MATHEMATICAL MODELLING OF URBAN WATER SUPPLY SYSTEM CRISIS

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Abstract:

Purpose – The chaotic growth of cities results in numerous problems related to public health and urban environment. One of these problems is the crisis in urban water supply systems. The objective of this paper is to develop a mathematical model for the water supply system crisis in urban environment (*WSC*) able to tackle with the ambiguity of the real available data.

Design/methodology/approach – The applied methodology comprises the following steps: (1) identification of the influencing factors in *WSC*; (2) proposal of a conceptual model for *WSC* description; (3) gathering and simulation of the necessary and available data; (4) optimization of the conceptual model parameters; and (5) verification of the proposed model performance.

Findings – The results indicated that there is a great amount of influencing factors in *WSC* (showed in the complete text); the conceptual model that was developed is composed by two others partial models ($WSC = WC - WA$). The first partial model explained the water consumption ($WC = f_{WC}(f_{WC1}, \dots, f_{WCn})$), and the second partial model explained the water availability ($WS = f_{WS}(f_{WS1}, \dots, f_{WSn})$), in which functions $f_{WC1}, \dots, f_{WCn}$ are related to influencing factors in water consumption (i.e. temperature, relative humidity, rainfall, revenues collected, unemployment indicator), and functions $f_{WS1}, \dots, f_{WSn}$ are related to the influencing factors in water availability (i.e. total water-loss, intermittence in water supply system). The proposed conceptual model has showed good agreement to the simulated data.

Originality/value – The paper is among the first works to describe a *WSC* model and to analyze the possibility of applying fuzzy logic to deal with the ambiguity of the real data. The water supply crisis in urban environments was adequately modelled.

Keywords: Water crisis, Water scarcity, Water vulnerabilities, Fuzzy Logic, Water consumption, Water demand

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1. INTRODUCTION

According to data from World Meteorological Organization, the global consumption of water increased more than six times in less than a century, more than the double of the rate of population growth and continues to grow with the increasing consumption by agricultural, industrial and domestic sectors (Freitas and Santos, 1999). Such data allow the conclusion that in the coming years the global situation of water reserves will tend to crisis, both in quantitative and qualitative aspects, if adequate water management actions are not be taken. More recently, it has been observed the existence of water supply system crisis in urban environment (*WSC*), context characterized by water scarcity and by damage for the environment and for the population health, especially among poor populations. As human populations continue to grow, these problems are likely to become more frequent and serious. One example is the case of New York City's water supply, which is facing a crisis. The social and economic development of New York City since the 1970s led to a sudden crisis in the city's water supply system in the 1990s (Gandy, 1997). Other examples also were reported, like in Palestine, where a case of *WSC* has been observed caused mainly by the inadequate access to freshwater resources and its inappropriate management (Zahra, 2001). The Tijuana city, in Mexico, has shown the highest rates of economic growth in the country, resulting in a rapid increase of water demand and a consequent appearance of a *WSC* (Fullerton Jr. *et al.*, 2007). In Brazil, the Campina Grande city faced, in the period 1998-2000, a *WSC* caused by severe periods of drought and the complete absence of management of freshwater resources (Rêgo *et al.*, 2001). This *WSC* lead Campina Grande city to serious water rationing with duration of one year. This is not a unique case in Brazil, since it has been observed frequent water rationing in Recife and São Paulo cities (Tucci *et al.* 2000). In the Brazilian Federal District, the accelerated non-planned urbanization and changes in land are causing a strong impact over water resources. The local water supplier predicts that, as soon as 2010, water demand will exceed the systems capability of water supply (IWAS, 2009).

Mathematical modeling is a well-known tool for management of the freshwater. However, when considering *WSC*, there are some limitations of the conventional mathematical modeling that are related to vague and ambiguous data (e.g. real water-loss, real available water, setting water tariffs, among others). The objective of this paper is to develop a mathematical model for the water supply system crisis in urban environment, dealing with this ambiguity and uncertainty of the real data.

2. METHODOLOGY

The methodology of this work comprised the following steps: (1) identification of the influencing factors in *WSC*; (2) proposal of a conceptual model for *WSC*; (3) data gathering and data simulation; (4) optimization of the proposed conceptual model parameters; and (5) assessment of conceptual model performance.

For step (1), a survey was conducted on the literature related to *WSC* management. For step (2) the definition of *WSC* present in the literature was taken and the fuzzy nonlinear programming was used (Motiee *et al.*, 2001; Thakre *et al.*, 2009). In this paper, an overview of the basic concepts of fuzzy mathematical programming is required. In general, a fuzzy set initiated by Zadeh (1965) can be summarized as follows. Definition 1: a subset *A* of a set *X* is said to be fuzzy set if $\mu_A: X \to [0,1]$, where μ_A denote the degree of belongingness of *A* in *X*. Definition 2: a fuzzy set *A* of set *X* is said to be normal if $\mu_A(x) = 1$, $\forall\, x \in X$. Definition 3: the height of *A* is defined and denoted as $h(A) = \sup \mu_A$, $\forall\, x \in X$. Definition 4: the α-cut and strong α-cut is defined and denoted respectively as $\alpha_A = \{x/\mu_A(x) \geq \alpha\}$, $\mu_A^+ = \{x/\mu_A(x) > \alpha\}$. Definition 5: let $\tilde{a}$, $\tilde{b}$ be two fuzzy numbers, their sum is defined and denoted as $\mu_{\tilde{a}+\tilde{b}}(z) = \sup \min_{z=u+v}\{\mu_{\tilde{a}}(u), \mu_{\tilde{b}}(v)\}$, where $0 \leq \lambda \in R$. Definition 6: if a fuzzy number $\tilde{a}$ is fuzzy set A on R, it must possess at last following three properties: (i)$\mu_A(x) = 1$; (ii) $\{x \in R/\mu_{\tilde{a}}(x) > \alpha\}$ is a closed interval for every α ∈ (0,1]; (iii) $\{x \in R/\mu_{\tilde{a}}(x) > 0\}$ is a bounded and it is denoted by $[a_\lambda^L\ ,\ a_\lambda^R]$. Theorem 1: a fuzzy set *A* on *R* is convex if and only if $\mu_A(\lambda x_1 + (1-\lambda)x_2) \geq min[\mu_A(x_1), \mu_A(x_2)]$, for all $x_1, x_2 \in X$ and for all $\lambda \in [0,1]$ where min denotes the minimum operator. Theorem 2: let $\tilde{a}$ be a fuzzy set on *R*, the $\tilde{a} \in f(R)$ if and only $\mu_{\tilde{a}}$ satisfies (equation 1):

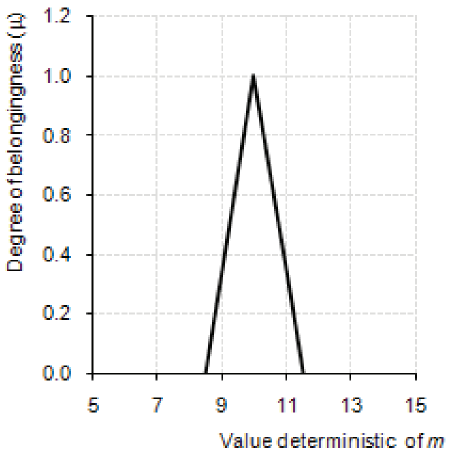
$$\mu_{\hat{a}}(x) = \begin{cases} 1, & for\ x \in [m,n] \\ L(x) & for\ x < m \\ R(x) & for > n \end{cases} \tag{1}$$

where $L(x)$ is the right continuous monotone increasing function, $0 \leq L(x) \leq 1$ and $\lim_{x \to \infty} L(x) = 0$, $R(x)$ is a left continuous monotone decreasing function, $0 \leq R(x) \leq 1$, and $\lim_{x \to \infty} R(x) = 0$. As examples of membership functions for a fuzzy number $\tilde{m}$, such as approximately $m = 10$, a triangular membership function (equation 2) and a bell-shaped membership function (equation 3) is widely used.

$$\mu_{\tilde{m}} = \left(0{,}1 - \frac{|x-m|}{a}\right), a > 0 \tag{2}$$

$$\mu_{\tilde{m}} = e^{-b(x-m)^2}, b \geq 1 \tag{3}$$

Such membership functions are illustrated in Figure 1 and 2. More information about fuzzy mathematical programming is available in the literature (Slowinski and Teghem, 1990; Sakawa, 1993; Peraei *et al.*, 2001; Cao, 2002; Thakre *et al.*, 2009).



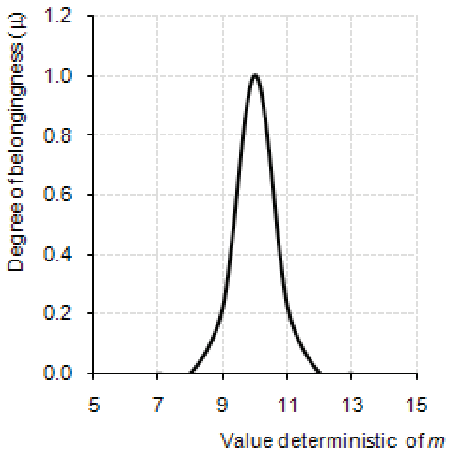


Figure 1 – Fuzzy number $\tilde{m}$, triangular membership function
Figure 2 – Fuzzy number $\tilde{m}$, bell-shaped membership function

For the third step (step 3), a case study was simulated in Brazil, more precisely in Federal District, taking into account predictions made by some researchers. The necessary data were gathered from the Brazilian Federal District's water supplier and sanitation company (CAESB), from the National Institute for Meteorology (INMET) and from the Brazilian Federal District's Government (GDF). The simulation was conducted assuming the hypothesis of significant increase in the water consumption in coming years and managerial and political stagnation of the water supplier and sanitation company. The time series analysis refers to the last three years. The period for model calibration was considered for two years (2007–2008) and the verification period is considered for one year (2009). Data were normalized prior to optimization of conceptual model parameters. This was done to restrict their range within the interval of –1.0 to +1.0, in order to eliminate the difference among scales measuring the influencing factors, according to equation 4:

$$x_{norm} = 1 - \frac{2 \times (x_{max} - x_0)}{x_{max} - x_{min}} \tag{4}$$

where x_{norm} is the normalized value, x_0 is the original value, x_{max} is the maximum value and x_{min} is the minimum value. For step (4), the minimization of the sum of squared errors and the Differential Evolution & Particle Swarm Optimization algorithm (DEPS) was employed, using the spreadsheet from Open Office (Calc-Solver). In step (5), some tests used to model performance assessment were proposed, among them, the correlation coefficient (r), the determination coefficient (R^2), the average absolute relative error (AARE) and graphic observed values *versus* estimated values.

3. RESULTS AND DISCUSSIONS

Table I shows the influencing factors in the *WSC*.

Table I – Influencing factors in the *WSC*

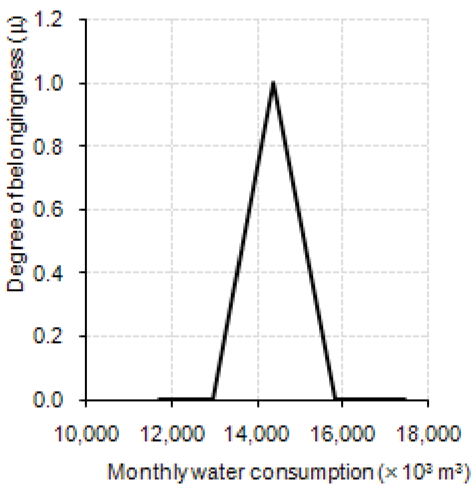
Item	Influencing factors
1	Population growth rate [2, 12,15, 17, 19, 20, 27, 31]
2	Human population density [12, 17, 19, 31]
3	Socio-economic level [1, 3, 10, 12, 17, 19, 30, 32]
4	Education level [1, 32]
5	Industry level [2, 17, 19, 27, 32]
6	Ambient temperature [2, 3, 10, 11, 13, 15, 19, 30, 32]
7	Relative humidity [10, 11, 13, 15, 19, 30, 32]
8	Rainfall [2, 3, 10, 11, 13, 15, 19, 21, 30, 31, 32]
9	Seasonality [1, 3, 4, 9, 13, 15, 19, 22, 27, 30, 32]
10	Size and topographic characteristics of the city [14, 27, 32]
11	Percentage of water metering [5, 16, 29, 32]
12	Water tariffs [2, 7, 8, 9, 11, 16, 18, 23, 28, 29, 30, 32]
13	Type of water tariffs policies [2, 7, 8, 9, 11, 16, 18, 23, 28, 29, 32]
14	Existence of wastewater collection systems [32]
15	Human Development Index [17, 32]
16	Pressure in the water distribution network [5, 25, 32]
17	Existence of conservation habits [6, 12, 32]
18	Number / type of hydro-sanitary equipment per household [1, 6, 14, 26, 28, 29, 32]
19	Constructed Area per household [1]
20	Number of rooms [1]
21	Abundance or scarcity of water sources [6, 22, 27, 29, 31, 32]
22	Water-loss [5, 32]
23	Social representation and identification of each family [1, 3, 6, 10]
24	Existence and type of municipal water resources policy [16, 29]
25	Acceptance of the population to water conservation and rational use actions [29]
26	Typology of land use [10]
27	Type of consumers [12]
28	Type of municipality [14, 32]
29	Predominant function of urban environment [32]
30	Existence of policies to promote water conservation [16, 29]
31	Intermittence in water supply system [32]
32	Energy consumption [30, 32]
33	Existence of regulatory policy on water consumption [16, 29]
34	Existence of environmental education program [5, 16, 29]
35	Dissemination of the belief: water is an inexhaustible resource and low-priced [6]

Source: [1] Keshavarzi *et al.* (2006); [2] Fullerton Jr *et al.* (2007); [3] Cochram and Cotton (1984); [4] Schindler and Donahue (2006); [5] Morais and Almeida (2006); [6] Corral-Verdugo (2003); [7] Savenije and Van der Zaag (2002); [8] Rogers *et al.* (2002); [9] Tillman *et al.* (2005); [10] López-Paredes *et al.* (2007); [11] Athanasiadis *et al.* (2005); [12] Froukh (2001); [13] Lertpalangsunti *et al.* (1999); [14] Albuquerque *et al.* (2008); [15] Mahabir *et al.* (2003); [16] Hoag (1992); [17] Altunkayank *et al.* (2005); [18] Melo and Jorge Neto (2007); [19] Qin *et al.* (2008); [20] Pinto and Araujo Neto (2009); [21] Miranda and Fill (2009); [22] Cardoso and Bordigon (2009); [23] Acselrad *et al.* (2009); [24] Belem (2009); [25] Galvão (2007); [26] Sim *et al.* (2005); [27] Motiee *et al.* (2001); [28] CUWA and A&N (2004); [29] Mitchell and Cubed (1997); [30] Silva *et al.* (2008); [31] Chakrabarti (2001); [32] Fernandes Neto *et al.* (2004)

The WSC has appeared as an inadequate ratio between water consumption and water supply (Motiee *et al.*, 2001). The water consumption and water available are vague and ambiguous terms, because are dependent of haziness measures, qualitative factors, scarcity data and low-quality data (Sim *et al.*, 2005). Some of these factors were considered in this paper, the faulty water metering, the imprecise value of the average pressure in the water distribution network and the imprecise value of water-loss in water supply system. A fuzzy mathematical model of the WSC is written as (equation 5):

$$WSC = \widetilde{WC} - \widetilde{WS} \qquad (5)$$

where $\widetilde{WC}$ is a fuzzy mathematical model that represent the average value of the water consumption and $\widetilde{WS}$ is a fuzzy mathematical model that represent the average value of the water supply. The membership functions for the fuzzy numbers $\widetilde{WC}$ and $\widetilde{WS}$ are approximately equal to the observed values of water consumption and water supply, following a triangular membership function as shown in Figures 3 and 4.



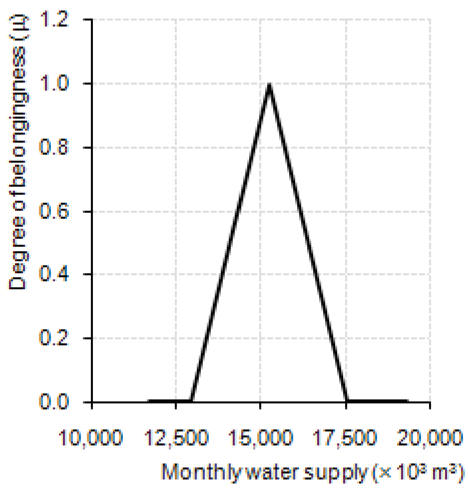


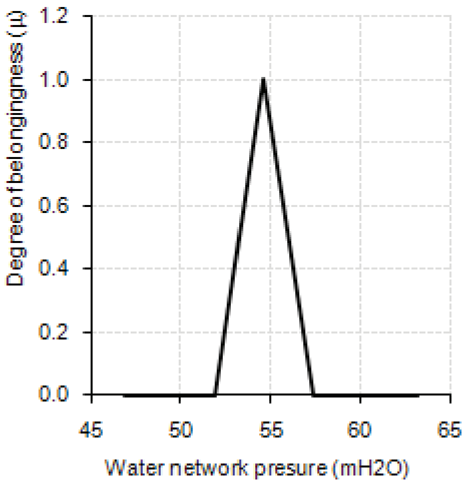
Figure 3 – Fuzzy number for water consumption
Figure 4 – Fuzzy number for water supply

For mathematical representation of the $\widetilde{WC}$, a fuzzy mathematical model was proposed considering some influencing factors in water consumption: the ambient temperature, the relative humidity, rainfall, collected revenues, unemployment indicator, and average pressure in the water distribution network. The $\widetilde{WC}$ model was based on some assumptions, as follows: the existence of a non-linear relationship among the influencing factors, the existence of a haziness of 10% in observed values of water consumption (error of household's water meter), the increase of the water consumption with the increase of the ambient temperature, the existence of a relationship between relative humidity and the rainfall, the reduction of water consumption with the increase relative humidity, the increase of the water consumption with the increase of the revenues collected, the reduction water consumption with the increase of the unemployment indicator, the increase water consumption with the increase of the average pressure in the water distribution network and the existence of a haziness of ±5% in observed values of the average pressure in the water distribution network. Likewise, a fuzzy mathematical behavior of the $\widetilde{WS}$ was proposed, considering as influencing factors the total water-loss in water supply system and the intermittence in water supply system. The $\widetilde{WS}$ model was based on the following assumptions: the existence of a non-linear relationship among the influencing factors, the existence of a haziness of ±10% in observed values of the water supply (error of waterworks' water meter), the reduction of the water supply with the increase of the intermittence in water supply system, the reduction of the water supply with the increase of the total water-loss in water supply system and the existence of a haziness of ±10% in observed values of the total water-loss. All assumptions made are according to previous research (Lertpalangsunti *et al.*, 1999; Froukh, 2001; Fernandes Neto *et al.*, 2004; Sim *et al.*, 2005; Fullerton Jr *et al.*, 2007). The equations 6 and 7 compose the proposed model:

$$\widetilde{WC} \cong \beta_0 + \beta_1^{tp} - \beta_2^{rh+rf} + \beta_3^{rc} - \beta_4^{ui} + \beta_5^{\widetilde{pr}} \quad (6)$$

$$\widetilde{WS} \cong \beta_6 - \beta_7^{\widetilde{wl}} - \beta_8^{ic} \quad (7)$$

where β_0, β_1,..., β_8 are parameters, tp is the ambient temperature, rh is the relative humidity, rf is the rainfall, rc is the amount of collected revenues, ui is the unemployment indicator, $\widetilde{pr}$ is the average pressure in the water distribution network, $\widetilde{wl}$ is the total water-loss in water supply system and ic is the intermittence in water supply system. The membership functions for the fuzzy numbers $\widetilde{pr}$ and $\widetilde{wl}$ were considered approximately equal to the observed values of the average pressure in the water distribution network and total water-loss in water supply system, following a pattern of a triangular membership function as shown in Figures 5 and 6. The gathering and simulated data and its respective descriptions are shown in Table II.



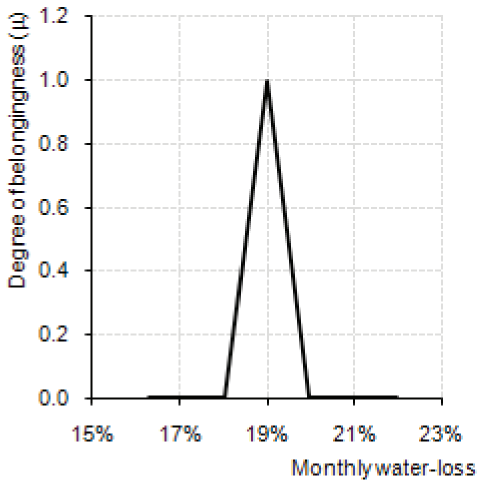


Figure 5 – Fuzzy number for pressure in the water distribution network
Figure 6 – Fuzzy number for total water-loss in water supply system

Table II – Gathering and simulated data

Gathering and simulated data	Average ± sd*	Symbol	Unit	Data source
Water consumption	14,381.2 ± 773.8	$\widetilde{WC}$	× 10^3 m^3.$month^{-1}$	Simulated
Water supply	15,234.0 ± 325.3	$\widetilde{WS}$	× 10^3 m^3. $month^{-1}$	CAESB **
Ambient temperature	21.1 ± 1.15	tp	ºC	INMET **
Relative humidity	67.83 ± 10.10	rh	%	INMET **
Rainfall	113.21 ± 82.26	rf	mm.$month^{-1}$	INMET **
Collected revenues	681.70 ± 41.05	ra	million R$.$month^{-1}$	GDF **
Water distribution network pressure	54.63 ± 6.62	$\widetilde{pr}$	mH2O	Simulated
Unemployment indicator	16.85 ± 1.13	ui	%	GDF
Total water-loss in water supply system	18.99 ± 4.41	$\widetilde{wl}$	%	Simulated
Intermittence in water supply system	35.32 ± 6.95	ic	hours.$month^{-1}$	Simulated

* sd is the standard error; ** availability of data on the Internet, partially simulated

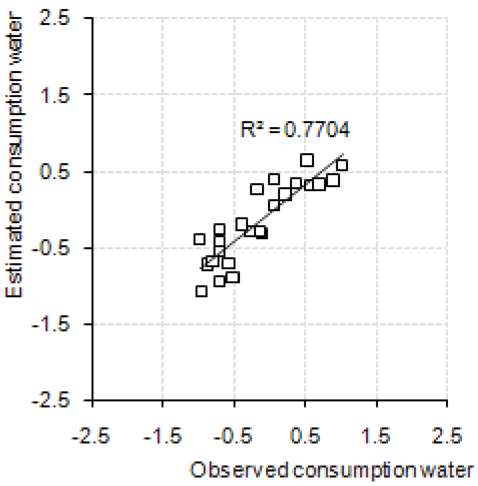
Equations 8 and 9 show the results of the optimization of the parameters in the proposed conceptual model when applying the previously described data normalized according to the Equation 4. Table III and Figures 7, 8, 9, 10, 11 and 12 show the results of the model performance.

$$\widetilde{WC} \cong -0.9859 + 1.2350^{\widetilde{tp}} - 1.4188^{\widetilde{rh+rf}} + 0.8302^{\widetilde{rc}} - 1.4983^{\widetilde{ui}} + 1.4620^{\widetilde{pr}} \quad (8)$$

$$\widetilde{WS} \cong 2.1559 - 1.7744^{\widetilde{wl}} - 1.4819^{\widetilde{ic}} \quad (9)$$

Table III – Results of calibration and verification of models

	Calibration			Verification		
Models	r	R^2	AARE	r	R^2	AARE
Water consumption - $\widetilde{WC}$	0.8777	0.7704	72.55	0.5994	0.3593	127.80
Water supply - $\widetilde{WS}$	0.9755	0.9516	45.05	0.9412	0.8858	69.93



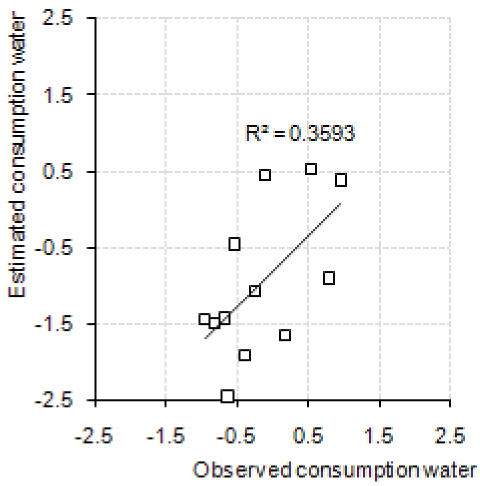
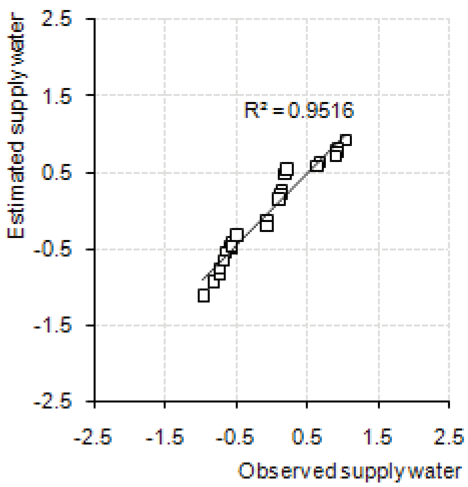


Figure 7 – Calibration $\widetilde{WC}$ model
Figure 8 – Verification $\widetilde{WC}$ model



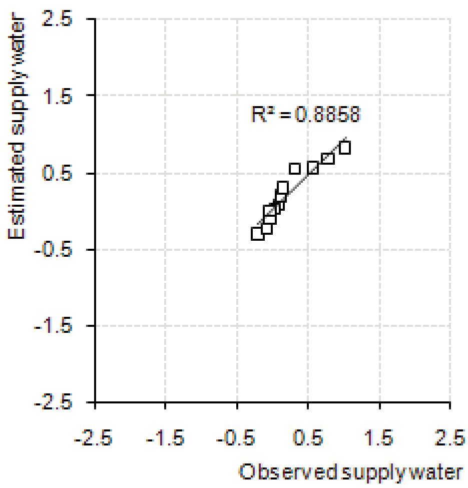
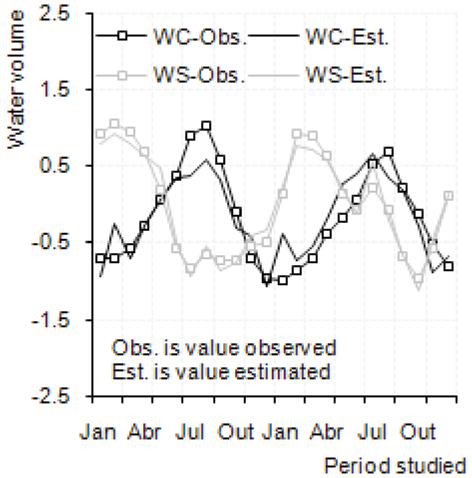


Figure 9 – Calibration $\widetilde{WS}$ model
Figure 10 – Verification $\widetilde{WS}$ model

The calibration and verification results indicated that the proposed conceptual model has shown good agreement to the gathered and simulated data, when considering some previous research. For instance, a study on water demand developed in Oklahoma and Tulsa cities, Oklahoma State, USA, resulted in a statistical model to explain water demand with R^2 range within the interval of 0.140 a 0.920 (Cocharn and Cotton, 1984). In a household water demand study in the northwest of Spain, price, billing, climatic, and sociodemographic variables were used as explanatory variables and the results showed a R^2 range within the interval of 0.198 a 0.891 (Martinez-Espiñeira, 2002). Another study with the objective of predicting future water consumption from Istanbul city, Turkey, was developed, using the Takagi Sugeno Fuzzy method for modelling monthly water consumption, and the overall prediction presented an average absolute relative error less than 10% (Altunkaynak *et al.*, 2005).



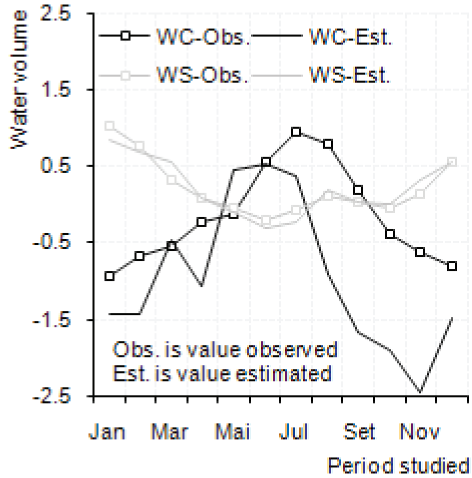


Figure 11 – Calibration $\widetilde{WC}$ and $\widetilde{WS}$ model
Figure 12 – Verification $\widetilde{WC}$ and $\widetilde{WS}$ model

In another regional water study, the case of Tijuana city, in Northwestern Mexico, the purpose was to analyze monthly water consumption dynamics, and the empirical estimation results were considered fairly satisfactory with the R^2 range from 0.4582 to 0.5932 (Fullerton Jr *et al.*, 2007).

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

It can be concluded that the water supply system crisis in urban environment was adequately modeled, the ambiguity and the lack of precision of the available real data was acceptably managed, and the fuzzy approach has been demonstrated to be adequate to the problem studied. The conceptual model developed in this research can contribute to the water conservation in urban environment, being an important tool for water resources planning.

4.2 RECOMMENDATIONS

The ambiguity and haziness index of the real data should be considered in next studies. In the future, more influencing factors in water crisis should enter in the model being developed, in order of improving prediction results.

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