Chapter

Fuzzy Modeling of Urban Water Supply Crisis

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Abstract

The chaotic growth of cities results in numerous problems related to public health and urban environment. One of these problems is the urban water supply system crisis. This research aims to develop a mathematical model for urban water supply crises (UWC) able to deal with the ambiguity of the real available data. The applied methodology comprises the following steps: (i) identifying the influencing factors in UWC; (ii) proposing a conceptual model for the description of UWC; (iii) collecting and simulating the necessary and available data; (iv) optimizing the conceptual model parameters; and (v) verifying the proposed model performance. The results indicate that there are many influencing factors in UWC. The model developed comprises two parts or two sub-models. The first sub-model explains water consumption, and the second sub-model explains water availability. In the first sub-model, the functions are related to the factors that influence water consumption. In the second sub-model, the functions are related to the factors that influence the availability of water. This research also aims to analyze the possibility of applying Fuzzy Logic to deal with the ambiguity of real data. It was concluded that, with the proposed model, the UWC was modeled appropriately. The model proposed can help to predict the impact of actions such as reducing losses, reducing pressure on the water supply network and intermittent supply on the intensity of water crisis cases in cities.

Keywords: water crisis, water scarcity, fuzzy logic, water consumption, water demand

1. Introduction

According to data from the World Meteorological Organization, global water consumption increased more than six-fold in less than a century, more than double the rate of the population growth, and continues to grow considering rising consumption in the agricultural, industrial and domestic sectors [1]. These data lead to the conclusion that in the coming years the global situation of water reserves will move towards a crisis, both in quantitative and qualitative aspects, if adequate water management actions are not taken. More recently, urban water supply crises (UWC) have been observed, a context characterized by water scarcity, as well as damage to the environment and 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 from the 1970s led to a sudden crisis in the city's water supply system in the 1990s [2]. Other examples were also reported, such as in Palestine, where a UWC case was observed caused mainly by the inadequate access to freshwater resources and inappropriate management [3]. The city of Tijuana, in Mexico, has shown the highest rates of economic growth in the country, resulting in a rapid increase of water demand and consequently the emergence of a UWC [4]. From 1998 to 2000, the city of Campina Grande in Brazil faced a WSC caused by severe periods of drought and the complete absence of freshwater resource management [5]. This UWC caused serious water rationing in Campina Grande that lasted one year. This is not a unique case in Brazil as frequent water rationing has been observed in the cities of Recife and São Paulo [6]. In the Brazilian Federal District, rapid non-planned urbanization and land changes have had a considerable impact on water resources. From 2016 to 2018, the city of Brasilia also went through a UWC situation, and governance, regulation, as well as management support strategies in the urban and rural environment were implemented [7].

In another study, an investigation into Qatar's sustainability crisis, originating from high levels of water, electricity and food consumption was carried out [8]. The high levels of consumption were made possible by the significant wealth of hydrocarbons, redistributive water governance of a generous rentier state and structural dependence on imported food and subsidies on food production. In this state, the water crisis is silent because it does not cause interruptions in supply or public discontent. The possible solution comes from programs that integrate the water, energy and food sectors [8].

The imprecise and ambiguity are inherent to the water supply system, e.g., pressures, flow rate supply and consumption, age and characterization of pipe resistance. Some researches that addressed this imprecise using Fuzzy Logic are briefly described below. A study to accommodate aleatory uncertainty was performed using stochastic analysis to represent the input uncertainties and to estimate resulting uncertainty in nodal pressures and pipe flows) [9]. Results of Fuzzy analyses for two realistically sized water distribution networks show that the proposed method performs with an acceptable level of accuracy and greatly reduces computational time [9].

The need to improve predictive models of hydraulic transients in water systems (water supply networks) was the subject of another study [10]. For this purpose, triangular Fuzzy numbers are used to represent the input uncertainties. Then, to obtain the extreme pressure heads in each location of the network and at each level of uncertainty, four independent optimization problems are solved. The results is found computationally fast and promising for real applications [10].

The Fuzzy Logic is a perfect tool among white-box methods (models based on laws of physics, chemistry, others, that govern the dynamic behavior of the system) for risk analysis due to the capabilities in dealing with limited data, subjective and temporal variables, and modeling expert opinions, among others [11]. For this reason, Fuzzy Logic was used as comprehensible framework for assessing water supply risk based on existing and under-construction projects in Mashhad city, Iran. The results showed that the framework based on the Fuzzy and possibility theory is befitting to information gathered from experts. Such a framework can provide a simple method to apply the proposed methodology to other water management projects, where, despite the high level of investment, there is no clear idea of the risks and their consequences [11].

Mathematical modeling is a well-known tool for water management. However, when considering UWC, there are some limitations of the conventional mathematical modeling that are related to vague and ambiguous data (e.g. real water-loss, real water availability, setting water tariffs, among others). In theory, the UWC problem can be formulated as a mathematical problem. In practice, rules are considered to be a more practical method. However, the combination of mathematical programming and Fuzzy rule has rarely been discussed in the literature [12]. The aim of this chapter is to describe the develop a mathematical model for UWC, dealing with this ambiguity and real data uncertainty.

2. Theoretical background

UWC modeling was essentially based on the definitions of water crisis and Fuzzy Logic. The topics are presented briefly below.

2.1 Urban water supply crisis (UWC)

A UWC case was presented in Iran, and information about its installation process, climatic characteristics of the region, range of per capita water consumption, among others was provided [13]. As the authors mention, up to 1990, water supply was not a critical problem and there was an acceptable relationship between water demand and distribution. Over the last decade, however, the problem has become critical and the reasons identified include rapid population growth. In addition, there is a reduction in the number of water supply systems (due to the loss of financial resources) and the widespread occurrence of droughts. Considering these observations, one can arrive at the concept of UWC, basically translated as a mismatch between water supply and consumption rates, according to Eq. (1).

$$UWC = C - A \tag{1}$$

In which: C is water consumption; A is the water availability.

According to [14], when clarifying the terms of water consumption (C) and water availability (A) and the definition of constraints, some issues then need answers. Is there a more suitable form of a mathematical model to represent water consumption (C)? Is there a mathematical model that is the water availability (A)? What and how many factors are there (socioeconomic, environmental, cultural, urban, and management conditions) that should be considered in these models? What restrictions should be imposed on the optimization model? The literature review suggests that Fuzzy Logic can help by incorporating imprecision and ambiguity in the translation of influential factors and field characteristics.

2.2 Fuzzy logic

The advent of Fuzzy Logic originates from the need of a method that can systematically express inaccurate, vague, ill-defined quantities [15]. For example, instead of using a complex mathematical model, industrial controllers based on Fuzzy Logic can be implemented using knowledge from human operators, or heuristic knowledge. This makes the control action using Fuzzy Logic as good as using the raw knowledge (generally better) and always consistent. In decision analysis, Fuzzy Logic can be used in tasks in which individual variables are not defined in exact terms. Some examples of this have been provided in the literature [16, 17]. In the environmental area, the population's preference for water conservation action, the assessment of the performance of environmental education programs and policies in preventing forest fires are examples of individual variables not defined in exact terms. The properties of Fuzzy Systems are demonstrated in several publications, as, for example, in [18]. An introduction to the theory of Fuzzy sets is presented below.

In general, a Fuzzy Set can be summarized as follows [15, 18, 19]:

- 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 (Eq. 2):

$$\mu_{\tilde{a}}(x) = \begin{cases} 1, & for\ x \in [m,n] \\ L(x), & for\ x < m \\ R(x), & for > n \end{cases} \tag{2}$$

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, $0 \leq R(x) \leq 1, \lim_{x\to\infty} R(x) = 0$.

The Fuzzy Linear Programming Problem (FLPP) with decision variables and coefficient matrix of constraints are in Fuzzy nature (Eqs. 3–6).

$$\tilde{z} = max \sum_{j=1}^{n} \tilde{c}_j x_j \tag{3}$$

subject to

$$\sum_{j=1}^{n} \tilde{A}_{ij} x_j \leq \tilde{B}_i \tag{4}$$

$$1 \leq i \leq m \tag{5}$$

$$x_i > 0 \tag{6}$$

The triangular Fuzzy numbers A which can be represented by three crisp numbers s, l, r (Eqs. 7–10).

$$f_i(x_j) = max \sum_{j=1}^{n} \tilde{c}_j x_j \tag{7}$$

subject to

$$\sum_{x \geq 0} (s_{ij}, l_{ij}, r_{ij}) x_{ij} \leq (t_i, u_i, v_i) \tag{8}$$

$$1 \leq i \leq m \tag{9}$$

$$1 \leq j \leq n \tag{10}$$

Where: $\tilde{c} = (c_s, c_l, c_r)$, $\tilde{A} = (s_{ij}, l_{ij}, r_{ij})$ and $\tilde{B} = (t_i, u_i, v_i)$ are Fuzzy numbers.

- Theorem 3: For any two triangular Fuzzy numbers $\tilde{A} = (s_1, l_1, r_1)$ and $\tilde{B} = (s_1, l_2, r_2)$, $\tilde{A} \leq \tilde{B}$ if and only if $s_1 \leq s_2, s_s - l_1$ and $s_1 + r_1 \leq s_2 + r_2$. Above problem can be rewritten (Eqs. 11–15).

$$f_i(x_j) = max \sum_{j=1}^{n} \tilde{c}_j x_j \tag{11}$$

subject to

$$\sum_{j=1}^{n} s_{ij} x_{ij} \leq t_i \tag{12}$$

$$\sum_{j=1}^{n} (s_{ij} - l_{ij}) x_j \leq t_i - u_i \tag{13}$$

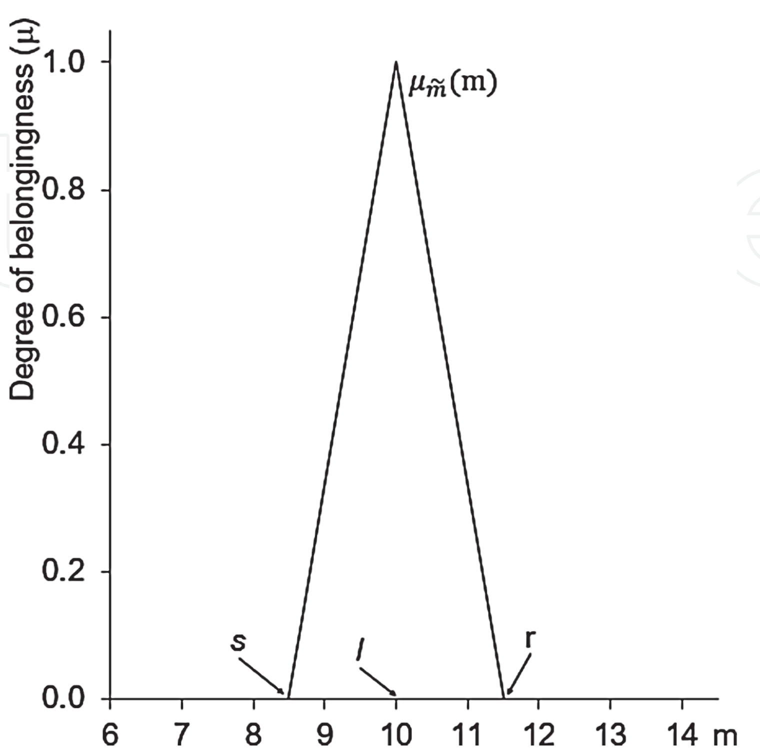

Figure 1.
Fuzzy number $\tilde{m} = (m_s, m_l, m_r)$, triangular membership function.

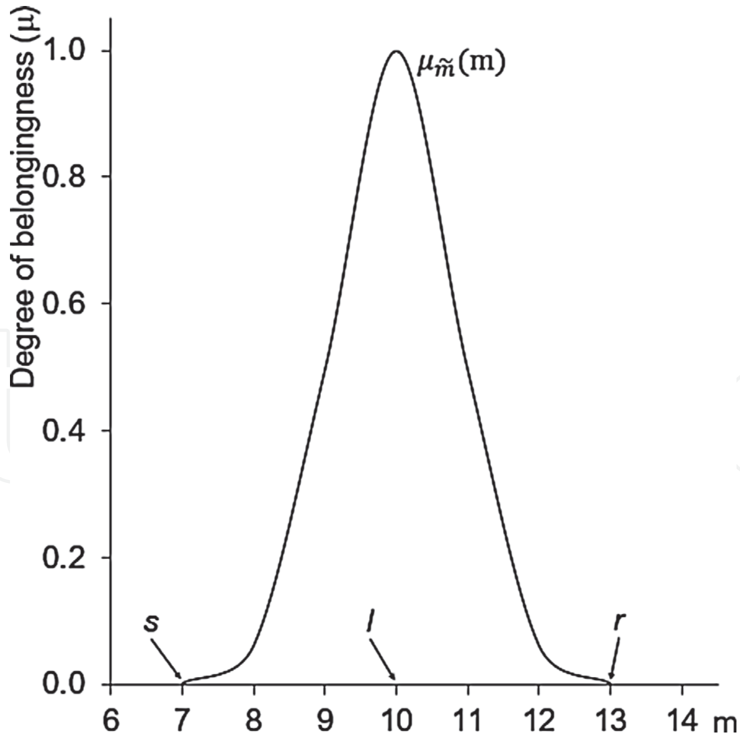

Figure 2.
Fuzzy number $\tilde{m} = (m_s, m_l, m_r)$, bell-shaped membership function.

$$\sum_{j=1}^{n} (s_{ij} - l_{ij}) x_j \leq t_i - v_i \tag{14}$$

$$x_i \geq 0 \tag{15}$$

As examples of membership functions for a Fuzzy number $\tilde{m}$, such as approximately $m = 10$, a triangular membership function (Eq. 16) and a bell-shaped membership function (Eq. 17) is widely used.

$$\mu_{\tilde{m}} = \left(0, 1 - \frac{|x - m|}{a}\right), a > 0 \tag{16}$$

$$\mu_{\tilde{m}} = e^{-b(x-m)^2}, b \geq 1 \tag{17}$$

Such membership functions are illustrated in **Figures 1** and **2**. More information about Fuzzy Mathematical Programming is available in the literature [15–23].

3. Methodology

The methodology of this work comprised the following steps: (1) identifying the influencing factors in UWC; (2) proposing a conceptual model for UWC; (3) data collection and data simulation; (4) optimizing the proposed conceptual model parameters (calibration); and (5) assessing conceptual model performance (verification).

For step (1), a literature review was conducted related to WSC management.

For step (2), the definition of UWC found in the literature was taken and the Fuzzy Non-Linear Programming (FNLP) was used [12, 15–24].

For the third step (step 3), a case study was simulated in Brazil, more precisely in the Federal District, taking into account predictions made by some researchers.

The necessary data were collected from the Brazilian Federal District's water supplier and sanitation company (CAESB), from the National Institute of Meteorology in Brazil (INMET) and from the Brazilian Federal District's Government (GDF). The simulation was conducted assuming the hypothesis of a significant increase in the water consumption in coming years, as well as managerial and political stagnation of the water supplier and sanitation company. The time series analysis refers to three years (2007, 2008 and 2009). The period for model calibration was considered for two years and the verification period was considered for one year. 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 to eliminate the difference among scales measuring the influencing factors, according to Eq. (18).

$$x_{norm} = 1 - \frac{2 \times (x_{max} - x_0)}{x_{max} - x_{min}} \tag{18}$$

Where: x_{norm} is the normalized value; x_0 is the original value; x_{max} is the maximum value; 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 adopted, using the spreadsheet from Open Office (Calc-Solver). As a justification for using the DEPS algorithm, it presents good performance to obtain global optimums, based on the synergy between Particle Swarm Optimization (PSO) and Differential Evolution (DE) [25].

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 relative error percentage (AREP) and graphic observed values *versus* estimated values.

4. Results and discussions

A bibliographic review was conducted by [26] and resulted in a list of influential factors presented below:

- Population growth rate.
- Human population density.
- Socio-economic level.
- Education level.
- Industry level.
- Ambient temperature.
- Relative humidity.
- Rainfall.
- Seasonality.
- Size and topographic characteristics of the city.

- Percentage of water metering.
- Water tariffs.
- Type of water tariff policies.
- Existence of wastewater collection systems.
- Human Development Index.
- Pressure in the water distribution network.
- Existence of conservation habits.
- Number/type of hydro-sanitary equipment per household.
- Constructed area per household.
- Number of rooms.
- Abundance or scarcity of water sources.
- Water-loss.
- Social representation and identification of each family.
- Existence and type of municipal water resources policy.
- Acceptance of the population to water conservation and rational use actions.
- Typology of land use.
- Type of consumers.
- Type of municipality.
- Predominant function of urban environment.
- Existence of policies to promote water conservation.
- Intermittence in the water supply system.
- Energy consumption.
- Existence of regulatory policy on water consumption.
- Existence of environmental education program.
- Dissemination of the belief: water is an inexhaustible resource and low-priced.

The UWC has appeared as an inadequate ratio between water consumption and water supply [12]. Water consumption and water availability are vague and ambiguous terms, because they are dependent on haziness measures, qualitative factors, scarcity data and low-quality data [27].

Design and analysis of water distribution networks (WDNs) are laden with uncertainty. There is natural randomness, such as variations in reservoir elevation heads, and there is epistemic randomness, i.e., incomplete knowledge, imprecise data, and linguistic ambiguity. Both are associated with the characterization of pipe resistance, nodal demands, and hydraulic responses [9]. The analysis of water distribution networks has to take into account the variability of users' water demand and the variability of network boundary conditions, e.g. the presence of local private tanks and intermittent distribution [28].

Some of these factors were considered in this paper, the faulty water metering ($\tilde{C}$ and $\tilde{A}$), the imprecise value of the average pressure ($\tilde{p}$) in the water distribution network and the imprecise value of water-loss ($\tilde{l}$) in the water supply system. A fuzzy mathematical model of the UWC is written as Eq. (19).

$$UWC = \tilde{C} - \tilde{A} \tag{19}$$

Where: $\tilde{C}$ is a fuzzy mathematical model that represents the average value of the water consumption; $\tilde{A}$ is a fuzzy mathematical model that represent the average value of the water availability.

For a mathematical representation of the $\tilde{C}$, 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 $\tilde{C}$ 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%, that is $\tilde{C} = (C_s, C_l, C_r)$, in observed values of water consumption (error of household's water meter), the increase in the water consumption with the increase in 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 in the water consumption with the increase in the revenues collected, the reduction in water consumption with the increase of the unemployment indicator, the increase in water consumption with the increase of the average pressure (p) 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, that is $\tilde{p} = (p_s, p_l, p_r)$.

Likewise, a Fuzzy mathematical behavior of the $\tilde{A}$ was proposed, considering the total water-loss in water supply system and the intermittence in the water supply system. The $\tilde{A}$ model was based on the following assumptions as influencing factors: the existence of a non-linear relationship among the influencing factors, the existence of a haziness of ±10%, that is $\tilde{A} = (A_s, A_l, A_r)$, in observed values of the water supply (error of waterworks' water meter), the reduction of the water supply with the increase in the intermittence in the water supply system, the reduction in the water supply with the increase in the total water-loss (l) in the water supply system and the existence of a haziness of ±10% in observed values of the total water-loss, that is $\tilde{l} = (l_s, l_l, l_r)$.

The membership functions for the fuzzy numbers $\tilde{C}$ and $\tilde{A}$ 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**.

The membership functions for the fuzzy numbers ($\tilde{p}$) and ($\tilde{l}$) were considered approximately equal to the observed values of the average pressure in the water distribution network and total water-loss in the water supply system, following a pattern of a triangular membership function as shown in **Figures 5** and **6**.

All assumptions, from $\tilde{C}$ and $\tilde{A}$, made are according to previous research [4, 27–31]. Eqs. (20) to (27) compose the proposed FNLP model.

$$\tilde{z}_C = min \sum_{i=1}^{n} \left(\tilde{C}_{E,i} - \tilde{C}_{O,i}\right)^2 \quad (20)$$

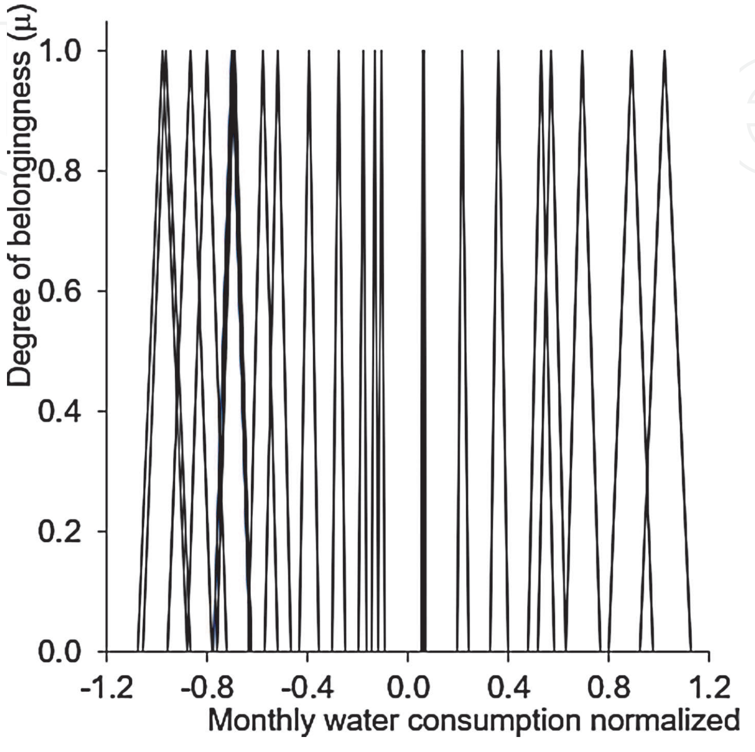

Figure 3.
Fuzzy number for water consumption, $\tilde{C}$.

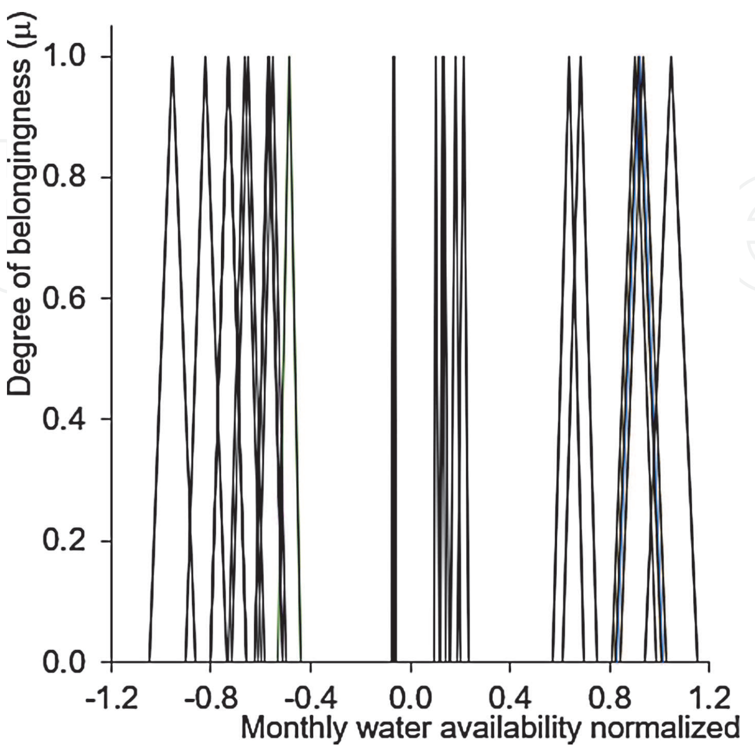

Figure 4.
Fuzzy number for water availability, $\tilde{A}$.

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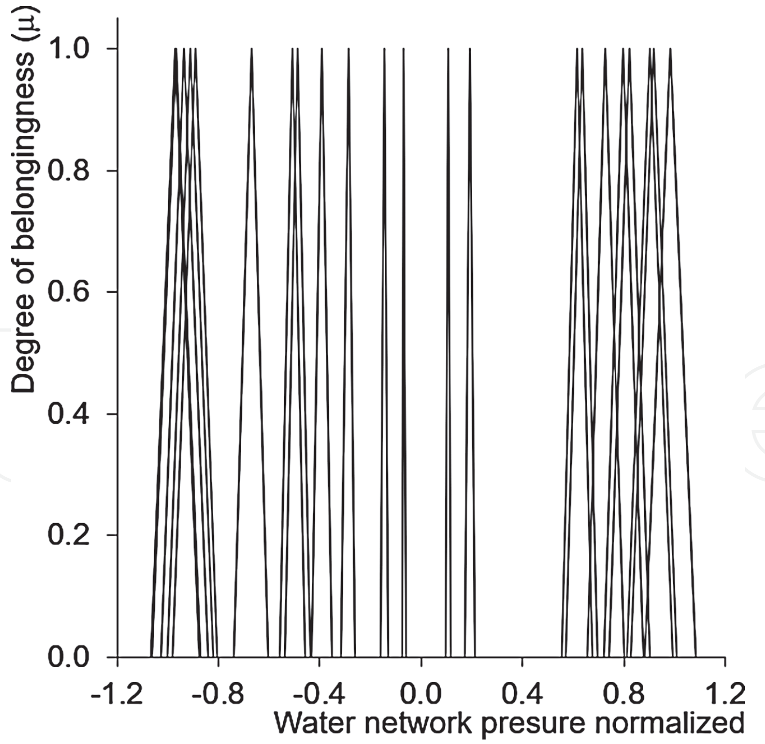

Figure 5.
Fuzzy number for pressure in the water distribution network, $\tilde{p}$.

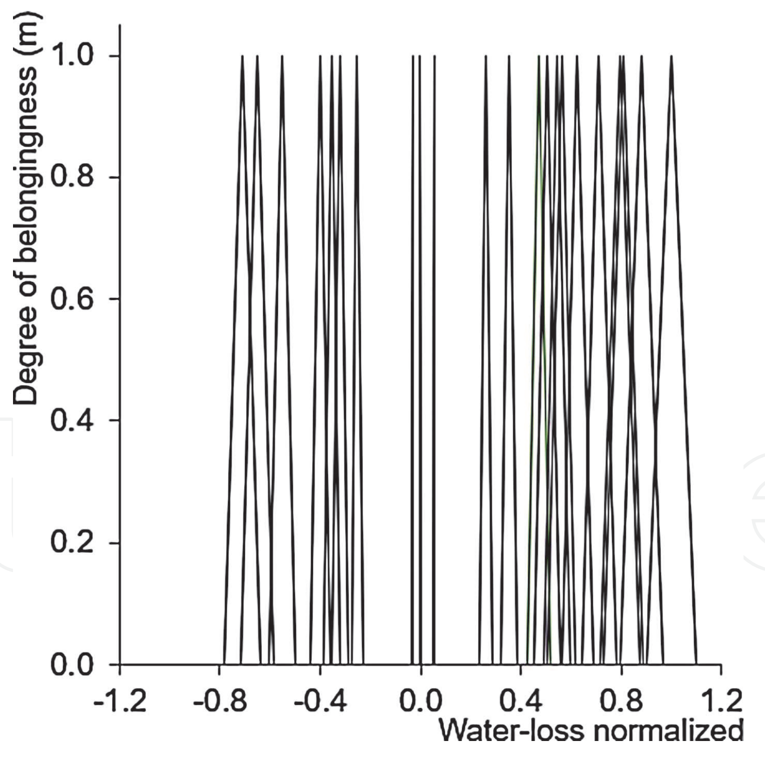

Figure 6.
Fuzzy number for total water-loss in water supply system, $\tilde{l}$.

subject to

$$\tilde{C}_{E,i} = \beta_0 + (\beta_1)^{x1_i} - (\beta_2)^{x2_i + x3_i} + (\beta_3)^{x4_i} - (\beta_4)^{x5_i} + (\beta_5)^{\tilde{p}_i} \tag{21}$$

$$\tilde{p} = (p_s, p, p_r) \tag{22}$$

$$\tilde{C}_{O,i} = (C_{O,i,s}, C_{O,i}, C_{O,i,r}) \tag{23}$$

$$\tilde{z}_A = \acute{m}in \sum_{i=1}^{n} \left(\tilde{A}_{E,i} - \tilde{A}_{O,i}\right)^2 \tag{24}$$

subject to

$$\tilde{A}_{E,i} = \beta_6 - \beta_7^{\tilde{l}} - \beta_8^{x6} \tag{25}$$

$$\tilde{l} = (l_s, l, l_r) \tag{26}$$

$$\tilde{A}_{O,i} = (A_{O,i,s}, A_{O,i}, A_{O,i,r}) \tag{27}$$

Where: $\tilde{z}_C$ is the objective function representing the calibration of $\tilde{C}$; $\tilde{C}_{E,i}$ is a fuzzy number representing the estimated water consumption; $\tilde{C}_{O,i}$ is a Fuzzy number representing the observed water consumption; $C_{O,i,s}$ and $C_{O,i,r}$ are the lower bound and upper bound of Fuzzy triangular numbers in the set $\tilde{C}_{O,i}$, as is shown in **Figure 1**; $\tilde{z}_A$ is the objective function representing the calibration of $\tilde{A}$; $\tilde{A}_{E,i}$ is a Fuzzy number representing the estimated water availability; $\tilde{A}_{O,i}$ is a Fuzzy number representing the observed water availability; $\tilde{A}_{O,i,s}$ and $\tilde{A}_{O,i,r}$ are the lower bound and upper bound of Fuzzy triangular numbers in the set $\tilde{A}_{O,i}$, as is shown in **Figure 1**; $\beta 0$, $\beta 1$, …, $\beta 8$ are parameters, $x1$ is the ambient temperature; $x2$ is the relative humidity; $x3$ is the rainfall; $x4$ is the amount of collected revenues; $x5$ is the unemployment indicator; $\tilde{p}$ is the average pressure in the water distribution network; $\tilde{l}$ is the total water-loss in the water supply system; $x6$ is the intermittence in the water supply system.

Eq. (28) and (29) show the results of the parameter optimization in the proposed conceptual model when applying the previously described data normalized according to Eq. 4.

$$\tilde{C}_P = -0.9859 + 1.2350^{x1} - 1.4188^{x2+x3} + 0.8302^{x4} - 1.4983^{x5} + 1.4620^{\tilde{p}} \tag{28}$$

$$\tilde{A}_P = 2.1559 - 1.7744^{\tilde{l}} - 1.4819^{x6} \tag{29}$$

Collected and simulated data	Average ± sd*	Symbol	Unit	Data source
Water consumption	14,381.2 ± 773.8	$\tilde{C}$	$\times 10^3$ m^3.month^{-1}	Simulated
Water availability	15,234.0 ± 325.3	$\tilde{A}$	$\times 10^3$ m^3. month $^{-1}$	Caesb** [32]
Ambient temperature	21.1 ± 1.15	*x1*	°C	INMET** [33]
Relative humidity	67.83 ± 10.10	*x*2	%	INMET** [33]
Rainfall	113.21 ± 82.26	*x*3	mm.month^{-1}	INMET** [33]
Collected revenues	681.70 ± 41.05	*x*4	million R$.month^{-1}	GDF** [34]
Water distribution network pressure	54.63 ± 6.62	$\tilde{p}$	mH_2O	Simulated
Unemployment indicator	16.85 ± 1.13	*x*5	%	GDF [34]
Total water-loss in water supply system	18.99 ± 4.41	$\tilde{l}$	%	Simulated
Intermittence in water supply system	35.32 ± 6.95	*x*6	hours.month^{-1}	Simulated

**sd is the standard error*
***availability of data on the Internet, partially simulated (fault fill)*

Table 1.
Collected and simulated data.

The collected and simulated data and its respective descriptions are shown in **Table 1**. **Table 2** and **Figures 7–12** show the results of the model performance.

The calibration and verification results indicated that the proposed conceptual model has shown good agreement for the collected and simulated data, when considering some previous research. For instance, a study on water demand developed in the cities of Oklahoma and Tulsa 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 [35].

In a household water demand study in the northwest of Spain, the 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 to 0.891 [36].

Another study aiming to predict future water consumption from Istanbul, Turkey, was developed using the Takagi Sugeno Fuzzy method for modeling monthly water consumption, and the overall prediction presented an AREP of less than 10% [37]. In this study, AREP ranged from −40% to 5% indicating an opportunity to improve the model developed. In another regional water study, in the case of Tijuana, in Northwest Mexico, the purpose was to analyze monthly water

	Calibration			Verification		
Models	**r**	**R^2**	**AREP**	**r**	**R^2**	**AREP**
Water consumption,	0.8777	0.7704	−7.95	0.5994	0.3593	−40.15
Water availability, $\tilde{A}$	0.9755	0.9516	5.32	0.9412	0.8858	−16.95

r: correlation coefficient
R^2: determination coefficient
AREP: average relative error percentage

Table 2.
Results of calibration and verification of models.

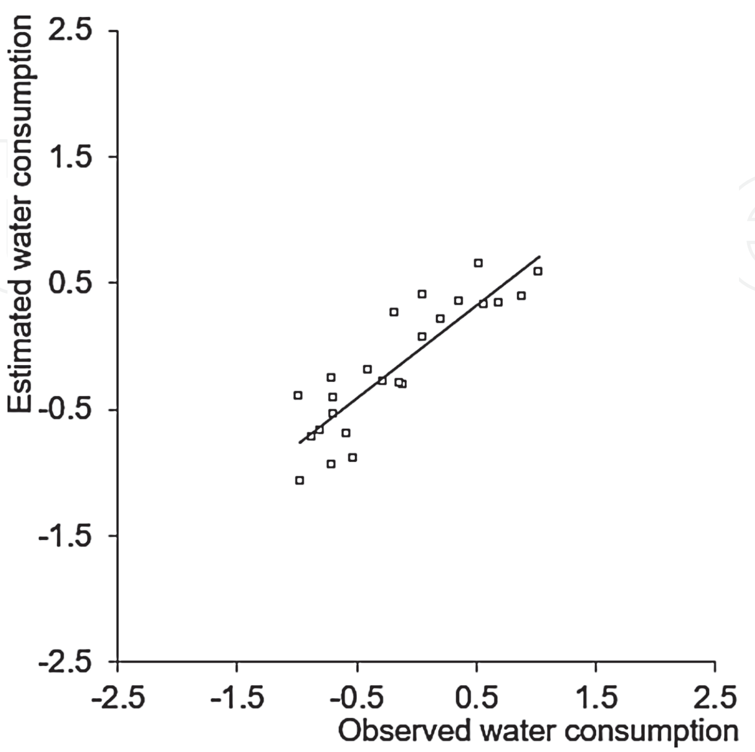

Figure 7.
Calibration $\tilde{C}$ model.

consumption dynamics, and the empirical estimation results were considered fairly satisfactory with the R^2 range from 0.4582 to 0.5932 [4].

The analysis in **Figure 12**, agreeing with the AREP of −40%, reinforces the difficulty of the model developed in the $\tilde{C}_P$ adjustment. The reasons for this difficulty are varied, including problems with data quality (simulation, filling in gaps), the need to incorporate influential variables, the need to improve Fuzzy modeling.

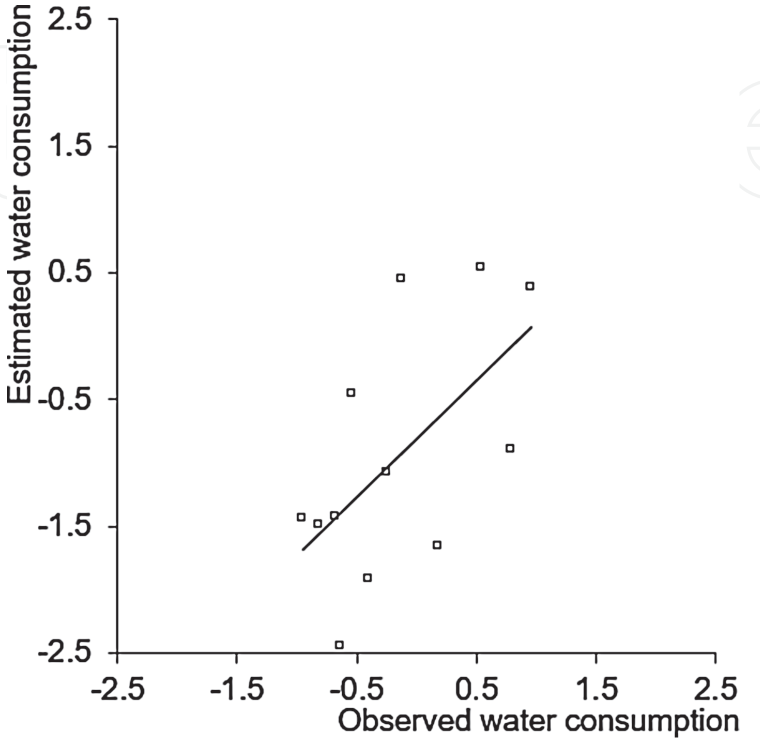

Figure 8.
Verification $\tilde{C}$ model.

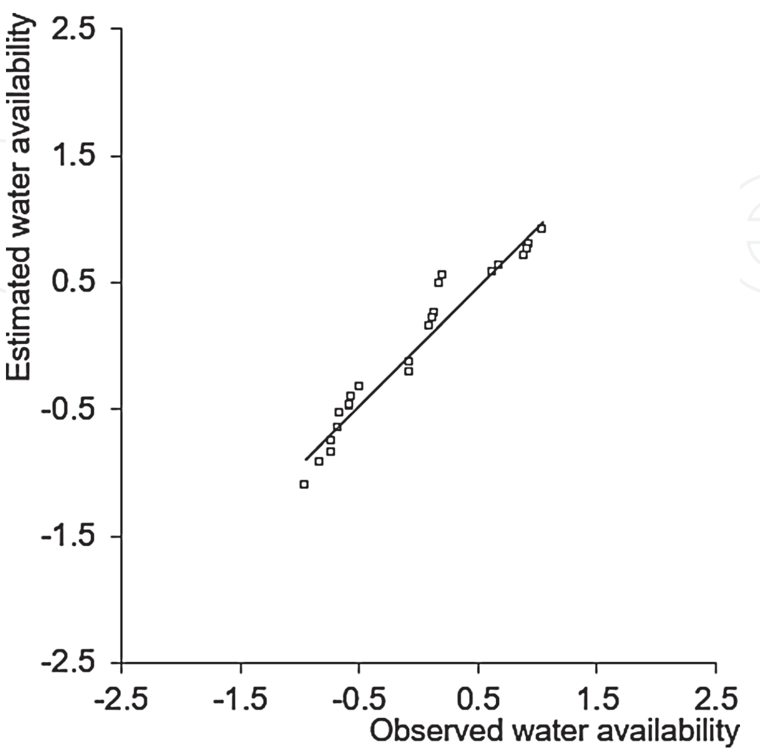

Figure 9.
Calibration $\tilde{A}$ model.

Therefore, we encourage continuous improvement of water consumption forecasting models focusing on optimizing the pertinence functions for the case (format, error rate rates, others).

In general, when considering the quality of the models developed ($\tilde{C}_P$ e $\tilde{A}_P$), according to **Table 2** and **Figures 7–12**, the viability of the FNLP can be verify. The Fuzzy Logic allowed inaccuracies inherent to the water system to be captured and

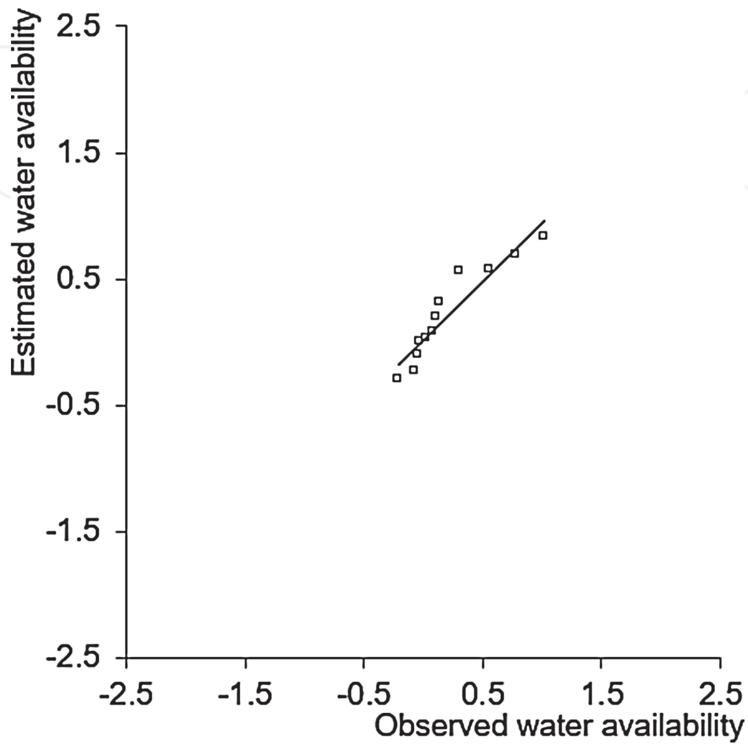

Figure 10.
Verification $\tilde{A}$ model.

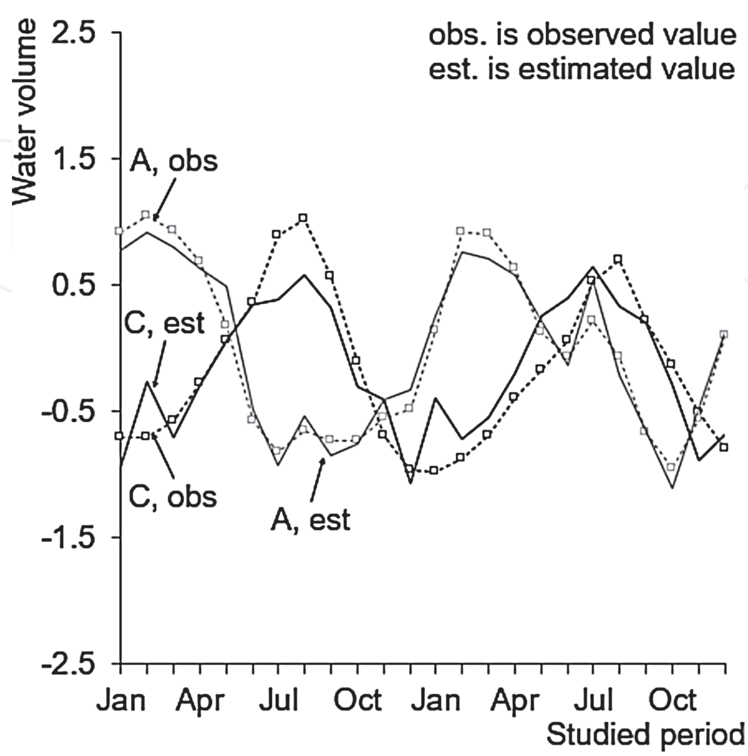

Figure 11.
Calibration model.

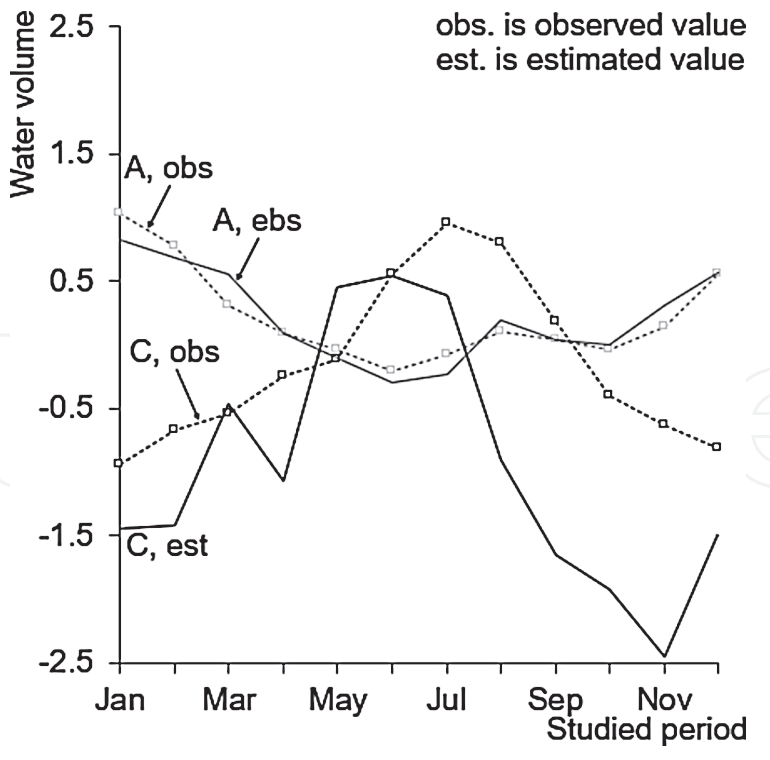

Figure 12.
Verification model.

incorporated into conventional mathematical programming techniques. The satisfactory results agree with previous studies [9, 27, 28].

5. Conclusions and recommendations

5.1 Conclusions

It can be concluded that the UWC was adequately modeled, the ambiguity and the lack of precision of the real data availability was acceptably managed, and the fuzzy approach showed to be adequate for the problem studied. The conceptual model developed in this research can contribute to the water conservation in an urban environment, which is an important tool for water resource planning. More specifically, the model helps to predict the impact of actions such as reducing losses, reducing pressure on the water supply network and intermittent supply on the intensity of water crisis cases in cities.

The methodology used for developing the model can be replicated in other cases. Influential variables can also be adjusted according to the desired responses and available resources. For example, variables such as type of tariff policy, implementation of environmental education programs and incentives to reduce water consumption are possible to be considered in this model. Thus, Fuzzy modeling is a very promising tool and should be encouraged so as to deepen and expand similar models.

5.2 Recommendations

The ambiguity and haziness index of the real data should be considered in further studies. In the future, more influencing factors in water crises should be included in the model being developed, in order to improve prediction results.

Finally, studies focusing on selecting the best forms of representation of Fuzzy variables (Fuzzy membership functions and optimized parameters) should be considered.

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Conflict of interest

The authors declare no conflict of interest.

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