiently the water resource and increase in production is not significant.

3.3.3. Rule base

System rules were designed by an expert in the subject by means of an interview (Table-4).

Table-4. Rule base defining performance of an irrigation system.

	Input variables		Output
No.	**IRIA**	**RWS**	**DSR**
1	LOW	LOW	LOW
2	LOW	MEDUM	HIGH
3	LOW	HIGH	LOW
4	MEDIUM	LOW	LOW
5	MEDIUM	MEDIUM	HIGH
6	MEDIUM	HIGH	MEDIUM
7	HIGH	LOW	MEDIUM
8	HIGH	MEDIUM	HIGH
9	HIGH	HIGH	MEDIUM

Rules are implications defined by means of a conditional statement of the if-then form and a logical operator that in this case is And. Figure-4 shows response surface of the fuzzy system.

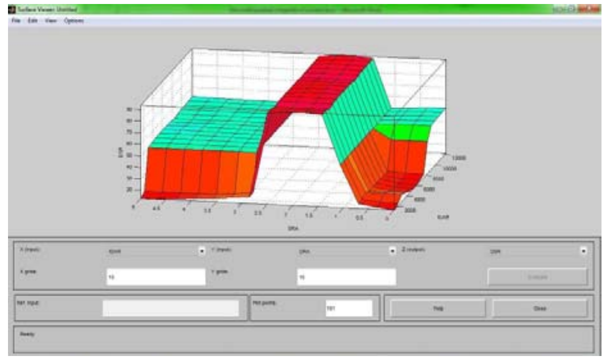

Figure-4. Three-dimensional diagram of the fuzzy system.

Figure-4 shows the system complexity, because response surface is not related to linearity conditions.

3.3.4. Evaluation of system

Once input variables are defined, the output variable and rule base are defined, it is possible to evaluate the designed system. For instance, for treating the drip irrigation, the input variables are: Output per cropped area (IGAR) = 6776 and Relative water supply (RWS) = 1.11. When executing the system of fuzzy logic rules 4, 5 and 6 were activated (Figure-5), resulting as output variable the performance of the irrigation system (PIS) [%] = 50.

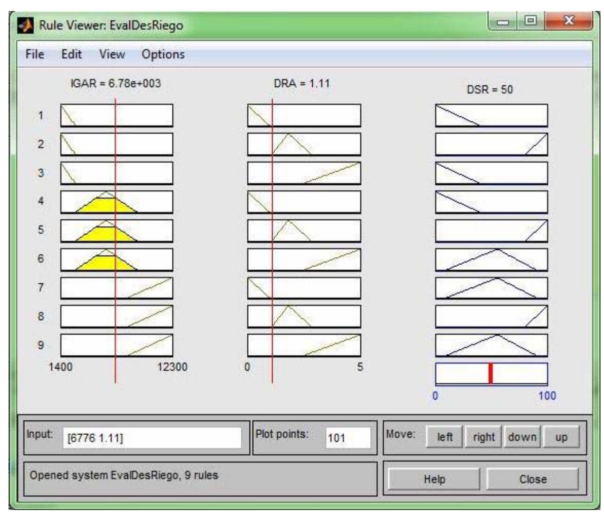

Figure-5. Evaluation of the system for drip irrigation.

Table-5 shows the results of the evaluation of fuzzy system for the three treatments evaluated. The T3: (control without irrigation) has a system performance of "low" irrigation (17%) because the rainfall regime of the northern area of Huila does not meet the water requirements of cocoa cultivation which, according to Carr and Lockwood (2011) are of 1300 - 2800 mm per year; while the total multiannual rainfall in the area is of 924 mm per year presenting a difficult situation of water deficit.

Table-5. Evaluation of fuzzy logic for the three treatments.

VARIABLES		T1: drip irrigation	T2: Surface irrigation	T3: control without irrigation
input	Income rate per area of irrigation cultivated ($/ha)	6776	3430	2450
	Relative availability of water()	1.11	2.5	0.47
output	Performance of irrigation system (%)	50	91.3	17

On the contrary, the T2 (drip irrigation) presents a better “high” performance (91.3%) because costs of irrigation technique implementation is much lower (-50%) in comparison to drip irrigation, and there is a gain margin higher than drip irrigation. However, this irrigation technique does not make efficient use of water resource.
Later, the T1 (drip irrigation) presents a “medium” (50%) performance of the irrigation system, despite the drip irrigation is the technique that makes the most efficient use of water resource, implementation costs are very high in comparison to the other irrigation techniques. Besides, the gain margin of drip irrigation is lower in comparison to surface irrigation. For the above, drip irrigation is considered an irrigation system of medium performance.

4. CONCLUSIONS

A methodology to evaluate the performance of irrigation systems is proposed, taking into consideration indicators of efficient use of water resource and tools of intelligent systems like fuzzy logic. The results of the study show that the set of indicators proposed is a basis to compare the productive and economic performance of the irrigation systems in Colombia which can help in the identification of infrastructure needs for irrigation, detection of needs for technology transfer and research and the improvement of the system operation.

A system of fuzzy logic was implemented in order to estimate the performance of an irrigation system based on the index of Output per cropped area and Relative water supply. This type of tool implemented in the agricultural sector and specifically in the evaluation of irrigation systems are innovative and can help in the making of decisions for the agricultural professional.

For the cocoa cultivation in the climatic conditions of the north of Huila, the drip irrigation technique presents a “High” performance (91.3%), on the contrary, the treatment without irrigation has a “Low” performance (17%) and drip irrigation has a “Medium” performance (50%).

Water stress in the north of Huila is a strong limitation for the cocoa producers. This area has two periods of water deficit. The first one from December to February and the second one, more intense and longer, from June to September. Total multiannual rainfall of the area is of 294 mm year^{-1}. This condition limits the cultivation yield because the recommended rainfalls for the good development of the cultivation are of 1300 - 2800 mm year^{-1}.

Nomenclature

I_{ac}	Output per cropped area, \$ ha^{-1}
A	Irrigation crop area, ha
R	Production, $
RWS	Relative water supply
Et	Crop demand, m^3
V	Total water supply, m^3
IRIA	index of income rate per irrigated area
PIS	Performance of irrigation system.

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