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Evaluation of Measures for Combating Water Shortage Based on Beneficial and Constraining Criteria

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Abstract Water Scarcity encompasses both permanent and occasional water resources shortages. Measures to combat water scarcity are of different nature dependent on whether they intend to withstand permanent or occasional water deficiency. It is the aim of this paper to discuss and propose a systematic framework for the evaluation of measures of the Contingency Plan of a drought affected area, so that the measures are compatible and complementary to the long term Strategic Plans. For this reason the establishment of two sets of criteria is proposed, the beneficial and the constraining criteria. The beneficial criteria are those representing the short term good performance, whilst the constraining criteria express the incompatibility with the long term Strategic Plans and the long term negative impacts to the environment and the society. The beneficial criteria are aggregated by applying the widely-used multicriteria method of the weighted Euclidean Distance. The compatibility of the constraining criteria with the beneficial criteria is expressed by the use of suitable fuzzy implications. Finally a simple weighted sum is used in order to take into account both the beneficial criteria and the compatibility between the beneficial and constraining criteria. Based on this approach the selection and prioritisation of measures is enhanced leading to a more balanced and realistic defence against drought and water shortage. A numerical application is presented for illustrating the proposed methodology taking the city of Heraklion (Crete) as a case study.

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1 Introduction

Drought is a recurrent natural phenomenon affecting most of the regions around the globe. The initiation and the termination of drought are difficult to be detected. This is the reason for the characterisation of drought by many authors as a "creeping phenomenon" (Wilhite 1993a).

Drought is caused mainly by a sustained deficiency of rainfall amounts in a large area for a considerable period of time.

Several comprehensive reviews have been written for the identification, characterisation and analysis of the drought phenomenon. For an-in depth-review on the subject, the reader can consult specialised books such as Wilhite (1993b), Rossi et al. (2007), FAO/NDMC (2008), Pereira et al. (2009), Iglesias et al. (2009) and review papers such as Tsakiris et al. (2007), Hayes et al. (2007), Niemeyer (2008), Mishra and Singh (2010), Van Loon and Van Lanen (2012) and Tsakiris et al. (2013).

The main consequence of drought is that it creates water shortages and therefore it impedes development and disrupts the activities of most economic sectors, creating anxiety and hardship to the people, and damages to the environment.

To combat situations of water shortage, preparedness and contingency plans are formulated so that rational decisions will be taken, before, during, and after each drought episode with the aim to minimise the negative consequences from the drought episode. The Preparedness Plans usually incorporate a number of actions which can be mainly taken prior or during the drought episode. In addition the Contingency Plans prepare solutions which are activated during the period of drought in a systematic and coherent way.

It is the aim of this paper to discuss the issue of rational selection of actions to combat drought effects during its occurrence, so that a scientifically supported and transparent decision framework is available in the Contingency Plan for decision makers, institutions, stakeholders and the public.

The rational evaluation of actions (alternatives), which is the cornerstone of the Drought Contingency Plan, can be achieved by adopting a clear and balanced set of criteria for the selection of actions to be realised during the period of drought.

It should be stressed that the actions for combating drought are not always in line with the measures included in the water resources management plans (Tsakiris and Spiliotis 2011).

The main objective of this paper is to devise a methodology for the rational selection of actions of the Contingency Plan in relation to the long term process measures, which are included in the water resources management plans of the areas under study.

2 The "Beneficial" and "Constraining" Criteria

The proposed methodology considers two sets of criteria, which will be referred to as beneficial and constraining criteria throughout the text. The beneficial criteria are those for which the successful proposals contribute to the solution of the problem directly and therefore receive high scores. The constraining criteria are additional criteria concerned with the secondary damages or losses created by each proposed action or with the incompatibility of the action in relation to the long-term water resources planning for the area.

It can be supported that the beneficial criteria express the direct necessity of an action under a set of physical and economic terms, while the constraining criteria express the aim to keep the solution within a sustainability framework.

According to Loucks (2000), sustainable water resources management is a concept that emphasizes the need to consider the long-term future as well as the present. Water resource systems which are managed to satisfy the changing demands placed on them, now and in the future, without system degradation, can be considered sustainable.

Useful in this context is the definition of sustainable water resource systems, which are those designed and managed so as to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity (ASCE 1998; UNESCO 1999).

It is known that, the "water resources management" planning safeguard the so called long term water resources sustainability. Consequently, the constraining criteria can be described by the direct negative effect on the environment and the society of the proposed actions and the incompatibility with the long term "water resources management" planning.

More specifically, in the present study the most important criteria of both categories are proposed as follows:

a. Beneficial criteria

   1. Viability

      This criterion assesses the actual capacity of the State or the Local Administration to construct the project proposed or implement the selected measures.

   2. Time Required

      Time is a crucial factor for actions to combat drought. Therefore, this criterion represents the time of response related to the implementation initiation of selected action.

   3. Cost Effectiveness

      This factor counts the cost of unit volume of water produced by the selected action. In fact this criterion reflects the results of the Cost Effectiveness Analysis used extensively in Water Resources Management Plans according to the WFD directive.

   4. Indicator of Significance

      This indicator reflects the volume or the percentage of the water shortage which can be covered by the corresponding action.

b. Constraining criteria

   1. Environment Compatibility

      It measures the (negative) effects on the environment which though in most of the cases may be delayed or difficult to quantify. Additionally in this category the total energy consumption and the total greenhouse gas emissions in the life cycle analysis of the proposed action, could be included (Tsakiris 2014).

   2. Social Acceptance

      This factor measures the level of acceptability of the action by the stakeholders and the society.

   3. Compatibility with the long term Strategic Water Resources Management.

      This indicator represents the level of agreement of each selected action to combat drought with the strategic Water Resources Management Plan of the area.

The evaluation of the various alternative actions can be achieved by considering both the "beneficial" and the "constraining" criteria. For this purpose, the use a multicriteria procedure using a fuzzy implication approach is proposed in this paper. The innovative character of the proposed method is that it includes the evaluation of the disagreement between the constraining and the beneficial criteria by using a fuzzy implication.

3 Fuzzy Implications: Basic Notions

In general, the methodology of fuzzy sets comprises a mapping from a general set *X* to the closed interval [0,1], which is described by the corresponding membership function. The operations of the fuzzy logic provide a variety of ways to simulate the human way of thinking. In general, these operations can be defined axiomatically. In this paper we use two fuzzy implications and some characteristic fuzzy intersections. Before applying methods of fuzzy logic, it is necessary to define the concepts of the fuzzy intersection and fuzzy implication.

In general a fuzzy intersection, T-norm, is a binary operation on the unit interval $T([0,1]\times[0,1]\rightarrow[0,1])$ that satisfies at least the following axioms for all a and b belonging to the interval [0, 1]:

$$\left.\begin{array}{ll} T(a,1) \;=\; a & (\text{boundary condition}) \\ a\leq c \text{ implies } T(a,b)\leq T(c,b) & (\text{monotonicity}) \\ T(a,b)=T(b,a) & (\text{symmetry}) \\ T(a,\ T(b,c))=T(T(a,b),c) & (\text{associativity}) \end{array}\right\} \quad (1)$$

The above set of axioms constitutes the axiomatic skeleton of fuzzy intersections, T-norms. All functions which satisfy the above axiomatic skeleton of fuzzy intersection are fuzzy intersections (e.g. Klir and Yuan 1995). In this paper two fuzzy intersections were selected to be used, the min intersection, T_{min} (Eq. 2), and the intersection of bounded difference, T_{bd} (Eq. 3):

$$T_{min}(a,b)=\min(a,b) \quad (2)$$

$$T_{bd}(a,b)=\max(a+b-1,0) \quad (3)$$

The fuzzy intersection is most appropriate for the interpretation of simultaneous evaluation of logical propositions (Tsakiris et al. 2009). However, with a fuzzy intersection we cannot achieve any compensation between the criteria.

Another fuzzy aggregator used in this paper, is the fuzzy implication. In the field of classical logic, for all propositions of P and Q defined on sets A and B respectively, the implication ‘P implies Q’ is equivalent to taking the union of elements in the complement of the set A with the elements of the set B (Ross 2004):

$$(P\rightarrow Q)\equiv\left(\overline{A}\cup B\right)\equiv(\text{either}'\text{not in } A'\text{ or}'\text{in } B') \quad (4)$$

For illustration purposes the area corresponding to the crisp implication is presented in Fig. 1. The implication is strongly related to the *difference* between the two sets. That is the complement of the set that A implies B, $\overline{(A\rightarrow B)}$ is equal to the difference A|B.

The white region in Fig. 1 expresses the difference between the two sets. Therefore, starting from the concept of fuzzy implication, the main idea is to select alternatives, which are located at the fuzzy set A, which expresses a successful evaluation of the beneficial criteria, without the region of the negative influence of the constraining criteria (set B in

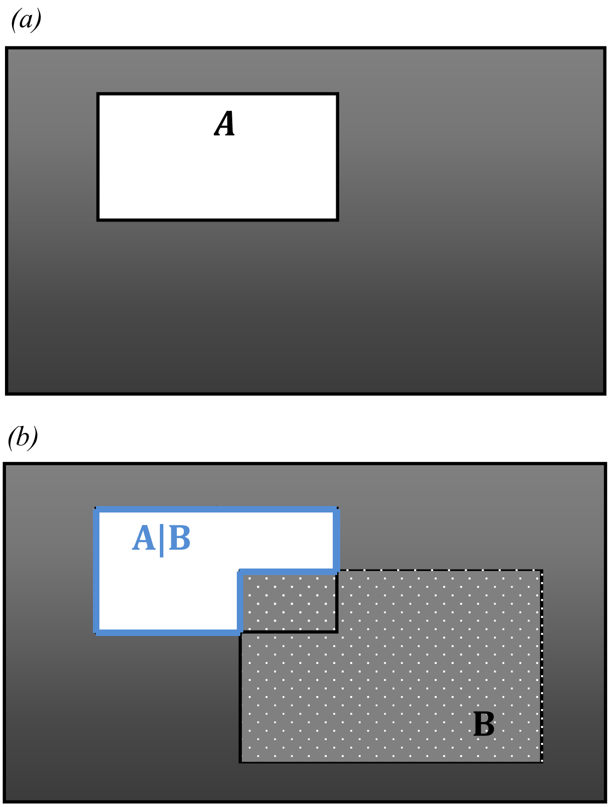

Fig. 1 **a** The crisp set A and its complement (*grey region*), and **b** the white region is the set $\overline{(A\rightarrow B)} = A|B$. All the other *grey area* is where implication holds (Ross 2004)

Fig. 1). It is evident that in fuzzy logic an alternative belongs to a fuzzy set, which expresses a criterion, with a degree, and therefore the boundaries are not so crisp and well defined as in Fig. 1.

Based on the above definition several fuzzy implications can be formulated. It is interesting to note that these implications become identical in case of crisp data. The most commonly used types of fuzzy implications are (e.g. Papadopoulos et al. 2007):

1. S-implications, based on the above classical idea of implication:

$$J(a,b) = S(N(a),b) \tag{5}$$

2. R-implications. These implications rest on the idea that they reflect a partial ordering proposition:

$$J(a,b) = \sup\{c\in[0,\ 1]|T(a,c)\leq b\} \tag{6}$$

3. QL-implications. These fuzzy implications are called *QL-implications,* since they were originally employed in quantum logic (Klir and Yuan 1995):

$$J(a,b) = S(N(a),T(a,b)) \tag{7}$$

where J is the fuzzy implication, S is the fuzzy union, T is the fuzzy intersection and N the fuzzy negation (i.e. complement).

In the next section we examine the appropriateness of the above three representative implication norms in order to express the compatibility between the beneficial and the constraining criteria.

4 The Proposed Methodology

The proposed methodology is comprised of three consecutive steps.

In the first step we focus only on the "beneficial criteria". In this step, a multicriteria method with the property of compensation is more appropriate. In this study, the widely-used, dimensionless weighted Euclidean Distance from the ideal solution is selected as the multicriteria method.

The basic equation of this method, which gives the evaluation index of each *j*-th alternative, f_j, is:

$$f_j = \sqrt{\sum_{i=1}^{N} \left(w_i \left(\frac{g_{ij} - g_i^*}{g_i^*} \right)^2 \right)}, \qquad \sum_{i=1}^{N} w_i = 1, \qquad w_i \geq 0 \tag{8}$$

where, g_{ij} is the score of the alternative *j* with respect of the criterion *i* and g_i^* is the ideal evaluation according to the criterion *i*. Also, w_i is the weight of the criterion *i*, and finally *N* is the total number of the beneficial criteria.

Further, instead of the measure f_j we could use its complement: $f_j^* = 1 - f_j$. It is obvious that the index f^* represents the overall evaluation of the *j*-th alternative with respect of all the beneficial criteria. Since the f^* takes values in the closed interval from zero to one, then it can be viewed as a fuzzy set which expresses the favourable evaluation of the overall index based on the beneficial criteria.

In the second step the basic challenge is to interpret the compatibility of the constraining criteria with the beneficial criteria, presented above. The comparison of the overall index of the beneficial criteria, f^*, with each constraining criterion follows. The compatibility index I_j for the alternative action *j*, is based on the interpretation of the logical proposition that "the negation of the statement that a good evaluation of the overall index f^* (with respect of the beneficial criteria) leads to (implies in mathematical terms) the occurrence of either negative effects on the environment (α') or unacceptability of the action by the stakeholders and the society (β'), or a disagreement with the strategic water resources management plans of the area (γ'). Therefore, the following logical equation can be written in case that the De Morgan laws hold:

$$\mathrm{I}_j = \overline{\left(f_j^* \rightarrow \alpha'_j\right)} \cap \overline{\left(f_j^* \rightarrow \beta'_j\right)} \cap \overline{\left(f_j^* \rightarrow \gamma'_j\right)} \tag{9}$$

According to the crisp logic this can be interpreted as the difference between the fuzzy set which expresses a satisfactory evaluation of the overall index of the beneficial criteria, f^*, and the sets α', β' and γ'.

Due to the fact that the use of the fuzzy implications is envisaged, the terms $\alpha'_j, \beta'_j, \gamma'_j$ can be expressed with the use of the complement of the dimensionless normalised evaluation of the constraining criteria (h_{1j}, h_{2j} and h_{3j}):

$$a_j^{'} = 1 - \frac{h_{1j}}{h_1^*}, \quad \beta_j^{'} = 1 - \frac{h_{2j}}{h_2^*}, \quad \gamma_j^{'} = 1 - \frac{h_{3j}}{h_3^*} \tag{10}$$

in which $\alpha_j = h_{1j}/h_1^*, \beta_j = h_{2j}/h_2^*, \gamma_j = h_{3j}/h_3^*$ are the normalised evaluations of the constraining criteria (positive influence), while Eq. 10 expresses the negative influence (impacts) by using the strict negation of the crisp logic ($\alpha_j^{'}, \beta_j^{'}, \gamma_j^{'}$).

Obviously, the logical term "and" is expressed by using the min-intersection. We select the use of the min-intersection because other fuzzy intersections can lead to unrealistic outcomes in case of a significant number of criteria.

In case that the crisp complement *($\alpha' = N(a) = 1 - \alpha$)* is used and the min intersection is selected as fuzzy intersection, the logical proposition of Eq. 9 can be written as follows:

$$\mathrm{I}_j = \min\left\{1 - \left(J\left(f_j^*, 1 - \alpha\right)\right), 1 - \left(J\left(f_j^*, 1 - \beta\right)\right), 1 - \left(J\left(f_j^*, 1 - \gamma\right)\right)\right\} \tag{11}$$

There are several fuzzy implications that can be examined. The R-implications place emphasis on the inclusion concept. For example by using the Goguen implication (R-implication family, Klir and Yuan 1995), the basic logical proposition (Eq. 9) is emitted, in case the constraining criteria are considered most significant than the beneficial criteria. This seems to be an extremely strict approach.

On the other hand, if we express the negative influence by using the crisp complement *($\alpha' = 1 - \alpha$)*, then the use of the S-implication leads to a corresponding fuzzy intersection with respect of α and f^*. The proof is briefly presented in the Appendix.

Finally since we often wish to give more emphasis on the beneficial criteria we mainly propose the use of the QL-implications. In the next sub-section we present briefly of the Klir and Yuan implication (QL implication) and the Lukasiewicz implication (S-implication).

4.1 Use of the QL-Implication of Klir and Yuan

The Klir and Yuan implication is used in this study:

$$J\left(f_j^* \rightarrow a_j^{'}\right) = 1 + a_j^{'} f_j^{*2} - f_j^* \tag{12}$$

The Klir and Yuan implication belongs to the QL-implication family. Indeed this implication is generated based on the general definition of the QL-implication (Eq. 7) by using the algebraic product as T-intersection, and the algebraic sum as a fuzzy union.

Then based on Eq. 11 the compatibility index can be expressed as follows:

$$\begin{aligned}\mathrm{I}_j = \min\left\{\left[1 - \left(1 - f_j^* + \alpha_j^{'} \cdot f_j^{*2}\right)\right], \left[1 - \left(1 - f_j^* + \beta_j^{'} \cdot f_j^{*2}\right)\right], \left[1 - \left(1 - f_j^* + \gamma_j^{'} \cdot f_j^{*2}\right)\right]\right\} = \\ \min\left\{\left[f_j^* - \alpha_j^{'} \cdot f_j^{*2}\right], \left[f_j^* - \beta_j^{'} \cdot f_j^{*2}\right], \left[f_j^* - \gamma_j^{'} \cdot f_j^{*2}\right]\right\}\end{aligned} \tag{13.a}$$

By expressing the negative influence of the constraining criteria with respect of the crisp complement, the above equation becomes:

$$\mathrm{I}_j = \min\left\{\left[f_j^* - (1 - \alpha_j) \cdot f_j^{*2}\right], \left[f_j^* - (1 - \beta_j) \cdot f_j^{*2}\right], \left[f_j^* - \left(1 - \gamma_j\right) \cdot f_j^{*2}\right]\right\} \tag{13.b}$$

An interesting point of view is that in general the QL implication does not lead to a fuzzy intersection with respect of α and f^*.

In Fig. 2 the compatibility index with respect of the total evaluation of the beneficial criteria f^*, and one constraining criterion, α, are presented.

4.2 Use of the Lukasiewicz Implication

In case the Lukasiewicz implication is used (Nguyen and Walker 2006):

$$J\left(f_j^*\rightarrow a_j^{'}\right) = \min\left(1 + a_j^{'} - f_j^*,\, 1\right) \tag{14}$$

The Lukasiewicz implication is a kind of S-implication since, indeed, it can been produced based on the general definition of the S-implication (Eq. 5) by using the bounded sum as fuzzy union (Nguyen and Walker 2006). Therefore based on Eq. 11 the compatibility index can be expressed as follows:

$$\mathrm{I}_j = \min\left\{\left[1-\min\left(\left(1-f_j^* + \alpha_j^{'}\right), 1\right)\right], \left[1-\min\left(\left(1-f_j^* + \beta_j^{'}\right), 1\right)\right], \left[1-\min\left(\left(1-f_j^* + \gamma_j^{'}\right), 1\right)\right]\right\} \tag{15}$$

Let us express the negative influence of the constraining criteria by using the crisp complement. Then it is easy to prove by simple algebraic calculations that each individual implication is equal with the bounded difference, which is a fuzzy intersection (Eq. 3). This fact can be seen in the framework of the corresponding general property of the S-implication presented in the Appendix. Therefore the above implication can be written as follows:

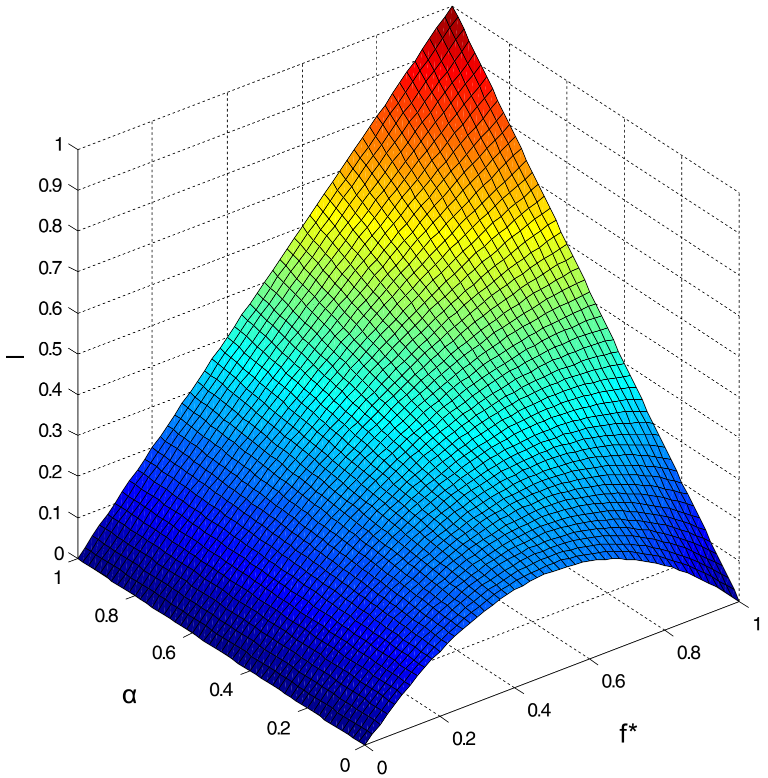

Fig. 2 Values of the compatibility index based on the complement of the Klir and Yuan implication with respect to the total evaluation of the beneficial criteria f^* and one constraining criterion, α

$$\mathrm{I}_j = \min\left\{\left[\max\left(\left(-1+f_j^*+\alpha_j\right),0\right)\right],\left[\max\left(\left(-1+f_j^*+\beta_j\right),0\right)\right],\left[\max\left(\left(-1+f_j^*+\gamma_j\right),0\right)\right]\right\} \tag{16}$$

In contrast with the Klir and Yuan implication, the use of the Lukasiewicz implication gives equal importance to both beneficial and constraining criteria. Using one of the terms of the left hand side of Eq. 16 with respect to the total evaluation of the beneficial criteria, f^*, and one constraining criterion, α, the compatibility index with respect of f^* and α is presented in Fig. 3 (equivalent with the bounded difference between f^* and α).

4.3 Final Aggregation of Beneficial and Constraining Criteria

During the last (third) step of the procedure we try to combine both indices, f^* and I using the weighted sum approach:

$$\mu = k_1 f_j^* + k_2 \mathrm{I}_j,\quad k_1 + k_2 = 1,\quad k_1, k_2 \geq 0 \tag{17}$$

The weight k_1 is the weight of the strategy of the beneficial criteria, whereas the weight k_2 expresses the importance of the compatibility between the beneficial and the constraining criteria.

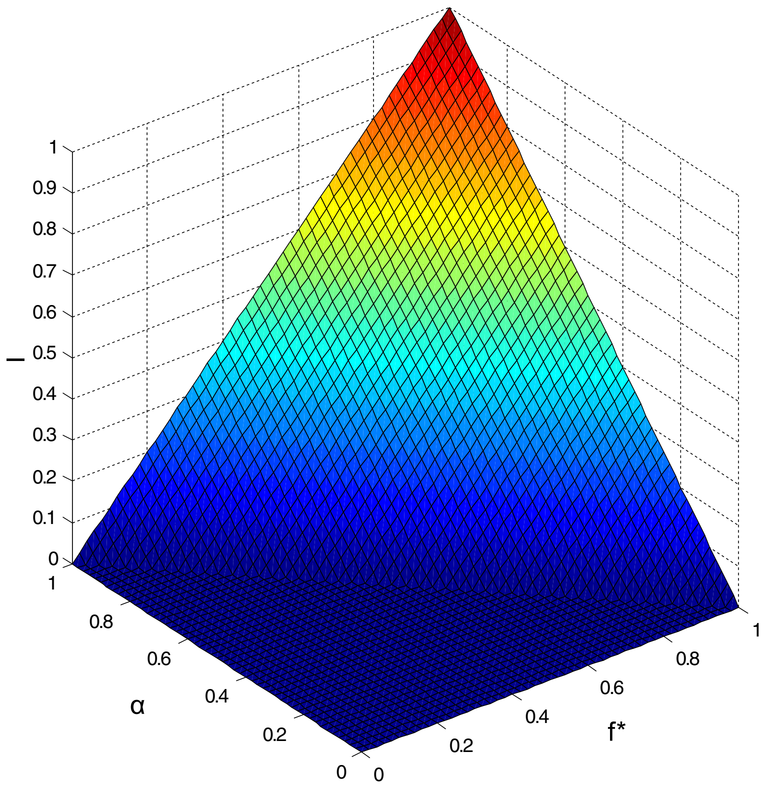

Fig. 3 Values of the compatibility index based on the complement of the Lukasiewicz implication with respect to the total evaluation of the beneficial criteria f^* and one constraining criterion, α

5 Case Study

5.1 The Study Area: Heraklion, Crete

The city of Heraklion is located in the north and central part of the island of Crete (Greece). The water distribution network of the city is operated by the "Heraklion Municipal Water Authority", a water utility company which serves all the residential sectors of the municipality of Heraklion and the neighbouring municipality of Nea Alikarnassos. The total area under this authority is about 27 km^2 and the served population is estimated to exceed 160,000 inhabitants. The current water demand for the area is estimated to 14.5 million m^3 per year and is expected to increase to 16.7 million m^3 for the year 2020.

Eleven well fields, comprising 62 production wells and 6 springs supply the water, which is distributed to the municipality through a system of storage and service reservoirs and a 147 km long distribution network. The water supply system of Heraklion appears in Fig. 4. The maximum total annual pumping volume at the sources is 16.5 million m^3, but only the volume of 14.4 million m^3 reaches the distribution network. About 6.1 million m^3 (42 % of the total inflows) are recorded as losses (real or apparent) in the entire municipal water supply and distribution system. This very high percentage of non-revenue water is mainly due to the inadequate metering practices and the ageing of some parts of the distribution network.

It is to note that a number of aquifers (Malia, Keri Tylisos and Thrapsano) have exhibited qualitative or quantitative problems due to their hydrogeological conditions and the existing withdrawal pattern. The rest of the well fields are not expected to develop such problems. According to an empirical vulnerability analysis and rating devised for all contributing supply aquifers, the proportion by which water withdrawals should be reduced for sustaining water quality and quantity at acceptable levels was determined. According to this study a 50 % pumping

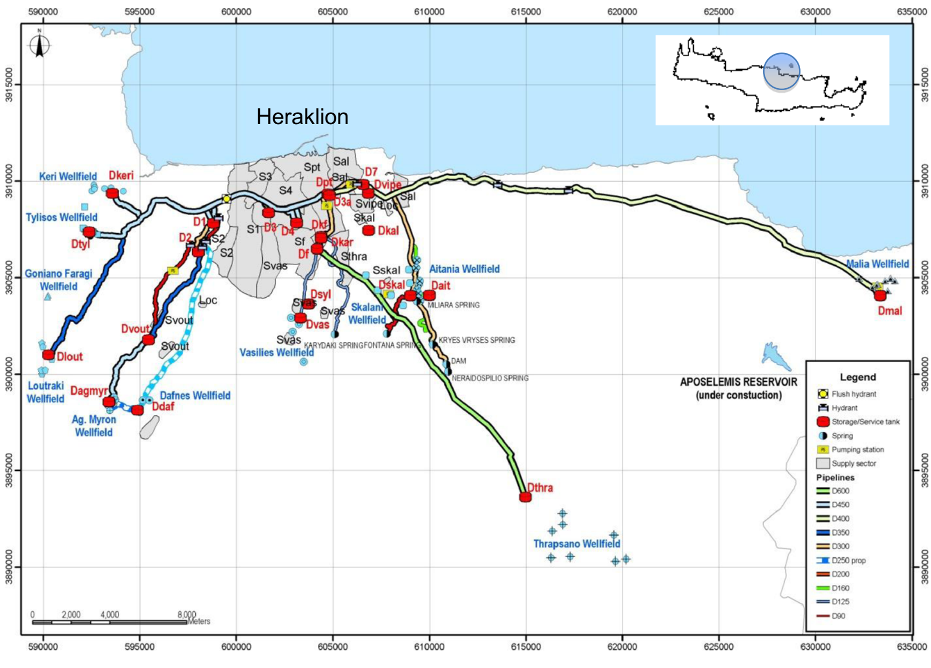

Fig. 4 The Heraklion municipal water supply system (redrawn from PRODIM 2008)

reduction should be applied to the Malia, Keri and Tylisos well fields, while an 80 % pumping reduction should be applied to the Thrapsano well field. The quantitative and qualitative reliability of all other aquifers will remain unchanged, provided that reasonable water abstraction levels are maintained.

The alternative (future) water supplies established so far include another well field (Dafnes), the Aposelemis dam (constructed recently but not in operation yet) and the Almyros brackish-water spring, which however still remains as a potential solution to the water shortage which often occurs in the area. It is interesting to note that Aposelemis dam with a capacity of 28 million m^3 can offer a sustained annual quantity of water in the range 11–13 million m^3 from which 7–9 million m^3 can be accounted for Heraklion municipality (PRODIM 2008).

The analysis which follows refers to severe drought situations, such as the period 1989–1993, which quite often occur in the area with varying intensity. Therefore the alternative solutions are formulated for combating drought episodes and not for solving the permanent water scarcity problems of the area which is the objective of the strategic water resources management plan of the area.

5.2 Solutions and Criteria

All significant alternative solutions which were technically viable in general were assessed and presented below. Most of them were also identified and accepted by a large number of experts and stakeholders who participated in a campaign by filling an opinion poll in the framework of the research project PRODIM (PRODIM 2008).

The alternative solutions of the contingency plan to combat drought and its effects are in brief:

1. Network improvement
2. Demand management
3. New groundwater development
4. New dam construction
5. Water transfer by vessels
6. Water mixing with brackish water
7. Desalination

These potential solutions were evaluated by a team of experts for the most important criteria. That is the viability, the required time for operation, the cost effectiveness, and the significance for covering the projected deficit. For simplicity the first two criteria were merged

Table 1 Evaluation of alternative solutions against the beneficial criteria

Solution	Viability and time required for implementation	Cost effectiveness	Indicator of significance
1. Network improvement	3	4	2
2. Demand management	4	4	3
3. New groundwater development	2	5	3
4. New dam construction	1	3	5
5. Water transfer by vessels	5	1	3
6. Water mixing with brackish water	3	4	3
7. Desalination	3	3	4

1 = bad, 2 = slightly negative, 3 = moderate, 4 = good, 5 = excellent

Table 2 Evaluation of alternative solutions against the constraining criteria

Solution	Environmental	Social	Long term planning
1. Network improvement	5	5	5
2. Demand management	5	3	5
3. New groundwater development	3	5	4
4. New dam construction	2	4	5
5. Water transfer by vessels	5	4	3
6. Water mixing with brackish water	5	4	5
7. Desalination	4	3	5

1 = bad, 2 = slightly negative, 3 = moderate, 4 = good, 5 = excellent

into one. The evaluation of the various alternatives against the selected criteria as given by the questioned experts, are presented in Table 1.

Further, the alternative solutions were examined for their compatibility to a set of conditions in order to secure their compatibility to the long term plans and that they are acceptable by the people and do not cause harm to the environment. In this category as mentioned in paragraph 2, three criteria were selected. The evaluations against these additional criteria as given by experts were presented in Table 2.

Both Tables 1 and 2 are self-explanatory reflecting the high engineering judgment of the members of the team questioned.

It should be stressed that the environmental criterion as presented to the experts did not include the total energy consumption and the GHG emissions through the life cycle of the project proposed for each action. This is so because some alternatives are not of permanent nature. It is therefore anticipated that if the energy and GHG emissions were taken into account the environmental criterion could appear with different scores from these of Table 2. However, the evaluation of the experts did not take into account the energy consumption and the GHG emissions.

Table 3 Multicriteria evaluation based on the beneficial criteria

Solution (alternatives)	Normalized distance from the ideal solution			f	f^*
	Viability and time required	Cost effectiveness	Indicator of significance		
1. Network improvement	0.400	0.200	0.600	0.432	0.568
2. Demand management	0.200	0.200	0.400	0.283	0.717
3. New groundwater development	0.600	0.000	0.400	0.416	0.584
4. New dam construction	0.800	0.400	0.000	0.516	0.484
5. Water transfer by vessels	0.000	0.800	0.400	0.516	0.484
6. Water mixing with brackish water	0.400	0.200	0.400	0.346	0.654
7. Desalination	0.400	0.400	0.200	0.346	0.654

Table 4 Activation of Eq. 13.b (Klir and Yuan QL-implication) and final evaluation

Solution	J_1	J_2	J_3	Min	Sum
1. Network improvement	0.568	0.568	0.568	0.568	0.568
2. Demand management	0.717	0.511	0.717	0.511	0.635
3. New groundwater development	0.447	0.584	0.516	0.447	0.529
4. New dam construction	0.343	0.437	0.484	0.343	0.427
5. Water transfer by vessels	0.484	0.437	0.390	0.390	0.446
6. Water mixing with brackish water	0.654	0.568	0.654	0.568	0.619
7. Desalination	0.568	0.483	0.654	0.483	0.585

5.3 Application of the Proposed Methodology

As mentioned earlier, the proposed methodology is comprised of three consecutive steps.

1) The dimensionless weighted Euclidean Distance from the ideal solution is used to achieve a global evaluation of the beneficial criteria. The outcomes based on the data of Table 1 and by applying Eq. 8 are presented in Table 3.
2) In the second step the compatibility between the beneficial and the constraining criteria is examined. At first the Klir and Yuan QL-implication is used according to Eq. 13.b and the results are presented in Table 4.

   As an alternative, the Lukasiewicz implication (Eq. 14) is also used for evaluating the compatibility between the beneficial criteria and each constraining criterion (columns 2, 3 and 4 in Table 5). Finally, the min intersection is used to aggregate the individual degrees of compatibility according to Eq. 16.
3) In the last step the two indices, I and f^* are combined. In Tables 4 and 5 the fifth column represents the total compatibility index based on the min intersection (Eq. 2) while the sixth column represents the final index evaluation (Eq. 17) for each alternative.

It can be easily seen that, as expected, the use of the implication rule leads to different ranking of alternatives compared to the evaluation which is based only on the beneficial criteria.

By selecting the weighted sum for the final evaluation in case of Lukasiewicz implication the "Network improvement" and the "Water mixing with brackish water" are preferred.

Table 5 Activation of the Lukasiewicz implication (Eq. 16) and final evaluation

Solution	J_1	J_2	J_3	Min	Sum
1. Network improvement	0.568	0.568	0.568	0.568	0.568
2. Demand management	0.717	0.317	0.717	0.317	0.557
3. New groundwater development	0.184	0.584	0.384	0.184	0.424
4. New dam construction	0.000	0.284	0.484	0.000	0.290
5. Water transfer by vessels	0.484	0.284	0.084	0.084	0.324
6. Water mixing with brackish water	0.654	0.454	0.654	0.454	0.574
7. Desalination	0.454	0.254	0.654	0.254	0.494

In case of the QL-implication use, the order of solutions is different. The alternative with highest rating is the "Demand management" followed by the alternative of "Water mixing with brackish water". The latter outcome seems more balanced according to practical engineering judgement.

It should be mentioned that a sensitivity analysis was performed by changing the values of the weights of the beneficial and the compatibility indices, f^* and I. (Eq. 17). It was concluded that with a conservative variation of the weight values, the results of ranking seem fairly stable.

6 Discussion

The main novelty of the paper is the distinction between the beneficial and the constraining criteria. In this paper this was achieved by using the Klir and Yuan implication. Therefore the proposed method gives emphasis on the beneficial criteria without the ignorance of the long-term constraints. However, the investigation can be continued in the field of QL-implication.

On the other hand the use of the Lukasiewicz implication leads to an interesting compensative fuzzy intersection. In case that we select the crisp complement, the use of S-implication between the f^* and α', β' and γ' leads to a fuzzy intersection between f^* and α, β and γ. In this case based on the symmetry principle we can deduce that equal weight is given to both types of criteria.

For the problem studied, it is to note that with respect to the cost effectiveness criterion, the alternative of new groundwater development has the highest priority. According to our proposed method this is not the case. This is because of the low evaluation of the other beneficial criteria (Viability and time required for implementation, and Indicator of significance) and simultaneously because of the corresponding low score against the environmental criterion (Tsakiris et al. 2009). This can be even worse if in the environmental criterion the total energy consumption and the GHG emissions for the life cycle of the corresponding project were taken into account.

7 Concluding Remarks

The paper proposes a methodology for the rational evaluation of all feasible alternatives for combating water shortage caused by drought based on both short and long term criteria. The methodology is general and can be incorporated in the drought contingency plan of any drought-prone area.

The proposed methodology is based on a simple widely-used multicriteria method such as the dimensionless Euclidean distance and a fuzzy implication. The fuzzy implications examined in this study are those of Klir and Yuan, and Lukasiewicz.

Two types of criteria are used (beneficial and constraining) for evaluating the short term and long term consequences, respectively.

It was observed that through the fuzzy implication a more balanced evaluation approach is achieved for comparing the actions against drought in comparison to the multicriteria evaluation which is based only on the short term criteria.

Further, from the two fuzzy implications examined, the Klir and Yuan implication gives more emphasis to the short term criteria whereas the Lukasiewicz implication results in an equally balanced evaluation of both short and long term criteria.

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Appendix

Proposition If we express the negative influence of the constraining criteria by using the crisp complement $(\alpha' = 1-\alpha)$, then the use of the S-implication with respect to α' and f^* leads to a corresponding fuzzy intersection with respect of α and f^*.

Proof Let J a S-implication and let the crisp complement, $\alpha' = 1-\alpha = \mathrm{N}(\alpha)$, then according to definition of the S-implications it holds (Eq. 5):

$$1-J(f^*, a') = 1-J(f^*, 1-a) = 1-(S(1-f^*, 1-a)) \tag{A1}$$

In fuzzy logic the De Morgan laws hold for a selected combination of the fuzzy union, S, fuzzy intersection, T, with respect to a fuzzy complement (here the crisp negation). Therefore for a dual choice of both the fuzzy intersection and fuzzy union it holds:

$$1-(S(1-f^*, 1-a)) = T(f^*, a) \tag{A2}$$

It should be mentioned that only some combinations of fuzzy unions, fuzzy intersections, and fuzzy complements can satisfy the De Morgan laws (Klir and Yuan 1995). In this case, a combination that can satisfy both the two laws of the conventional logic (which are widely known as De Morgan Laws) could be selected.

References

ASCE Task Committee on Sustainability Criteria (1998) Sustainability criteria for water resource systems. ASCE, Reston, 253 pages

FAO/NDMC (2008) The Near East Drought Planning Manual: Guidelines for Drought Mitigation and Preparedness Planning. Knutson CL (Lead Author), Food and Agriculture Organization of the United Nations Regional Office for the Near East (Cairo, Egypt) and the National Drought Mitigation Centre (USA). FAO, Rome, Italy, 52 p

Hayes MJ, Alvord C, Lowrey J (2007) Drought indices. Feature article. Intermountain West Climate Summ 3(6): 2–6

Iglesias A, Garrote L, Cancelliere A, Cubillo F, Wilhite D (2009) Coping with drought risk in Agriculture and Water Supply Systems, Drought Management and Policy Development in the Mediterranean. Springer (Advances in Natural and Technological Hazards Research, Volume 26), Springer Science, 320 p

Klir G, Yuan BT (1995) Fuzzy sets and fuzzy logic theory and its applications. Prentice Hall, New York

Loucks D (2000) Sustainable water resources management. Water Int 25(1):3–10

Mishra AK, Singh VP (2010) A review of drought concepts. J Hydrol 391(1–2):202–216

Nguyen H, Walker E (2006) A first course in fuzzy logic. CRC Press, Taylor and Francis Group, Boca Raton

Niemeyer S (2008) New drought indices. Proceedings of the 1st International Conference "Drought management: Scientific and technological innovations" Option Méditerranéennes, Series A, No. 80, 12–14 June 2008, Zaragoza (Spain), pp 267–274

Papadopoulos B, Trasanides G, Hatzimichailidis A (2007) Optimization method for the selection of the appropriate fuzzy implication. J Optim Theory Appl 134(1):135–141

Pereira LS, Cordery I, Iacovides I (2009) Coping with water scarcity. Addressing the challenges. Springer, Dordrecht, 382 p

PRODIM (2008) Proactive Management of Water Systems to Face Drought and Water Scarcity in Islands and Coastal Areas of the Mediterranean (PRODIM)—Final Report, Tsakiris G (ed) CANaH—Publication 6 / 08. Athens, Greece, 448 p

Ross T (2004) Fuzzy logic with engineering application, 2nd edn. John Wiley and Sons, Ltd, Chichester, pp 123–137

Rossi G, Vega T, Bonaccorso B (2007) Methods and tools for drought analysis and management, Springer (Water Science and Technology Library, Volume 62), Dordrecht, The Netherlands, ISBN: 978-1-4020-5923-0, 418 p

Tsakiris G (2014) Rational design of urban water supply and distribution systems. Water Util J 8:5–16

Tsakiris G, Spiliotis M (2011) Planning against long term water scarcity: a fuzzy multicriteria approach. Water Resour Manag 25(4):1103–1129

Tsakiris G, Pangalou D, Vangelis H (2007) Regional drought assessment based on the Reconnaissance Drought Index (RDI). Water Resour Manag 21(5):821–833

Tsakiris G, Spiliotis M, Paritsis S, Alexakis D (2009) Assessing the water potential of Karstic Saline Springs by applying a fuzzy approach: the case of Almyros (Heraklion – Crete). Desalination 237:54–64

Tsakiris G, Nalbantis I, Vangelis H, Verbeiren B, Huysmans M, Tychon B, Jacquemin I, Canters F, Vanderhaegen S, Engelen G, Poelmans L, De Becker P, Batelaan O (2013) A system-based paradigm of drought analysis for operational management. Water Resour Manag 27(15):5281–5297

UNESCO Working Group M.IV (1999) Sustainability criteria for water resource systems. Cambridge University Press, Cambridge

Van Loon AF, Van Lanen HAJ (2012) A process-based typology of hydrological drought. Hydrol Earth Syst Sci 16(7):1915–1946

Wilhite DA (1993a) The enigma of drought (chapter 1, part one). In: Wilhite DA (ed) Drought assessment, management and planning: theory and case studies. Kluwer Academic Publishers, Norwell, pp 3–15

Wilhite DA (1993b) Drought assessment, management and planning: theory and case studies. Kluwer Academic Publishers, Norwell, 294 p