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Water and wastewater quality assessment based on fuzzy modeling for the irrigation of Mandarin

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ABSTRACT

A fuzzy model was designed to characterize the quality of mandarin irrigation water. The model consisted of individual cascade submodels. This procedure simplifies the process, and on the other hand allows us to study the effect of individual variables in the final decision. Precisely, the effect of three irrigation water resources (Irrigators association water (IW), Reclaimed Water, and Transferred Water) were studied on the development of mandarin's tree crop. The application of the model showed that the IW irrigation gives the best results.

Keywords: Irrigation; Mandarin; Fuzzy logic

1. Introduction

Irrigated agriculture is the primary user of developed water globally, reaching a proportion that exceeds 70–80% of the total in the arid and semi-arid zones [1]. Nevertheless, irrigated agriculture in many areas in the world operates with complete disregard to the basic principles of resource conservation and sustainability practices. One strategy for maintaining or increasing productivity in the face of resource scarcity is to make greater use of marginal quality lands and waters. In implementing such a strategy, a key factor for sustainability is soil salinity. Soil secondary salinization in the semi-arid regions seriously affects the productivity of at least 20–30 million ha [2]. However, the predominantly intensive agriculture may present a risk of soil salinization due to overuse of fertilizers or irrigation mismanagement [3]. Irrigation waters, especially Reclaimed Water (RW), contain salts and toxics ions that can accumulate in soils over time and reduce yields. In arid and semi-arid regions where rainfall is not sufficient to leach the salts from the root zone, it is necessary to apply excess irrigation water.

In many arid parts of the world, like in southern Mediterranean coast of Spain, irrigation water supplies, particularly RW and groundwater sources are saline, containing a high concentration of Na^+, SO_4^{2-}, Cl^-, Mg^{2+}, and Ca^{2+} salts in addition to high B. Although several studies have shown the advantages and disadvantages of using RW for citrus crops irrigation [3–7], and the reuse of saline water for irrigating

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forage crops has been successfully demonstrated [8–11], little is known about the interaction between the use of saline irrigation water on the long term. Recently, studies on citrus trees demonstrated that it is necessary to carefully monitor the concentration of different ions in the plant and used models as the fuzzy logic if RW irrigation is used in the long term [12].

In Murcia, the overexploitation of many aquifers has resulted in a widespread loss of water quality, especially in the lower areas of valleys and in the coastal zone. The continued use of these water resources for irrigation will probably put crops and the environment at risk from salinization, soil compaction, and undesirable ions toxicity [13]. An estimated 100,000 ha of land are irrigated with water from aquifers, of which 85% have very high level of salts [14]. However, despite the high salt concentration in the RW, the ever-increasing demand for fresh water owing to the urban growth in the coastal zone of Murcia and the large demand from intensive agricultural activity have made the RW reuse indispensable for irrigation [15].

Fuzzy logic is a very flexible model since it is capable of handling both qualitative and quantitative, correlated, or completely uncorrelated variables, used widely [16–22]. It seems that the rule-based fuzzy modeling is a promising approach because it can be applied in many topics of agriculture such as in selecting a site for wastewater treatment plant [17], or to study the effect of wastewater evapotranspiration on citrus cultivation [12].

The objective of this study is to show the long-term effects of different irrigation water qualities under Mediterranean conditions though a Mamdani fuzzy modeling scheme, where rules are based on multiple knowledge sources, such as previously published databases and models, existing literature, intuition, and solicitation of expert opinion to verify the gathered information. The Mamdani scheme is a type of fuzzy relational model where each rule is represented by an IF–THEN relationship. The output from a Mamdani model is a fuzzy membership function based on the rules created [23,24]. The aim of the paper is to decide which of the three examined irrigation treatments (Irrigators association water (IW), RW, and Transferred Water (TW)), is most appropriate for mandarin water treatment, taking into account the total effect of 11 input variables. The final evaluation for each treatment is expressed by a single number (from 0 to 1), allowing us an unbiased judgment. The cascade construction of the model is an additional feature of it, since it allows us to see the partial effect of the individual group of variables on mandarin cultivation.

2. Experimental site and conditions

The experiment was conducted over a two-year period (2008–2009), in a commercial orchard located in Campotejar-Murcia, Spain (38˚07_18__N; 1˚13_15__W). The experimental plot of 0.5 ha was cultivated with eight-year-old (in 2007) mature mandarin trees (*Citrus clementina* cv. "Orogrande") grafted on Carrizo citrange (*Citrus sinensis* [L.] Osb. × *Poncirus trifoliata* [L.]). The soil had a loamy texture (26% clay, 32% loam, and 42% sand) with an average bulk density of 1.37 g/cm^3. The trees were spaced at 3.5 m between plants and 5 m between rows. The irrigation system consisted of a single lateral drip line laid on the soil surface next to the tree trunk. It provided three self-pressure compensating on-line emitters per tree discharging 4 l h^{-1} each, placed at 0.85 m from the trunk, and spaced 0.9 m apart.

A total of 192 trees were used in this study. The experimental design was a randomized complete design with four experimental plots per block. The standard plot was made up of 12 trees, organized in 3 adjacent rows with 4 trees per row. The two central trees of the middle row were used for measurements and the other 10 trees were guard trees.

Three irrigation water treatments were applied as follows: the first (TW) was pumped from the Tajo-Segura water transfer channel (EC = 1 dS m^{-1}), the second (IW) was delivered by the irrigators association of Campotejar (EC = 1–3 dS m^{-1}), and the third water source (RW) was pumped from the "North of Molina de Segura" wastewater treatment plant (WWTP) (EC = 3 dS m^{-1}).

3. Soil measurements

One central tree in each of four replicates per treatment was equipped with a metallic access tube to 1.2 m depth at the level of the first emitter (0.85 m away from the trunk). A calibration relationship was developed to convert neutron count ratios (soil:water drum) to volumetric water content (_v, cm^3 cm^{-3}). The _v was measured every other week at 0.2 m away from the first emitter and perpendicular to the irrigation lateral, using the time-domain reflectometry technique "TDR" (Model 1502C, Tektronix Inc., OR, USA) for the top 0.1 m and the neutron probe (Troxler 4300, Raleigh, NC, USA) from 0.2 down to 1 m depth following a 0.1 m step. Gravimetric soil samples were collected from four replicates per treatment, two times a year from three soil layers (0–0.3, 0.3–0.6 and 0.6–0.9 m) and at three distances from the emitter (0.1, 0.3 and 0.6 m) The TDR readings overestimated the _v by 15–20%. The remaining soil was used to evaluate the accumulation of salts within the soil profile. The soil samples were air dried and ground before being sieved to a particle size of 2 mm. Afterward, soluble salts were determined in the saturated paste extract as described by Rhoades [25]. The ECe was measured with a multi-range Cryson-HI8734 electrical conductivity meter (Crison Instruments, S.A., Barcelona, Spain). Soluble Ca and Mg were measured using the EDTA titration method and Na was measured using a flame photometer [26].

4. Water measurements

Three water samples from each irrigation water source were collected monthly between 2008 and 2009 in order to characterize irrigation water quality. The samples from each irrigation source were collected in glass and plastic bottles, transported in an ice chest to the laboratory and stored at 5˚C before being processed for chemical analysis. The concentration of Na, Ca, and Mg were determined by inductively coupled plasma (ICP-ICAP 6500 DUO Thermo, England). Electrical conductivity (EC) was determined using an EC meter as above.

5. Leaf analysis

Spring flush leaves from nonfruiting branches were sampled every three months during 2008 and 2009. Twenty leaves per tree were sampled in the two central trees of each replicate per treatment. Leaves were washed with a detergent (alconox 0.1%), rinsed with tap water, cleaned with a dilute solution of 0.005% HCl and finally rinsed with distilled water, and left to drain on a filter paper before being oven-dried for at least 2 d at 65˚C. Dried leaves were ground and digested in 2:1 nitric–perchloric acid mixture [27]. Replicate samples (0.25 g) were digested by Aqua Regia acid HCl/HNO_3. The concentration of macroelements, microelements, and heavy metals were determined by inductively coupled plasma (ICP-ICAP 6500 DUO Thermo, England). Anions were analyzed by ion chromatography with a Chromatograph Metrohm (Switzerland) after using a standard leaf-to-distilled-water ratio of 1:2.5 (w:w).

6. The fuzzy inference system

6.1. A model overview

The Fuzzy Logic tool was introduced in 1965, also by Lotfi Zadeh, and is a mathematical tool for dealing with uncertainty. Basic elements of fuzzy systems are the membership functions (mfs) and rules. The mfs of a fuzzy system measure the degree to which the fuzzy set elements meet the specific properties or in other words they measure the "degree of belongingness" of an element to a specific fuzzy set. Membership value is between 0 and 1. The input space is referred to as universe of discourse or simply universe [23,24].

The feature of a membership function is defined by three properties: the support, the core, and the boundary. The support is the region of universe that is characterized by a nonzero membership. The core is the region of universe that is characterized by full membership (1), and the boundary is the region of universe that has a nonzero but not full membership. Some of the most commonly used mfs are the Gaussian, trapezoid, triangular, etc. The design of mfs used for the description of the model's input variables was based on critical values of each variable as described below.

Designing a Mamdani rule base requires three steps: first determine appropriate fuzzy sets over the input and output domain; second determine a set of rules between the fuzzy inputs and the fuzzy outputs that model system behavior; and finally create a framework that maps crisp inputs to crisp outputs [24].

In the present model the number of input variables is large (11). A large number of input variables create a complex system and therefore the number of variables was divided into classes, two for soil and one for leaves. This separation simplifies the model maintaining accuracy. These classes were:

(1) The elements concentration class of soil in %Ca, %Mg, and %Na.
(2) The electrochemical properties of soil SAR and ECe (dS m^{-1}).
(3) The concentration of leaves in elements %B, %N, %Ca, %Mg, %P, %K.

Thus we formed a cascade fuzzy logic system for each treatment (TW, RW, IW) as follows:

Initially two fuzzy systems of soil, one for the content in %Ca, %Mg, and %Na, named Soil_elem and one for the electrochemical properties of the soil named Soil_ew created. Output of each fuzzy system was a crisp variable in the range of 0–1 evaluating the appropriateness of each class (1: appropriate, 0: not at all appropriate).

These two outputs were used as inputs to a third, in turn, fuzzy system (Soil) with output the total suitability of the soil.

For leaves, a fourth fuzzy system (Plant) was established with inputs as the percentage of chemical elements in leaves and output as the quality of leafs.

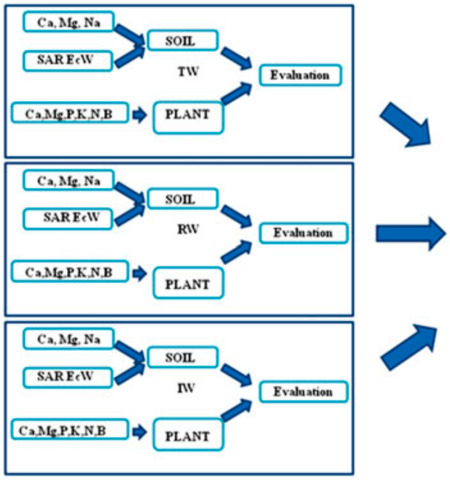

Fig. 1. Overview of the fuzzy decision system.

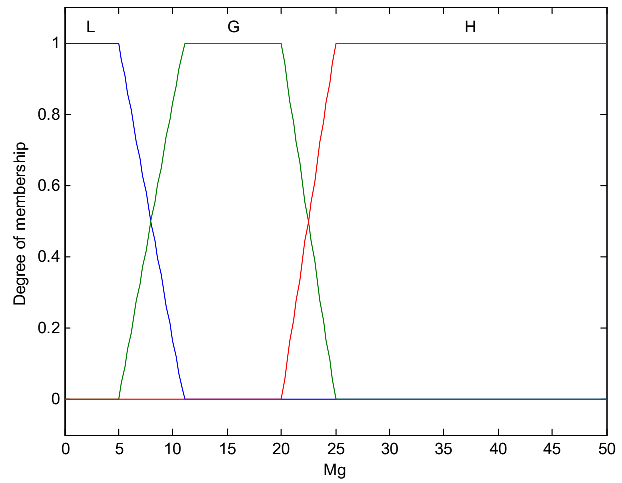

Fig. 2. Mfs of % concentration of soil in Mg.

The fuzzy model, named Final with inputs the quality of leaves and soil had as output the final decision on process quality. Fig. 1 shows the overall procedure followed.

The MATLAB software was used for the establishment of the model. Fig. 1 shows an overview of the fuzzy decision system.

6.2. Mfs of the soil fuzzy inference system

The construction of mfs was based on the critical values of soil as shown in Table 1. Looking at Table 1, and taking into account the "normal," "very low," and "very high" concentration it seems that overlapped trapezoidal mfs are good enough to be used. For each element, three overlapped trapezoidal functions, called Low (L), Good (G), and High (H), having as core the above mentioned ranges were used. The boundary (50% overlapped) region was determined by the low and high values of the nearest region as shown in Table 1. Fig. 2 shows the mfs of the concentration of leaves in Mg. More precisely, the core of G mf covers concentration in the range of 11–20%, and the support covers the ranges 5–10% and 21–25%, 50% overlapped by the supports of L and H. This means that a concentration of 25% in Mg is 50% normal and 50% high.

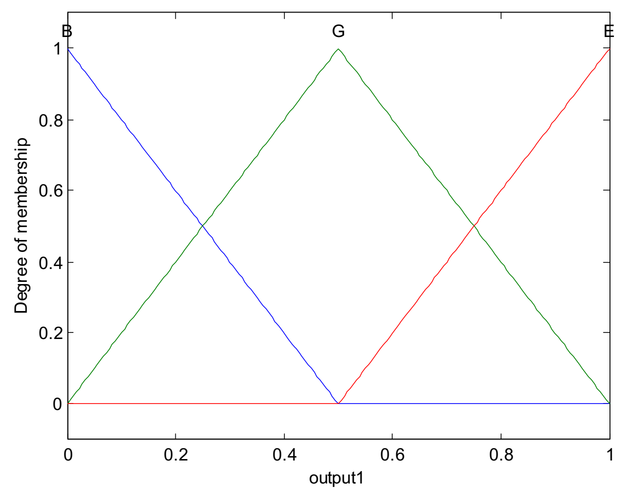

Fig. 3. Mfs of output.

Table 1
Critical values of soil

	Very low	Low	Normal	High	Very high	Source
Ca (%)	<25	25–45	46–75	76–90	>90	Legaz et al. [28]
Mg (%)	<5	5–10	11–20	21–25	>25	Legaz et al. [28]
Na (%)	<1	1–2	3–9	10–15	>15	Grattan [29]
SAR		0–10	10–18	18–26		Rengasamy [30]
ECe (dS m^{-1})		<1	1–3	>3		Mass [31]

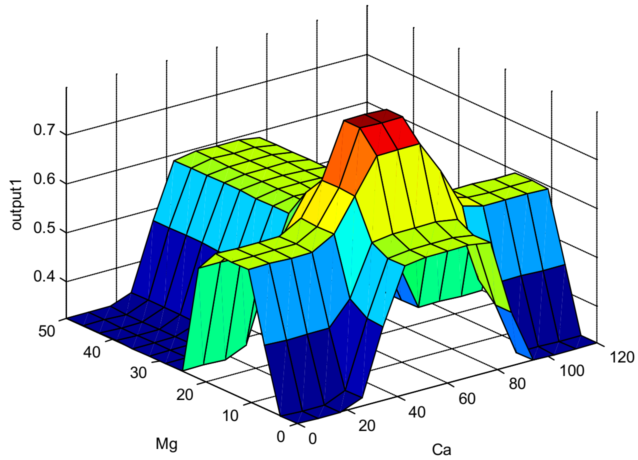

Fig. 4. Output of the Soil_elem model as a function of Mg and Ca concentration in soil. The concentration of Soil in Na is assumed to be constant (10%).

For the output, if we take into account the above reasoning, it seems that triangular mfs are most suitable. Three equally spaced triangular mfs (B, G, and E), 50% overlapped, was used for output as shown in Fig. 3.

The fuzzy association between the inputs and output of the model is achieved via a number of IF–THEN rules. This rule-based system is known as Fuzzy Associative Memory (FAM). The theory of fuzzy logic involves several possibilities using the OR NOT, AND, and THEN logical operations. For the purposes of this work the most commonly applied min, max logical operators and the max-min implication operator (Mamdani implication) are considered to be sufficient. In a Mamdani-type fuzzy logic system model, the output is a fuzzy membership function based on the rules created. Depending on the values used, the input mfs are activated to a certain degree. The contributed output from each rule reflects this degree of activation. The final output is a fuzzy set created by the superposition of individual rule actions. An example of FAM rules used in this model is: “IF concentration in Mg is good (G) AND the concentration of Na is not good (NOT G) AND the concentration of Ca is Good (G) THEN the concentration of

Table 2
Critical values of leaves

	Very low	Low	Normal	High	Very high	Source
B (ppm)	<21	21–30	31–100	101–260	>260	Grattan [29]
N (%)	<2.2	2.20–2.40	2.41–2.70	2.71–2.90	>2.90	Ramos [32]
Ca (%)	<1.6	1.6–2.9	3–5	5.1–6.5	>6.5	Legaz et al. [28]
Mg (%)	<0.15	0.15–0.24	0.25–0.45	0.46–0.9	>0.90	Legaz et al. [28]
P (%)	<0.09	0.09–0.11	0.12–0.15	0.16–0.19	>0.19	Legaz et al. [28]
K (%)	<0.5	0.5–0.7	0.71–1	1.01–1.3	>1.3	Legaz et al. [28]

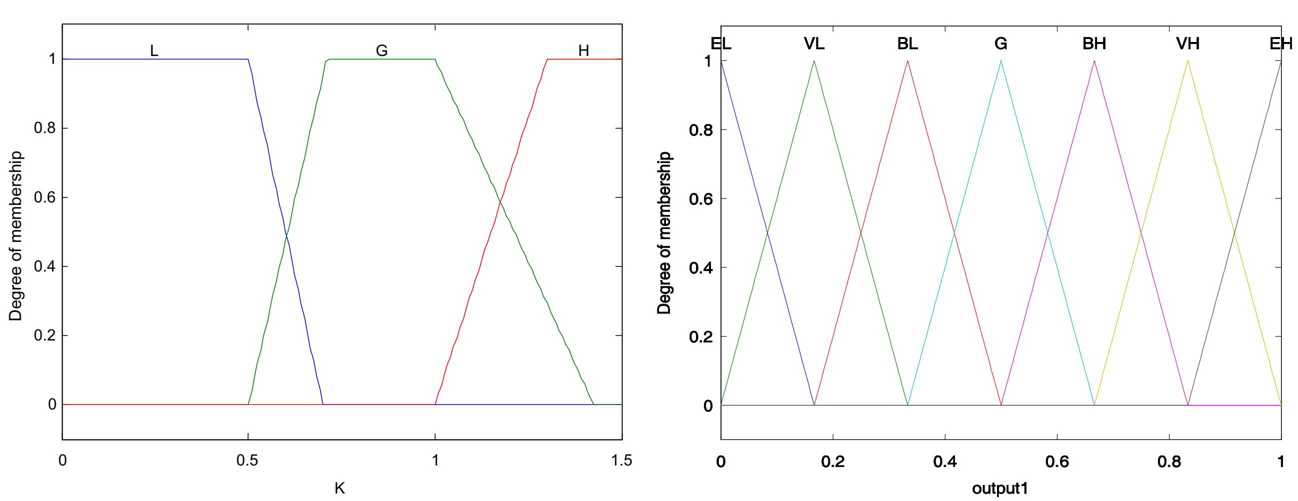

Fig. 5. Membership function of K (left) and mfs of output (right).

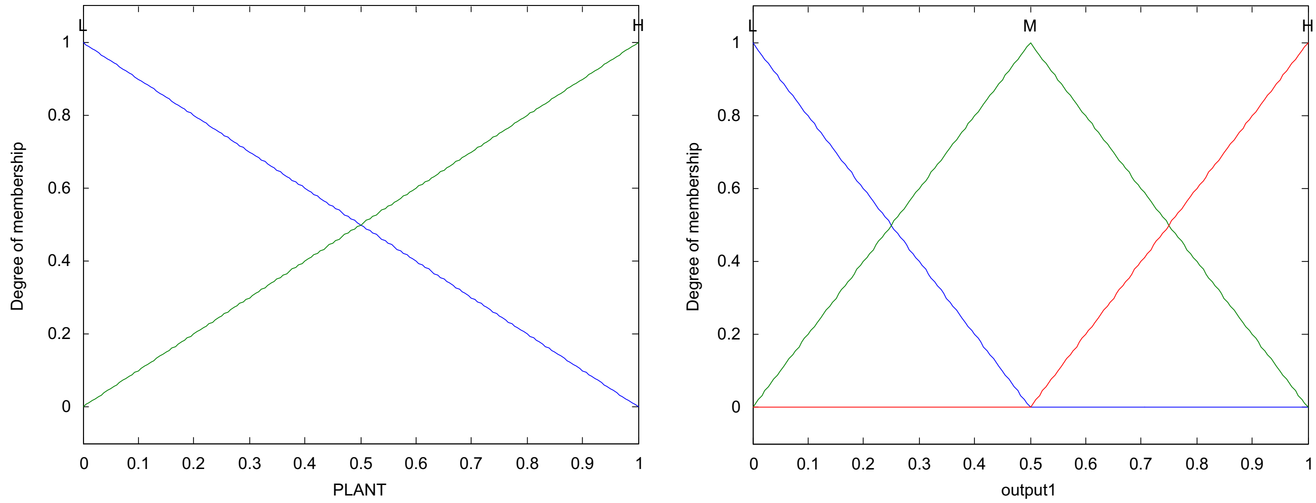

Fig. 6. Mfs of Plant and Soil input fuzzy system (left) and output (right).

Table 3
Measured values of soil parameters

Date	Soil Trat	Ca (%)	Mg (%)	Na (%)	SAR	ECe
01-01-08	TW	9.15	4.72	29.27	24.85	6.02
10-08-08	TW	20.34	9.08	16.18	9.34	3.68
10-12-08	TW	22.64	8.87	19.29	11.86	4.92
14-08-09	TW	25.14	10.05	22.11	11.71	4.59
		Ca (%)	Mg(%)	Na(%)	RAS	CEe
01-01-08	RW	10.70	6.29	70.53	54.11	10.25
10-08-08	RW	18.40	7.97	37.00	23.05	7.94
10-12-08	RW	11.13	6.81	44.95	34.28	6.29
14-08-09	RW	20.29	12.19	70.84	38.78	7.01
01-01-08	IW	5.09	2.95	26.38	29.42	4.32
10-08-08	IW	31.53	19.64	116.09	51.22	6.39
10-12-08	IW	8.83	3.94	26.98	29.90	4.90
14-08-09	IW	21.05	9.89	39.77	22.51	5.85

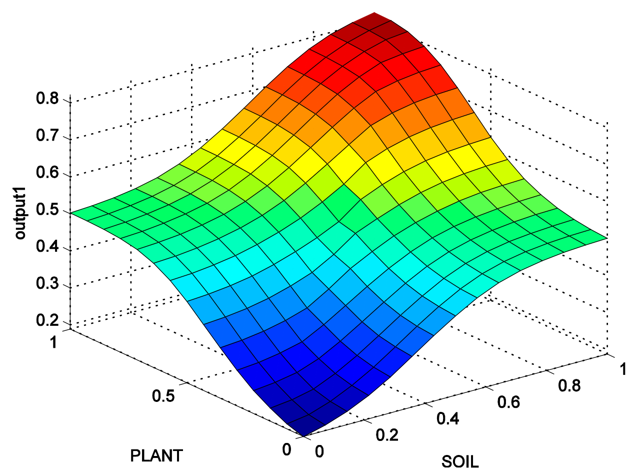

Fig. 7. Output of the final model as a function of plant and soil evaluation of watering IW.

elements is good (G)." The operator NOT G means that the concentration belongs to either L or H mf.

Since a crisp output value is required, a defuzzification is need. In the present paper the centroid method was used for this action [23]. According to this method, for each input combination (L, G, H) the degree of fulfillment and the consequent set of each rule are computed. Then all consequent sets are aggregated and finally the center of gravity of the resulted set was computed, giving the corresponding output [23,24].

Fig. 4 shows the output of the model, after defuzzification, as a function of two inputs namely Mg and Ca The other input (Na) is assumed to be constant at the value of 10%. The output of this sub model is a number between 0 and 1 and assesses the combination of elements concentration in the ground.

Fig. 4 shows the output of the SOIL_elem model as a function of Ca and Mg. The concentration in Na is constant (12%). For example, looking at Fig. 4, we can see that if the concentration of soil in Na is 10%, in Mg 40%, and in Ca 80% the calculated crisp output is 0.6.

For the electrochemical properties of the soil three mfs were used, two triangular and one trapezoid. The core of the trapezoid defined by the values "Normal" presented in Table 1, while the vertex of the triangles specified by the values "very low" and "very high" of

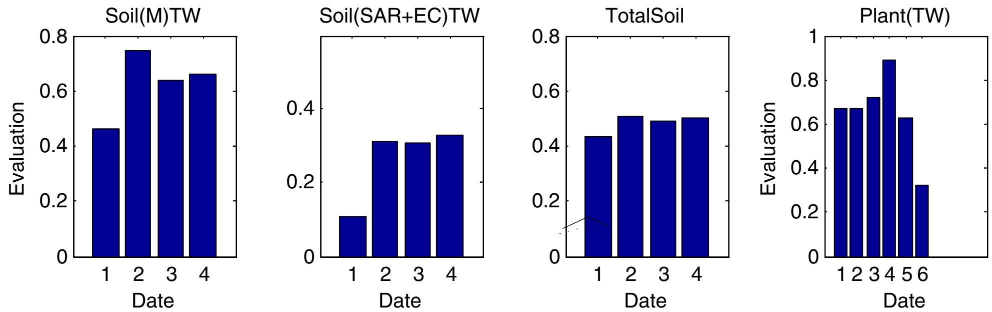

Fig. 8. Fuzzy system outputs for TW treatment.

the same table. The triangles sides was overlapped by 50% by the sides of G trapezoid function

The structure of output and the rules was designed by similar way as above.

6.3. Mfs of the leaves fuzzy inference system

For the leaves fuzzy system named "Plant," six input variables were used, with three trpezoid mfs each, following the same procedure as above. Table 2 shows the corresponding critical values of leaves, found in literature.

For the output, seven evenly spaced triangular 50% overlapped mfs in the range of 0–1 named EL, VL, BL,G, BH, VH, and EH were used, as shown in Fig. 5 (right). The structure of the rules had same type as above.

6.4. Final model

The final model had two inputs, the output of Soil fuzzy system and the output of Plant fuzzy system. Two triangular mfs (L and H), 50% overlapped, were used for each input as shown in Fig. 6 (left). For the

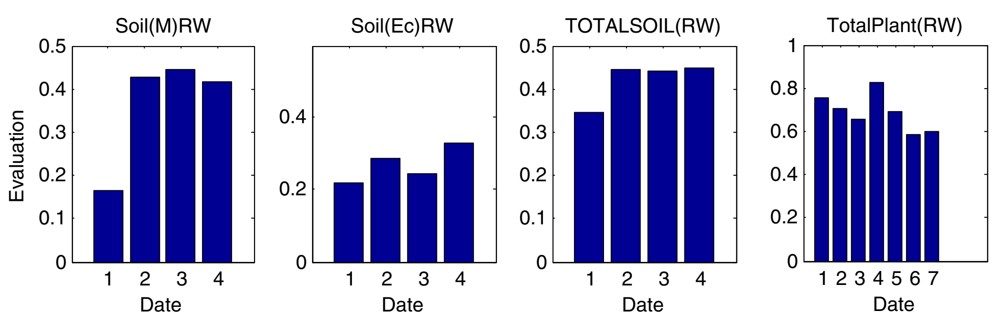

Fig. 9. Fuzzy system outputs for RW treatment.

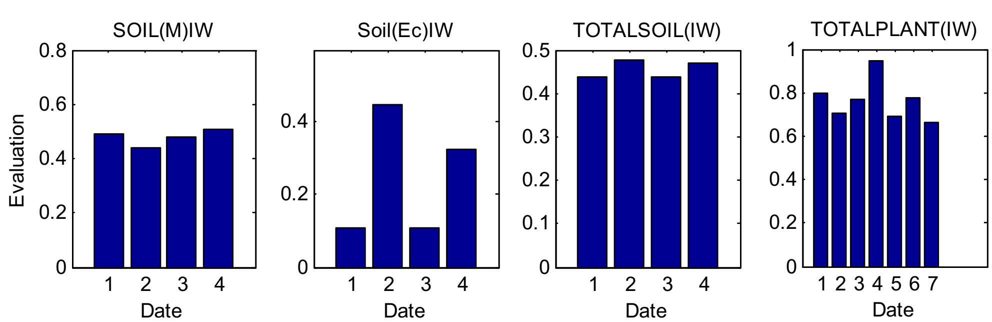

Fig. 10. Fuzzy system outputs for RW treatment.

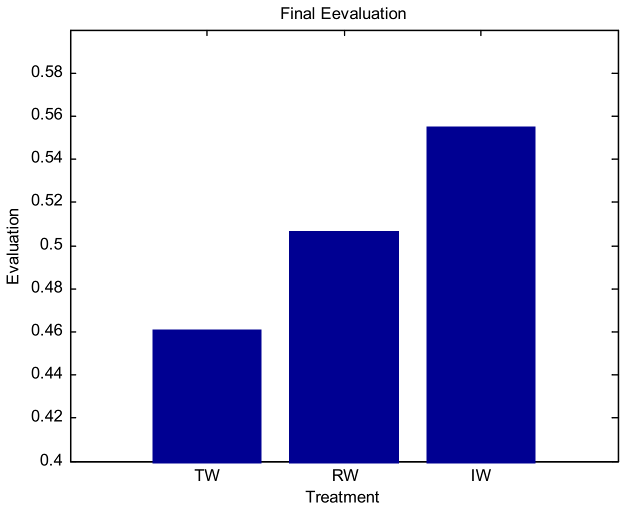

Fig. 11. The final classification of treatments.

output three mfs (L, M, H) were used. The rules had the same structure as above.

7. Results

Table 3 shows the collected data, as described above. The soil data were collected from 1 January 2008 to 14 August 2009. The plant data were collected from 1 January 2008 to 14 August 2009.

The surface shown in Fig. 7 corresponds to the output of the final model after defuzzification, as a function of plant and soil evaluation.

Figs. 8–10 show the fuzzy system outputs for TW, RW, and IW treatments. The upper row of each figure corresponds to the output of each soil submodel, and the second row the output of leaves submodel. The *x*-axis labels correspond to the sampling date described in Table 3.

Fig. 11 shows the comparison outputs of the model corresponding to the three treatments TW, RW, and IW. This is the final decision, that takes into account the total effect of 11 input variables and all measurements. As one can see, IW treatment is the better than the others (Table 4).

8. Discussion

A multi input/single output cascade fuzzy model, comparing the effect of three water treatments on mandarin, was established. The model was based on two-year measurements and takes into account the effect of 11 variables on the growth of mandarin. The main advantages of the model is that it handles

Table 4
Measured values of plant elements

	Plant						
Date	Trat	B (ppm)	N (%)	Ca (%)	Mg (%)	P (%)	K (%)
01-01-08	TW	66.88	1.98	4.77	0.37	0.11	1.42
22-04-08	TW	90.29	1.81	3.21	0.47	0.14	0.48
10-09-08	TW	67.51	2.16	3.12	0.42	0.16	1.30
21-01-09	TW	83.22	2.36	3.88	0.36	0.13	0.73
24-06-09	TW	127.68	1.87	3.39	0.40	0.16	1.43
14-08-09	TW	167.53	3.50	6.86	0.65	0.14	1.48
01-01-08	RW	64.02	1.74	5.09	0.41	0.11	0.78
22-04-08	RW	83.50	1.66	3.01	0.37	0.15	0.54
10-09-08	RW	71.80	2.37	3.16	0.47	0.19	1.43
21-01-09	RW	104.44	2.16	3.29	0.36	0.13	0.83
29-04-09	RW	187.35	1.94	5.41	0.41	0.14	0.74
24-06-09	RW	191.65	2.02	3.80	0.45	0.16	1.41
14-08-09	RW	199.70	3.19	4.16	0.48	0.12	1.28
01-01-08	IW	76.46	1.77	5.16	0.47	0.12	0.82
22-04-08	IW	85.23	1.82	3.01	0.37	0.14	0.54
10-09-08	IW	65.67	2.18	3.56	0.41	0.16	1.16
21-01-09	IW	76.46	2.50	3.55	0.34	0.13	0.75
29-04-09	IW	185.08	2.00	3.34	0.34	0.12	0.65
24-06-09	IW	145.38	1.95	3.92	0.38	0.12	0.92
14-08-09	IW	158.23	3.28	4.67	0.49	0.10	0.99

variables with low correlation to each other, and that can be improved in the future, taking into account other variables (if data exist), not necessarily quantitative but qualitative, as for instance the quality of the fruit. The structure of the model into sub models simplifies the model and allows us to see additionally the individual effects of each input. Thus, we can decide to continue or change the treatment.

9. Conclusions

Any water treatment enriches the soil by chemical elements which in turn penetrate in the leaves. Such enrichment has an impact on the growth of trees. The type of water treatment either improves or worsens the concentration of the soil and leaves to each chemical element, which makes it difficult to answer the question what the best treatment is.

The application of fuzzy modeling showed that the fuzzy model can describe well the effect of the irrigation in the mandarin cultivation. This is because the models take into account a large number of parameters, whatever the degree of correlation between them. The division of the fuzzy model into submodels enables us to compare the effect of irrigation on individual characteristics of the system, such as the quality of the leaves, and soil.

The application of these models by comparing the results (Figs. 8–10) showed that the electrochemical properties of the soil were hardly affected by the manner and amount of irrigation. In all cases, the content data at a maximum leaf notes on 21 January 2009 and after this day quality gradually decreases. From Fig. 7 it is shown that the overall effect of watering IW gives the best results, although, as the water quality from this treatment is not always the same because of the different water sources donation; intensive soil status monitoring is needed to avoid the salt accumulation, and a reduction in the physical soil properties. The model can be further improved, to include and other measurable or nonmeasurable variables, as for example the mandarin quality, and this is another feature of it.

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